# EASTERN INTERCONNECTION BASELINING STUDY
# Subcontract 6996016

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2014/2015 Final Report

August 4, 2015

Prepared for

CERTS
Consortium for Electric Reliability Technology Solutions

Prepared by

Electric Power Group

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**ACKNOWLEDGEMENT**

This work was coordinated by the Consortium of Electricity Reliability Technology Solutions and was funded by the Office of Electricity Delivery and Energy Reliability, Energy Infrastructure Modeling and Analysis Program in the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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# 1 EXECUTIVE SUMMARY

Synchrophasor technology enables control center operators to monitor power grid dynamics in real time over a wide area of an interconnection or the entire interconnection. To make use of synchrophasor technology to prevent blackouts, operators need information on normal and abnormal grid performance patterns for a range of key system parameters such as system stress (angle differences), low damped or growing inter-area oscillations, voltage degradation, sensitives and other parameters so that the operators are alerted to take appropriate action and avoid cascading blackouts. Programs are now available to monitor these dynamic power system metrics in real-time.

To distinguish normal and abnormal parameter ranges that can be expected in real-time operations, the EI baselining study was started. The objective of this study is to analyze grid metrics and baseline performance for a range of metrics including:

- Wide Area angle pairs (Inter-ISOs for wide area stress).
- Inter-area power flows and oscillations (major inter-area power transfers).
- Voltages on sensitive/critical busses.
- Voltage and angle sensitivities at critical busses.

These baselining analysis results can provide guidance to operators on:

- normal range
- abnormal range
- pattern of metrics
- establish thresholds for alarms that warrant operators action.

Electric Power Group (EPG) was asked to work with the leadership of the Operations Implementation Task Team (OITT) and the Planning Implementation Task Team (PITT) of North American Synchro-Phasor Initiative (NASPI), as well as independent system operators (ISOs), regional transmission owners (RTOs), and utilities to carry-out interconnection baselining analysis. The PITT and OITT teams identified baselining phase angles as their highest priority. Although, the analysis can be conducted for all four metrics quantities, this present work has been limited to "Wide Area Angle Pair Analysis". The goal of this Eastern Interconnection Baselining Analysis Project is to work with the NASPI Operations

and Planning teams and other Consortium for Electric Reliability Technology Solutions (CERTS) research performers, such as Pacific Northwest National Laboratory (PNNL), to carry out a comprehensive baselining analysis for establishing the high/low ranges for selected angle pairs. The study covered the four ISO regions in Eastern Interconnection, NYISO, PJM, MISO and ISO New England.

As a first step in the analysis process, only the five minute State Estimator (SE) data was used for previous years analysis. The State Estimator data from different ISO's ranged from a few months to about two years (2010-2011). Twenty two (22) angle pairs were selected based on either input from the ISOs or by analyzing different sources and sinks in the region. Detailed statistical analysis was conducted on the data extracted from the SE data, and a recommended range was provided for each of the angle pairs. Box-whisker plot and time duration curve were introduced to set the operational monitoring range. The methodology was applied to all four individual ISOs. For Inter-ISO study, SE data from different ISOs was "stitched"or combined and time aligned to obtain ranges for wide area (Inter-ISO) angle pairs. It was soon realized that this approach was not feasible with SE data and instead synchronized phasor data is required. The analysis results using State Estimation data can be found in the 2013 "BASELINING STUDY WITH A FOCUS ON EASTERN INTERCONNECTION"report submitted on August 6, 2014 [6].

The analysis methodology developed with state estimation data has been extended and applied to synchrophasor data. The methodology was applied to two months of phasor data from December 15, 2013 to February 14, 2014, and two months of phasor data from September 1, 2014 to October 31, 2014, representing the winter and fall periods respectively but used one second data samples. This analysis work accomplished the following:

- data quality review
- data filtering process to eliminate bad data
- baselined voltage angle pair performance (ranges, thresholds)
- recommended operational ranges (limited due to use of limited data)

The proposed ranges were examined by four ISOs and it was concluded that further and more detailed research is needed to support operations. This will require at least 12-18 months of phasor data. The monitoring range should be set based on the seasonal, hourly and on-peak and off-peak performance that will give more meaningful guidance to the operators to understand the system status.

Clustering analysis for all selected angle pairs is conducted for both seasons. It is observed that overall the angle pairs have higher correlation with each other

during winter than in fall. This observation can be attributed to higher system stress during winter due to high loading conditions which results in higher power flow and tighter alignment in angle difference pairs from west to east.

Initial oscillation study was performed and showed that Raun-Ramapo (wide area) has 0.2 Hz oscillatory mode and Niagara-Ramapo (Local-area) has 0.39 Hz and 0.41 Hz oscillatory modes. Detection of frequency modes higher than 0.5 Hz which may be possibly present in the data would require higher sampling data rate for analysis.

In addition to baselining of angle pairs, the ISO Technical Advisor Group (TAG) members requested an analysis of the correlation between the angle pair differences and the Locational Marginal Price (LMP). The LMP data of four ISOs was provided by ISOs/collected by CERTS-EPG. Overall, analysis shows no strong correlation between LMP and angle difference. But, it is observed that LMP price spike up when certain angle differences are high, which may indicate that system is in stress. However, this may be the effect of grid stress and hence LMP's follow high stress and not vice-versa. The detailed study results of five stress cases and high LMP are provided in this report.

Based on ISO members request, the angle pair difference behavior during stressed conditions was also studied. Event analysis is performed using the control chart analysis on the data during Dec 1-Dec 7 2014. The method of using control-chart analysis with one-minute angle difference change range is described. Three NERC major events and some small local events are detected. Angle pairs close to the event location can detect the event. Angle pairs that are far away from the event location do not detect the event. It is also observed that stress levels are correlated with angle differences and voltages during events. Bus with highest voltage change is the weakest bus and often closest to event.

In the conclusion, research results are listed below:

- State estimator data does not have sufficient resolution and time synchronization to provide good baselining results.
- Phasor data can be used effectively for baselining performance - ranges and operating thresholds.
- To inform operations and establishing ranges, baselining analysis should be conducted for 12 to 18 months of data.
- Data quality is big issue - extensive data checking and filtering is required to perform baselining analysis. Doing this manually is very time consuming.
- LMP's and phase angle differences show a weak correlation with LMP's following increase in angle differences.

- Statistical control chart methodology can be used to identify extreme events.

The analysis technique successfully detected events for one week of December 2014. More work is needed to test different statistical control levels to identify near misses. Baselining analysis should be extended to a research and study event precursors (thresholds, trends and rate of change of metrics), which could be used by operators in improving the system performance.

# 2 BACKGROUND

Major blackouts that have occurred in the last twenty years worldwide have identified the need for real-time wide-area monitoring of power system dynamics using phasor system technology. With the advancement in the phasor system technology, it is now possible to identify the system stress and other problems, such as growing inter-area oscillations or voltage degradation early enough so that the operators are alerted to take appropriate action and avoid cascading. Real-time tools are available to monitor these dynamic metrics. However, operators need guidance on the normal and abnormal ranges that can be expected in real-time operations, as well as to define thresholds to alert the operators when the system is moving from a secure state to a less secure state warranting action. Some of the metrics that can be monitored using the high-speed and high-resolution phasor system data are:

- Wide Area angle pairs (Inter-ISOs for wide area stress).
- Inter-area power flows and oscillations (major inter-area power transfers).
- Voltages on sensitive/critical busses.
- Voltage and angle sensitivities at critical busses.

The Department of Energy, via Lawrence Berkeley National Lab (LBNL), commissioned Electric Power Group, LLC (EPG) to work on the Eastern Interconnection Baselining Study under subcontract 6996016. EPG is a member of the Consortium for Electric Reliability Technology Solutions (CERTS). EPG was asked to work with the leadership of NASPI's Operations Implementation Task Team (OITT) and the Planning Implementation Task Team (PITT), as well as independent system operators (ISOs), regional transmission owners (RTOs), and utilities to carry-out interconnection baselining. The PITT and OITT teams of North American Synchro Phasor Initiative (NASPI) identified baselining Eastern Interconnection phase angles as their highest priority.

The goal of this Eastern Interconnection Baselining Analysis Project is to work with the PITT and other CERTS research performers, such as Pacific Northwest National Laboratory (PNNL), to carry out a comprehensive baselining study. This analysis focuses on presenting statistical measures of phase angle range for the Eastern Interconnection covering the footprints of the four Independent System Operators (ISOs) in the Eastern region. The four ISOs currently being analyzed are PJM Interconnection, Midwest ISO, New York ISO, and ISO New England. Prior work which has been performed by using 5-minute state estimator was summarized in 2013 technique report submitted on August 6, 2014[6]. With synchrophasor data becoming available, the State Estimator results can be used as a

starting point. We will use the information and methodology developed in an earlier study to build a historic view for four ISOs by using synchro-phase data. The data from these ISOs has been received for two months of winter phasor data from December 15, 2013 to February 14, 2014, and two months of fall phasor data from September 1, 2014-October 31, 2014. Interest inspired during group discussion led to study the correlation between the angle pair differences and the Locational Marginal Price (LMP) differences. The detail will be described in the following sections.

# 3 ANALYSIS APPROACH

## 3.1 PMU Data Processing Procedure

PMU data was received for the required buses to be used for analysis from all four ISOs as separate data files. The data sample rate was 1 sample per second. The data files were provided either in comma separated (CSV) or Microsoft Excel files. This data was first preprocessed to clean, condition, and then time-synchronize to create a single dataset for analysis. The following steps were taken to prepare the individual data files into the final dataset for analysis:

**Combine individual files from each ISO into single files:** The data files received from each ISO were combined together into a single time-series comma separated (CSV) dataset with first column is date-time column and subsequent columns are select PMU Voltage Angle data. If the data quality status flag information is available, then it was also included as a column to be used later for data conditioning.

**Clean data using filters** The data was cleaned using Phasor Data Conditioning Application (PDCA) [1]which uses status flag, extreme value and repeating value filters to clean the data

***Status flag***-when available, the status flag in the provided data file is used to clean data that was flagged to be bad.

***Extreme values***-when data exceeds known limits (for example, for voltage angle data in degrees the data should not exceed -180 to 180)

***Repeating values***-data with repeating values such as repeating 0, 120, -9999 are considered as non-functioning PMUs and the data is eliminated

**Fill missing timestamps:** In some data files it was identified that there were missing rows of data which would have to get filled before merging the files to create a single dataset for calculating voltage angle difference. It was also discovered that in some data files there were duplicate rows which had to be eliminated. The gaps and duplicates were identified by looking at difference in consecutive timestamps in the first column. If the difference is more than 1 second then a gap is identified and missing data was filled by inserting "NaN", and if the difference is less than 1 second then duplicate rows were identified and eliminated. At the end of this process we have evenly spaced dataset ready to be merged.

**Time zone conversion:** The last step before merging files from ISOs into one is to convert the time zones to a common base. This is done to time synchro-

nize the datasets for calculating voltage angle differences. The selected base time zone is UTC and time zones files from NYISO and ISO-NE which was provided in Eastern time zone were converted to UTC by adding appropriate offset (+5 hours for standard time and +4 hours for daylight time).

The Figure 1 below described the procedure used to process PMU data from four ISOs.

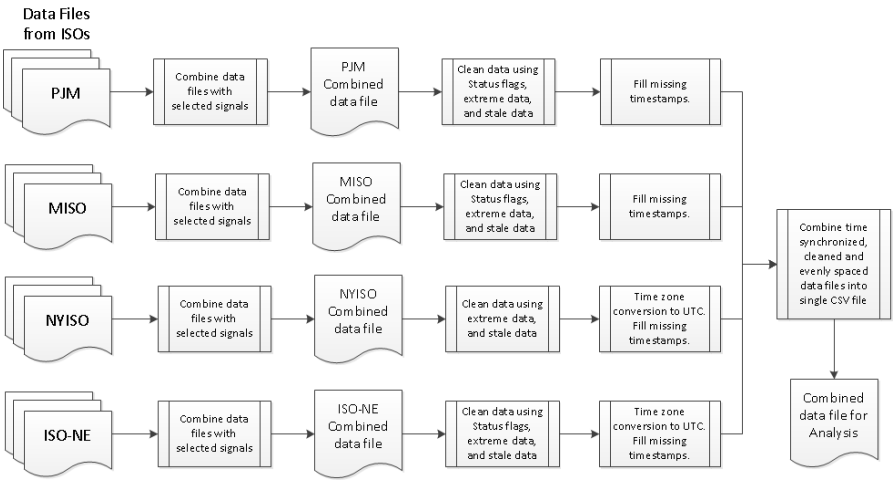



**Figure 1:** Process Used to Condition Data Files from ISOs to Create Data Set for Analysis

## 3.2 Methodology to Establish High and Low Values

After creation of combined and cleaned data file, angle difference values for selected angle difference pairs were calculated. The angle difference data was plotted to check for any sudden abnormal data spikes, which can happen if any bad data was not removed from the dataset during the cleaning process. These spikes were removed by replacing the bad data value with "NaN"to prevent their influence in subsequent baselining analysis.

Baselining analysis was performed on the select angle difference pairs for identifying High and Low values and other statistics from the data. These High and Low values are used as a guideline to define alarm threshold values to identify any abnormal system condition. First, statistical analysis was performed on the selected angle difference pairs and following values were calculated such as:

- **Max**-Maximum value in the dataset for each angle difference pair
- **Min**-Minimum value in the dataset for each angle difference pair

- **Median**-Median value in the dataset for each angle difference pair
- **Mean**-Average value in the dataset for each angle difference pair
- **Percent Positive** Percentage of data greater than 0, indicates percentage of time power flow from the "from bus"to the "to bus".

The High and Low values for each angle difference pair was calculated by eliminating high 0.5% and low 0.5% data, which was done to eliminate any other possible data spikes which may be present in the dataset.

## 3.3 Angle Adjustments "Offset"

For some angle difference pairs, when the angle difference was calculated, plotted, and compared with the maximum and minimum known values for the same angle difference pairs from previous studies using State Estimator data[6]. This comparison sometimes reveals that angle difference values calculated using some PMUs are offset by 60 or 120 degrees. These angle difference pairs which when adjusted by the offset value get back to reasonable range and ready for analysis. The angle difference pairs for which adjustment was done include PMUs at Arcadian (MISO) and Millbury (ISO-NE).

# 4 ANGLE DATA

## 4.1 Angle Pair Selection

Angle difference pairs were selected based on the input from TAG members and is the same as it was for the 2013 EI baselining study using State Estimator data. The angle pairs and reasons for selection are listed in Table 1 below. The geographic map for the selected angle pairs is presented in Figure 2.

**Table 1:** Selected Angle Difference Pairs for Analysis

| Index | From bus | To bus | Reason |
|---|---|---|---|
| 1 | Raun | Sub 91 | IA Wind Transfers |
| 2 | Goodings | Arcadian | Wi-Chi Transfers |
| 3 | Goodings | Palisades | Chi-MI Transfers |
| 4 | Labadie | Hanna | West to East Transfers |
| 5 | Labadie | Cumberland | St Louis South Transfers |
| 6 | Jacksons Ferry | Cumberland | TVA to PJM (Southwest) Transfers |
| 7 | Canton Centr. | Monroe | SE MI Transfers |
| 8 | Alburtis | Canton Centr. | West to East Transfers (Lake Erie Loop) |
| 9 | Alburtis | Jacksons Ferry | Southwest to East Transfers |
| 10 | Alburtis | Ramapo | PJM to NYISO |
| 11 | Niagara | Monroe | NYISO to MISO |
| 12 | Niagara | Ramapo | West to Southeast Transfers |
| 13 | Ramapo | Millbury | NYISO to ISONE |
| 14 | Raun | Ramapo | MISO to NYISO |
| 15 | Arcadian | Ramapo | MISO to NYISO |
| 16 | Goodings | Monroe | Close the loop |
| 17 | Goodings | Hanna | Close the loop |
| 18 | Hanna | Monroe | Close the loop |
| 19 | Hanna | Canton Centr. | Close the loop |
| 20 | Palisades | Monroe | Close the loop |
| 21 | Raun | Millbury | MISO to ISONE |
| 22 | Arcadian | Millbury | MISO to ISONE |

## 4.2 Angle Data Availability and Quality

As discussed in Section 3.2, the voltage angle data from the PMU data files from all four ISOs was preprocessed to clean the data using data quality status flags. And known bad samples such as repeating 0, 120, -9999 and other stale data indicators were eliminated. Data was also cleaned by removing any data outside their typical range. Angle difference was calculated using the clean data and sudden abnormal data spikes were eliminated.

After each signal data is cleaned, good data quality and data availability percentage is calculated by dividing the number of good quality data points by total

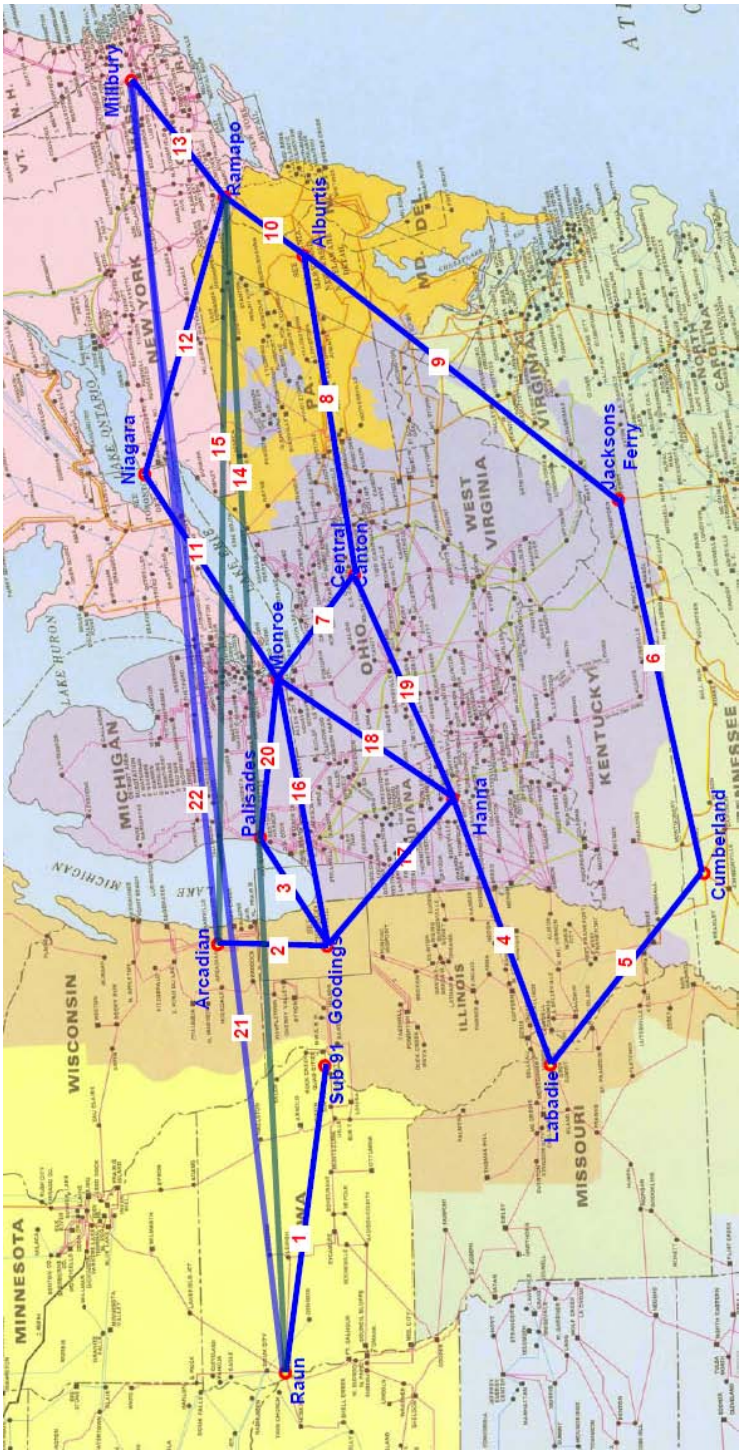



**Figure 2:** Geographic Representation of Select Angle Difference Pairs Used for Analysis

number of expected data points. This process revealed that for some of the PMUs near the selected substations for the study do not have good quality data or are not available for the duration of the study. The ISOs were contacted and alternative replacement PMUs with good data quality were identified to be used for analysis. The PMUs used for analysis, their replacements (if needed) with good data availability is listed in Table 2 below for Winter 2014 data and Table 3 for Fall 2014 data.

**Table 2:** PMU and Substation Mapping with Data Availability for Winter 2014

| Index | Substation | Alternative | PMU/Signal Name | Data Provider | Good Data % |
|---|---|---|---|---|---|
| 1 | Alburtis 500kV | | alburtis:500-500-br | PJM | 97.1 |
| 2 | Arcadian 345kV | | Wec Arcadn 01-B345_1 | MISO | 99.5 |
| 3 | Canton Centr. 345kV | | cantonce:345-bb_9395 | PJM | 81.3 |
| 4 | Cumberland 500kV | | Tva 8Cumberl 01-B500108 | MISO | 98.9 |
| 5 | Goodings 345kV | | 116 good:345-bb_44 | PJM | 96.7 |
| 6 | Hanna 345kV | | Ipl Hannaipl 01-L345C | MISO | 93.6 |
| 7 | Jacksons Ferry 765kV | | jacksons:765-bb_5876 | PJM | 94.1 |
| 8 | Labadie 345kV | | Ammolabadie 02-L3452 | MISO | 98.8 |
| 9 | Millbury 345kV | | NE_MILLBURY_3A | NEISO | 97.1 |
| 10 | Monroe 345kV | | Decomonroe4 01-L345A1 | MISO | 99.5 |
| 11 | Niagara 345kV | | NIAGARA230_B.V1_NEBUS | NYISO | 88.5 |
| 12 | Palisades 345kV | | Conspalisad2 01-L3451F | MISO | 90.8 |
| 13 | Ramapo 500kV* | Buchanan | BUC | NYISO | 75.1 |
| 14 | Raun 345kV* | Lehigh | Mec Lehigh2 01-L3453020 | MISO | 99.7 |
| 15 | Sub 91 345kV | | Altwrock_Ck 01-L345799 | MISO | 94.8 |

**Table 3:** PMU and Substation Mapping with Data Availability for Fall 2014

| Index | Substation | Alternative | PMU/Signal Name | Data Provider | Good Data % |
|---|---|---|---|---|---|
| 1 | Alburtis 500kV | | PL ALBURTIS 52.L500HOSENSAK | PJM | 96.31 |
| 2 | Arcadian 345kV | | Wec Arcadn 01-B345_1 | MISO | 97.03 |
| 3 | Canton Centr. 345kV | | AA 05CANTNC 01.L34505SCANTO | PJM | 94.03 |
| 4 | Cumberland 500kV | Ammojopa | Ammojopa_345 01-L34546 | MISO | 92.2 |
| 5 | Goodings 345kV | | CE GOODI;4B 12.L345GOODI;4B | PJM | 99.6 |
| 6 | Hanna 345kV | | Ipl Hannaipl 01-L345C | MISO | 97.09 |
| 7 | Jacksons Ferry 765kV | Broadford | AA 05BROADF 01.L76505BAKER | PJM | 89.54 |
| 8 | Labadie 345kV | Montgomery | Ammomtgy 01-L34518 | MISO | 91.69 |
| 9 | Millbury 345kV | | NE_MILLBURY_3A | NEISO | 70.58 |
| 10 | Monroe 345kV | Decoplacid | Decoplacid 01-L345B2 | MISO | 96.89 |
| 11 | Niagara 345kV | | NIAGARA345.N345_NS1_V1 | NYISO | 98.39 |
| 12 | Palisades 345kV | | Conspalisad2 01-L3451F | MISO | 96.01 |
| 13 | Ramapo 500kV | Buchanan | BUC.V1VPM | NYISO | 81.77 |
| 14 | Raun 345kV | Lehigh | Mec Lehigh2 01-L3453020 | MISO | 95.73 |
| 15 | Sub 91 345kV | | Altwrock_Ck 01-L345799 | MISO | 96.3 |

## 4.3 Establish High and Low Values for Angle Pair for Winter 2014

After calculating the angle difference, statistical analysis was performed on these angle difference data and summary results (such as Max, Min, Mean, Median, and Percent positive) were calculated and reported. The High and Low limit values were estimated by eliminating top and bottom 0.5% of data. This was done to eliminate any data spikes and other noisy data that may have escaped the data cleaning process. The detail trend chart, Box-Whisker, Time Duration and hour of day Box-Whisker for each angle pair can be found in Appendix 8.1. These statistical summary results are presented in Table 4 below:

**Table 4:** Summary of Statistical Analysis Results Using Angle Difference Data for Winter 2014 (Dec 15, 2013 - Feb 15, 2014)

| Index | From bus | To bus | Avail % | Min 0.5% | Max 0.5% | Range | Min | Max | Media | Mean | Pos % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Raun | Sub 91 | 94.6 | -28 | 28 | 56 | -32 | 32 | 5 | 4 | 62.7 |
| 2 | Goodings | Arcadian | 96.4 | -14 | 16 | 30 | -20 | 20 | -2 | -1 | 41 |
| 3 | Goodings | Palisades | 90.3 | -5 | 27 | 32 | -10 | 30 | 15 | 14 | 95.6 |
| 4 | Labadie | Hanna | 92.5 | 14 | 60 | 46 | 9 | 64 | 41 | 40 | 100 |
| 5 | Labadie | Cumberland | 97.8 | -6 | 45 | 51 | -13 | 49 | 25 | 24 | 97.4 |
| 6 | Jacksons Ferry | Cumberland | 92.1 | -53 | -5 | 48 | -60 | -1 | -32 | -32 | 0 |
| 7 | Canton Centr. | Monroe | 77.7 | -32 | 15 | 47 | -38 | 18 | -6 | -5 | 32.8 |
| 8 | Alburtis | Canton Centr. | 79.4 | -58 | 1 | 59 | -67 | 12 | -35 | -34 | 0.7 |
| 9 | Alburtis | Jacksons Ferry | 94.6 | -72 | 6 | 78 | -82 | 18 | -42 | -41 | 1.3 |
| 10 | Alburtis | Ramapo | 73.6 | -2 | 48 | 50 | -12 | 56 | 27 | 26 | 99.4 |
| 11 | Niagara | Monroe | 74.8 | -46 | 42 | 88 | -55 | 65 | -7 | -8 | 36.1 |
| 12 | Niagara | Ramapo | 69.4 | 23 | 85 | 62 | 16 | 94 | 55 | 55 | 100 |
| 13 | Ramapo | Millbury | 74.0 | -30 | 20 | 50 | -37 | 26 | 3 | 1 | 57.7 |
| 14 | Raun | Ramapo | 74.9 | 23 | 202 | 179 | 12 | 214 | 119 | 117 | 100 |
| 15 | Arcadian | Ramapo | 74.9 | 21 | 153 | 132 | -3 | 165 | 91 | 89 | 100 |
| 16 | Goodings | Monroe | 96.3 | -4 | 49 | 53 | -10 | 55 | 29 | 27 | 98.6 |
| 17 | Goodings | Hanna | 90.3 | -19 | 26 | 45 | -23 | 29 | 8 | 7 | 77.6 |
| 18 | Hanna | Monroe | 93.2 | -15 | 42 | 57 | -19 | 47 | 21 | 20 | 96.4 |
| 19 | Hanna | Canton Centr. | 71.6 | -4 | 46 | 50 | -13 | 52 | 26 | 25 | 96.5 |
| 20 | Palisades | Monroe | 91.9 | -2 | 25 | 27 | -5 | 30 | 13 | 13 | 98.2 |
| 21 | Raun | Millbury | 98.5 | 16 | 207 | 191 | -19 | 221 | 125 | 122 | 100 |
| 22 | Arcadian | Millbury | 97.3 | 14 | 159 | 145 | -6 | 174 | 93 | 91 | 100 |

## 4.4 Establish High and Low Values for Angle Pair for Fall 2014

The analysis as described in the last section is repeated for the period of Fall 2014. The detail trend chart, Box-Whisker, Time Duration and hour of day Box-Whisker for each angle pair can be found in Appendix 8.2. The statistics results are listed in the Table 5 below:

**Table 5:** Summary of Statistical Analysis Results Using angle Difference Data for Fall 2014 (Sep 1, 2014 - Oct 31, 2014)

| Index | From bus | To bus | Avail % | Min 0.5% | Max 0.5% | Range | Min | Max | Media | Mean | Pos % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Raun | Sub 91 | 95 | -9 | 28 | 37 | -13 | 32 | 10 | 10 | 87.7 |
| 2 | Goodings | Arcadian | 97 | -12 | 15 | 27 | -17 | 19 | 2 | 2 | 63.2 |
| 3 | Goodings | Palisades | 96 | -5 | 23 | 28 | -8 | 26 | 10 | 11 | 94.7 |
| 4 | Labadie | Hanna | 92 | 0 | 48 | 48 | -5 | 54 | 29 | 29 | 99.6 |
| 5 | Labadie | Cumberland | 92 | -4 | 22 | 26 | -7 | 26 | 10 | 10 | 95.5 |
| 6 | Jacksons Ferry | Cumberland | 82 | -47 | -4 | 43 | -52 | 8 | -28 | -27 | 0.1 |
| 7 | Canton Centr. | Monroe | 91 | -9 | 27 | 36 | -15 | 35 | 9 | 9 | 85.9 |
| 8 | Alburtis | Canton Centr. | 91 | -52 | 20 | 72 | -60 | 25 | -5 | -3 | 41 |
| 9 | Alburtis | Jacksons Ferry | 86 | -63 | 29 | 92 | -74 | 36 | -6 | -7 | 37.2 |
| 10 | Alburtis | Ramapo | 78 | -2 | 26 | 28 | -4 | 29 | 12 | 12 | 98.1 |
| 11 | Niagara | Monroe | 95 | -7 | 62 | 69 | -17 | 68 | 31 | 32 | 98.4 |
| 12 | Niagara | Ramapo | 80 | 15 | 69 | 54 | 9 | 78 | 41 | 41 | 100 |
| 13 | Ramapo | Millbury | 57 | -25 | 11 | 36 | -30 | 15 | -10 | -11 | 10.5 |
| 14 | Raun | Ramapo | 77 | 7 | 142 | 135 | -13 | 158 | 67 | 64 | 99.7 |
| 15 | Arcadian | Ramapo | 78 | 43 | 168 | 125 | 27 | 185 | 89 | 85 | 100 |
| 16 | Goodings | Monroe | 97 | -1 | 46 | 47 | -5 | 62 | 21 | 22 | 98.9 |
| 17 | Goodings | Hanna | 97 | -16 | 22 | 38 | -21 | 26 | 5 | 5 | 68.5 |
| 18 | Hanna | Monroe | 97 | -1 | 40 | 41 | -4 | 51 | 17 | 17 | 99.2 |
| 19 | Hanna | Canton Centr. | 91 | -11 | 30 | 41 | -17 | 40 | 8 | 7 | 81.6 |
| 20 | Palisades | Monroe | 96 | 0 | 27 | 27 | -2 | 41 | 11 | 11 | 99.6 |
| 21 | Raun | Millbury | 68 | 0 | 128 | 128 | -16 | 144 | 56 | 55 | 99.4 |
| 22 | Arcadian | Millbury | 69 | 27 | 154 | 127 | 8 | 173 | 78 | 74 | 100 |

## 4.5 Comparison and Observations for Winter 2014, Fall 2014 and State Estimator Data

The High (0.5% max), Low (0.5% min) and median values from both the study periods (Winter 2014 and Fall 2014) are listed in the Table 6 below for comparison. Also listed are the High and Low values from the State Estimator data study for March 2011 as reference.

**Table 6:** Comparison of Angle Difference High and Low Values for PMU Data Study (Fall and Winter) and SE Data Study

| Index | From bus | To bus | SE Data | | PMU Data (1) | | | PMU Data (2) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mar-11 | | 12/15/2013-2/15/2014 | | | 9/1/2014-10/31/2014 | | |
| | | | Low | High | Low | Median | High | Low | Median | High |
| 1 | Raun 345kV | Sub 91 345kV | -13 | 48 | -30 | 5 | 30 | -9 | 10 | 28 |
| 2 | Goodings 345kV | Arcadian 345kV | -8 | 14 | -14 | -2 | 18 | -12 | 2 | 15 |
| 3 | Goodings 345kV | Palisades 345kV | 7 | 29 | -6 | 15 | 28 | -5 | 10 | 23 |
| 4 | Labadie 345kV | Hanna 345kV | 23 | 57 | 12 | 41 | 63 | 0 | 29 | 48 |
| 5 | Labadie 345kV | Cumberland 500kV | 9 | 35 | -11 | 25 | 47 | -4 | 10 | 22 |
| 6 | Jacksons Ferry 765kV | Cumberland 500kV | -47 | -19 | -54 | -32 | -4 | -47 | -28 | -4 |
| 7 | Canton Centr. 345kV | Monroe 345kV | -10 | 12 | -34 | -6 | 17 | -9 | 9 | 27 |
| 8 | Alburtis 500kV | Canton Centr. 345kV | -46 | -10 | -61 | -35 | 8 | -52 | -5 | 20 |
| 9 | Alburtis 500kV | Jacksons Ferry 765kV | -60 | -12 | -76 | -42 | 11 | -63 | -6 | 29 |
| 10 | Alburtis 500kV | Ramapo 500kV | 2 | 18 | -3 | 27 | 49 | -2 | 12 | 26 |
| 11 | Niagara 345kV | Monroe 345kV | -26 | 12 | -49 | -7 | 50 | -7 | 31 | 62 |
| 12 | Niagara 345kV | Ramapo 500kV | 9 | 57 | 22 | 55 | 88 | 15 | 41 | 69 |
| 13 | Ramapo 500kV | Millbury 345kV | -26 | 17 | -36 | 3 | 24 | -25 | -10 | 11 |
| 14 | Raun 345kV | Ramapo 500kV | 66 | 154 | 19 | 119 | 208 | 7 | 67 | 142 |
| 15 | Arcadian 345kV | Ramapo 500kV | 39 | 109 | 19 | 91 | 159 | 43 | 89 | 168 |
| 16 | Goodings 345kV | Monroe 345kV | 22 | 54 | -6 | 29 | 51 | -1 | 21 | 46 |
| 17 | Goodings 345kV | Hanna 345kV | 0 | 23 | -21 | 8 | 27 | -16 | 5 | 22 |
| 18 | Hanna 345kV | Monroe 345kV | 11 | 46 | -18 | 21 | 46 | -1 | 17 | 40 |
| 19 | Hanna 345kV | Canton Centr. 345kV | 13 | 42 | -5 | 26 | 48 | -11 | 8 | 30 |
| 20 | Palisades 345kV | Monroe 345kV | 8 | 29 | -3 | 13 | 27 | 0 | 11 | 27 |
| 21 | Raun 345kV | Millbury 345kV | 26 | 117 | 8 | 125 | 213 | 0 | 56 | 128 |
| 22 | Arcadian 345kV | Millbury 345kV | 51 | 159 | 2 | 93 | 165 | 27 | 78 | 154 |

The Low and High values for the PMU data are typically around the same Low and High values for State Estimator data which provides enough confidence on the PMU data. The following Figure 3 displays the change in High, Low and median values for Winter and Fall 2014.

Following observations can be made from the comparison:

- System overall is less stressed in Fall than in Winter (high, low and median values moving closer to zero. Range (high-Low) reduced)
- Fall angle difference data indicates higher Northeast-West power flow compared to Winter data where the power flow is predominantly from West-Northeast.
- High and low limits identified for winter period will not be suitable to identify abnormal system condition for fall period and the reverse is also true.

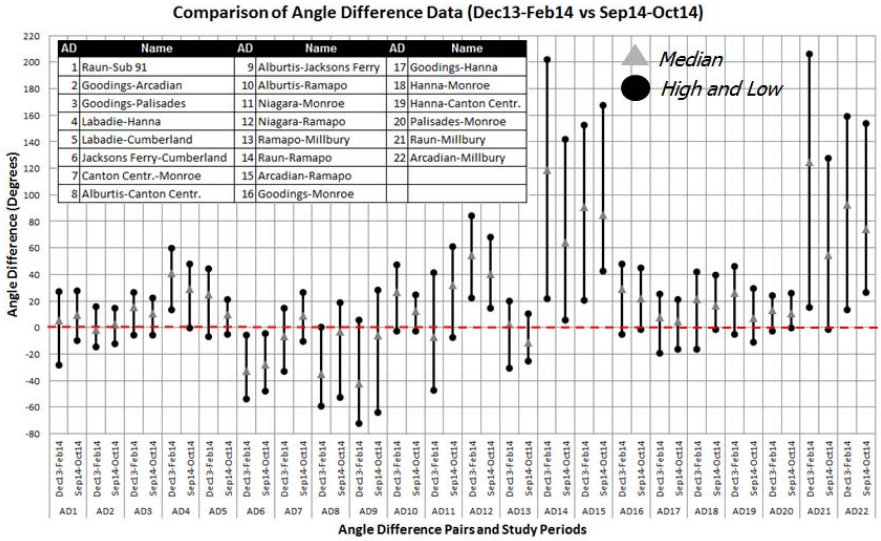



**Figure 3:** Comparison of High, Low and Median Values of Angle Difference Data for the Periods of Winter 2014 and Fall 2014

## 4.6 Clustering Analysis

Clustering analysis was conducted using all the 22 angle difference pairs to estimate the correlation coefficient between them. High correlation coefficient value (>0.8) indicates that the angle difference pairs move together which may help in predicting behavior of one pair if the movement of the other correlated pair is known. This is also helpful in reducing the number of angle difference pairs to monitor during real time operations.

For the period of winter 2014 (Dec 15, 2013-Feb 15, 2014), three clusters were identified. The reference angle pair was selected for each cluster is the one which has the most angle pairs correlated with highest correlation coefficient. The cluster and correlation coefficients are listed Table 7 below. The map of identified clusters is presented in Figure 4.

**Table 7:** Identified Clusters Based on Winter Data

| Cluster | Angle Difference pairs | Correlation Coefficient |
|---|---|---|
| Cluster-1 | Arcadian-Ramapo (Reference) | 1 |
| | Arcadian-Millbury | 0.95 |
| | Raun-Ramapo | 0.93 |
| | Raun-Millbury | 0.93 |
| | Canton Centr.-Alburtis | 0.89 |
| | Jacksons Ferry-Alburtis | 0.85 |
| | Hanna-Canton Centr. | 0.82 |
| Cluster-2 | Goodings-Monroe (Reference) | 1 |
| | Goodings-Palisades | 0.94 |
| | Palisades-Monroe | 0.90 |
| Cluster-3 | Goodings-Arcadian (Reference) | 1 |
| | Goodings-Hanna | 0.83 |

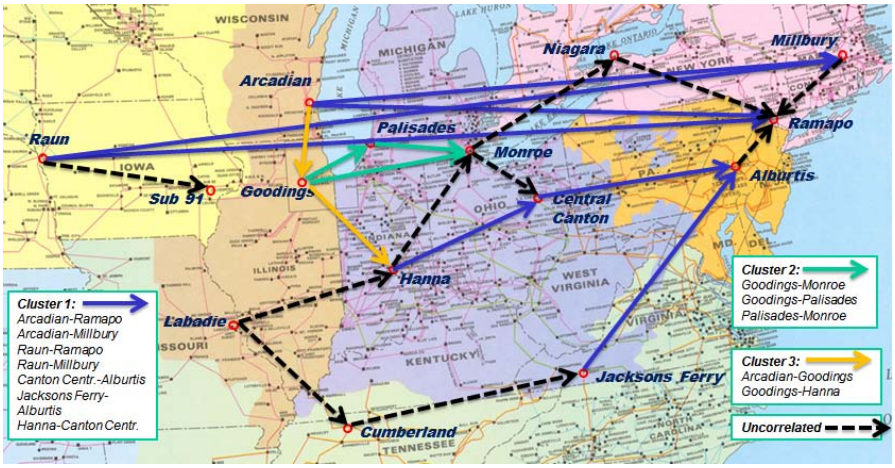



**Figure 4:** Angle Difference Pair Clusters Identified for Winter 2014

Clustering analysis was repeated for fall 2014 period (Sep 1, 2014 Oct 31, 2014) to evaluate if the clusters are the same or there are any changes. The results are presented Figure 5.

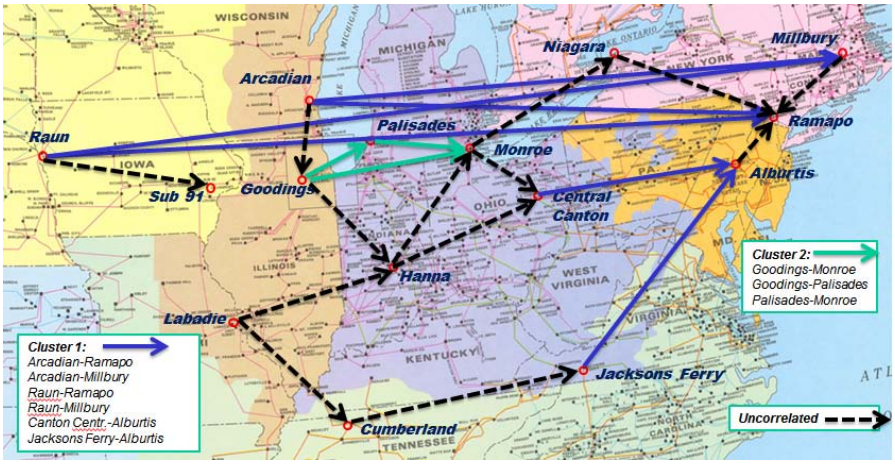



**Figure 5:** Angle Difference Pair Clusters Identified for Fall 2014

As a comparison, the correlation coefficients for Winter-2014 and Fall-2014 are presented side by side in Table 8 below:

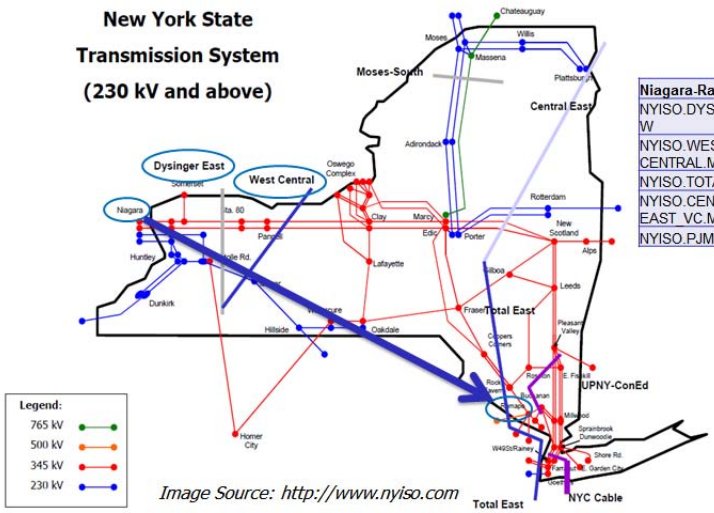
**Table 8:** Comparison of Angle Difference Pair Clusters and Their Correlation Coefficients for Winter and Fall 2014

| Cluster | Angle Difference Pairs | Correlation Coefficient Winter - 2014 | Correlation Coefficient Fall - 2014 |
|---|---|---|---|
| Cluster-1 | Arcadian-Ramapo (Reference) | 1 | 1 |
| | Arcadian-Millbury | 0.95 | 0.95 |
| | Raun-Ramapo | 0.93 | 0.87 |
| | Raun-Millbury | 0.93 | 0.84 |
| | Canton Centr.-Alburtis | 0.89 | 0.82 |
| | Jacksons Ferry-Alburtis | 0.85 | 0.81 |
| | Hanna-Canton Centr. | 0.82 | 0.56 |
| Cluster-2 | Goodings-Monroe (Reference) | 1 | 1 |
| | Goodings-Palisades | 0.94 | 0.88 |
| | Palisades-Monroe | 0.90 | 0.83 |
| Cluster-3 | Goodings-Arcadian (Reference) | 1 | 1 |
| | Goodings-Hanna | 0.83 | 0.52 |

From the comparison it is observed that overall the angle pairs have higher correlation with each other during winter than in fall. This observation can be attributed to higher system stress during winter due to high loading conditions which results in higher power flow and tighter alignment in angle difference pairs from west to east.

## 4.7 Examine the Correlation between Angle Difference and MW Flow

The MW flow data was only available from NYISO and was used to calculate correlation between the power flow corridors and angle difference pairs. Correlation analysis revealed that only angle difference pair Niagara-Ramapo was correlated with the MW flow data. The Figure 6 below illustrates the five power-flow corridors and their correlation coefficient with angle difference pair Niagara-Ramapo. The highest correlation was observed with the MW flow data from Dysinger East and West Central.




| Niagara-Ramapo | 1 |
|---|---|
| NYISO.DYSINGER_EAST.MW | 0.85 |
| NYISO.WEST-CENTRAL.MW | 0.81 |
| NYISO.TOTAL-EAST.MW | 0.53 |
| NYISO.CENTRAL-EAST_VC.MW | 0.52 |
| NYISO.PJM-NYISO.MW | 0.15 |

**Figure 6:** Niagara-Ramapo Correlated with MW Flow Shown on Map and Correlation Coefficients Table

The following Figure 7 shows the correlation plot of Niagara-Ramapo with Dysinger East (Coefficient 0.85).

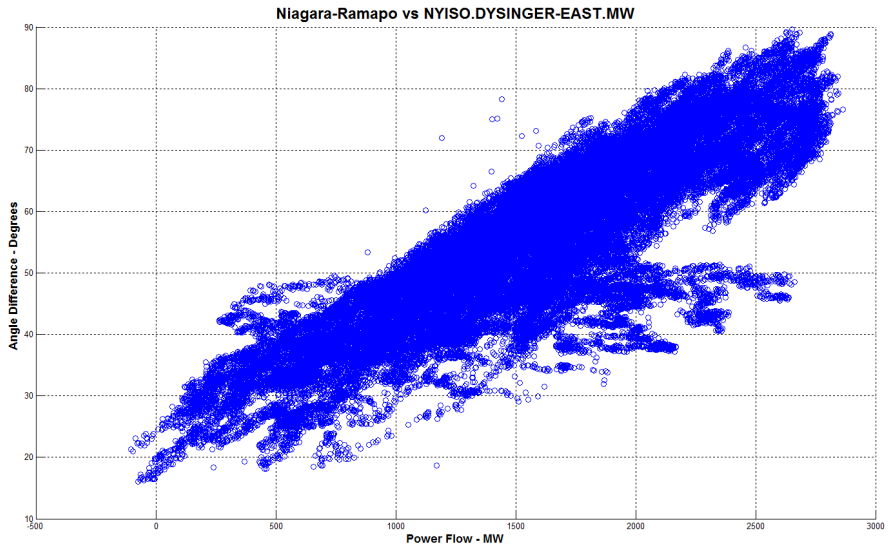



**Figure 7:** Plot of Dysinger East MW Flow vs Niagara-Ramapo Angle Difference Displaying High Correlation

## 4.8 Oscillation Analysis

Study was done to identify oscillation modes in the angle difference data. As the data provided was at 1 sample/second resolution, only oscillation modes lower than 0.5 Hz could be detected. Two angle pairs were selected to identify oscillation modes:

- Raun-Ramapo (Wide-Area)
- Niagara  Ramapo (Local Area)

For each of the pairs Oscillation modal frequencies were analyzed and following modes were detected as shown in Figure 8 and 9.

- Raun-Ramapo:about 0.2 Hz, well damped
- Niagara-Ramapo:about 0.39-0.41 Hz, moderately damped

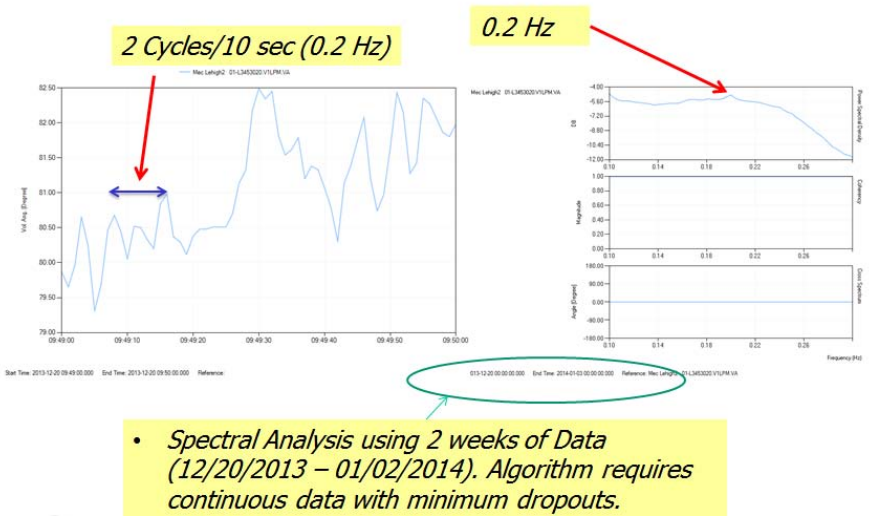



**Figure 8:** 0.2 Hz Oscillation Mode Detected for Wide-Area Angle Pair Raun-Ramapo

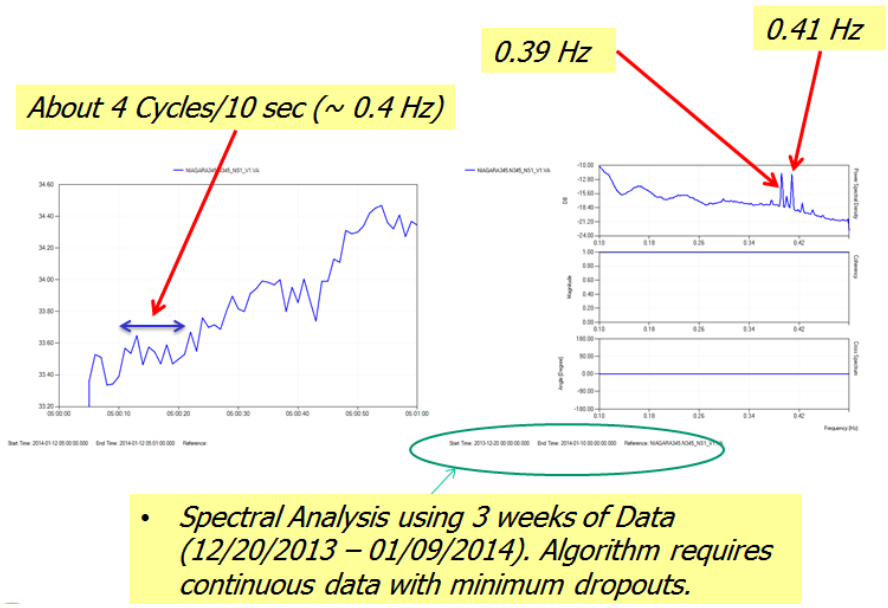



**Figure 9:** 0.4 Hz Oscillation Mode Detected for Local-Area Angle Pair Niagara-Ramapo

Detection of frequency modes higher than 0.5 Hz which may be possibly present in the data would require higher sampling data rate for analysis.

## 4.9 Summary

In conclusion, following summary points can be made from the study results and observations:

- The Low and High values for the PMU data are typically around the same Low and High values for State Estimator data which provides enough confidence on the PMU data.
- System overall is less stressed in Fall than in Winter (high, low and median values moving closer to zero. Reduced range (High-Low)).
- Angle difference data correlates well with system stress level and using tools to monitor and generate alarms using critical angle difference data and typical High-Low value thresholds would be helpful in identifying abnormal system conditions.
- High and low limits identified for winter period may not be suitable to identify abnormal system condition for fall period and the reverse is also true. Baselining analysis performed during a particular period to identify normal system conditions is dependent on prevalent system topology during the period and seasonal loading conditions.
- Fall angle difference data indicates higher Northeast to West power flow compared to Winter data where the power flow is predominantly from West to Northeast.
- Angle difference pairs from west to east have strong correlation as majority of power flow is in the same direction.
- Overall the angle pairs have higher correlation with each other during winter than in fall. This observation can be attributed to higher system stress during winter.
- The highest correlation was observed with the NYISO MW flow data from Dysinger East, West Central and angle difference Niagara-Ramapo.
- Raun-Ramapo (Wide-area) has 0.2 Hz oscillatory mode and Niagara-Ramapo (Local-area) has 0.39 Hz and 0.41 Hz oscillatory modes.
- Detection of frequency modes higher than 0.5 Hz which may be possibly present in the data would require higher sampling data rate for analysis.

# 5 LMP DATA

Locational marginal price (LMP) is the marginal cost of supplying the next increment of electric energy at a specific bus considering the generation marginal cost and the physical aspects of the transmission system. It was used in energy market to reflect the value of the energy at the specific time and location it is delivered. It is the additional cost for providing one additional MW at a certain node. The interest is expressed during the TAG members discussion to study the co-relation between the angle pair differences and the Locational Marginal Price (LMP) differences.

## 5.1 LMP Data Availability and Data Type

It is agreed the study focuses on the LMP data from September 1, 2014 to October 31, 2014. Three ISOs, NYISO, ISONE and MISO provided LMP data to EPG. EPG collected PJM LMP data from provided PJM website. There are three different price types (Congestion Price Component, Loss Component and Total LMP) available for four ISOs. The detailed LMP price type and sampling rate are listed in Table 9.

**Table 9:** LMP Price Type and Sampling Rate

| ISO Name | Sampling Rate | Price Type | Provider |
|---|---|---|---|
| PJM | 1 hour | CongLMP, LossLMP, TotalLMP | Collected by EPG from PJM website[4, 3] |
| ISONE | 5 minutes | Congenstion component, Loss component, LMP | ISONE |
| MISO | 1 hour | LMP(locational marginal price), MCL(Loss component of LMP), MCC(Congestion component of LMP) | MISO |
| NYISO | 5 minutes | LBMP, Loss, Congestion* | NYISO |

The LMP node and required bus mapping information for each ISO is provided in Table 10. There are some nodes that are not available in NYISO, MISO and PJM. The representatives from NYISO and MISO suggested alternative nodes which are close to the required bus listed in the table. For node price which are not available in PJM area, CERTS/EPG selected to use prices of buses which are close to the required bus. For example, the price of SCanton is selected as the alternative for the price of Canton Centr. For the bus with multiple available nodes in MISO area, average value of these multiple nodes will be used for the price of the required bus.

In order to better understand the LMP, the characteristics of LMP is studied. Figure 10 shows the characteristics example for total LMP-loss component price for Niagara in NYISO. The sampling rate for Niagara is 5-minute. From the figure,

**Table 10:** Required Bus and LMP Node Mapping

| Required Bus Name | Node Name | AlternativeName |
|---|---|---|
| PJM (5 nodes) | | |
| Alburtis | Alburtis | |
| Goodings | | Wilton, Collins |
| Jacksons Ferry | Jacksons | |
| Canton Centr. | | SCanton |
| ISONE (1 node) | | |
| Millbury | Millbury | |
| MISO (2233 nodes) | | |
| Arcadian | | WEC.ERG1<br>WEC.ERG2 |
| Cumberland | | EAI.PLUM1A_TEA<br>EAI.PLUM_1C<br>EAI.PLUM_PPEA |
| Hanna | AMMO.HANN_1.AZ | |
| Labadie | AMMO.LABADIE1<br>AMMO.LABADIE2<br>AMMO.LABADIE3<br>AMMO.LABADIE4 | |
| Monroe | DECO.MONROE1<br>DECO.MONROE2<br>DECO.MONROE3<br>DECO.MONROE4 | |
| Raun | | MEC.NEALN_1<br>MEC.NEALN_2<br>MEC.NEALN_3<br>MEC.NEALN_4 |
| Sub 91 | | MEC.LOUISA_1 |
| NYISO (4 nodes) | | |
| Niagara | | WEST |
| Ramapo | | DUNWOD<br>MILLWD<br>HUD VL |

it can be found that price changes very fast. At the time 15:45, price was around $200. At the next sample time, 15:50, price changed to $1200. It is also found the price fluctuation range is very high. The price change range is from $0 to $1600 in this example.

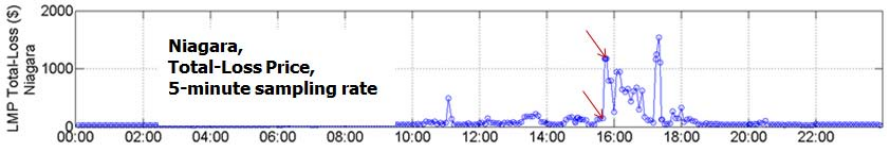



**Figure 10:** Total-Loss Price Characteristics Example-Niagara

Figure 11 shows another characteristics example for congestion component price for Ramapo. The top figure shows the congestion component price for Ramapo with 5-minute sampling rate. The bottom figure shows the same price but with 1-hour sampling rate by using hour ending average method. It is obvious the price spike will be delayed when hour ending averaging method is introduced.

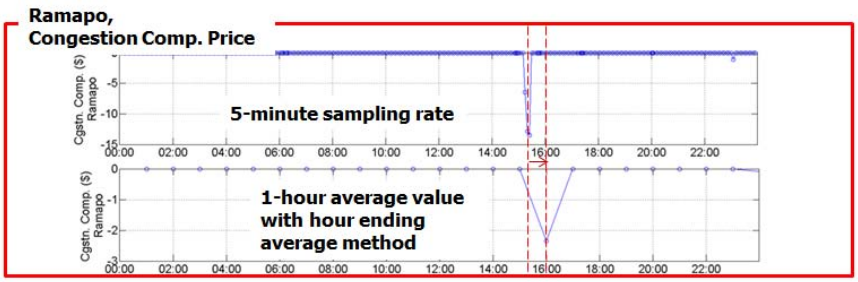



**Figure 11:** Congestion Component Price Characteristics Example-Ramapo

## 5.2 Locational Marginal Price of Individual Bus Statistics Result

Generally, there are three components that are involved in market and operation: Total LMP, Loss LMP and Congestion LMP. The basic relationship among them is: Total LMP = generation marginal cost + congestion cost + cost of marginal losses.

Figure 12 is a plot example of PJM Alburtis LMPs during September to October 2014, showing the three components total, loss and congestion LMPs of this location. Total LMP has periodical and regular ups and downs every day, loss LMP

is mostly zero with occasional waves, and congestion LMP has spikes irregularly. The Figure 13 is a box-whisker chart example of total LMP and congestion LMP. It indicates the total LMP will go up during the daytime and reach to the top during the peak hours (PJM 8AM-10PM; MISO 3PM-8PM; NYISO 4PM-6PM; ISONE 3PM-8PM) then go back down during nighttime, and congestion LMP is mostly zero but with irregular spikes. All plots for each individual bus are in Appendix 8.4.

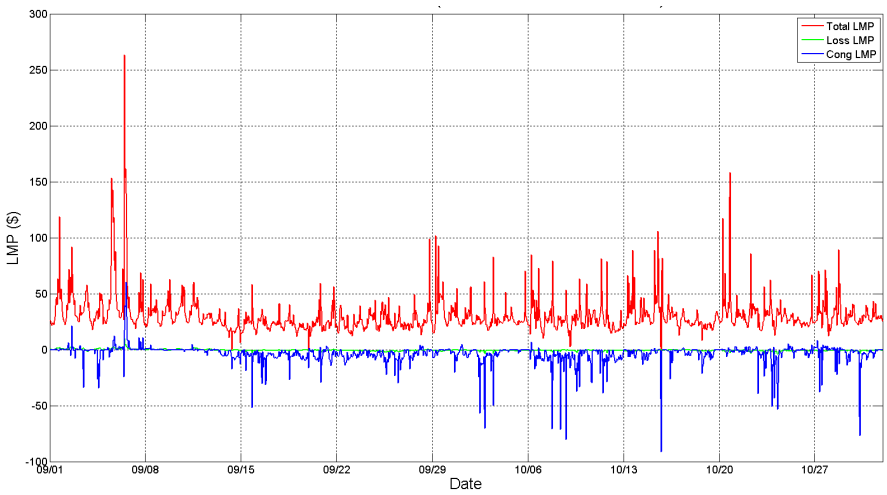
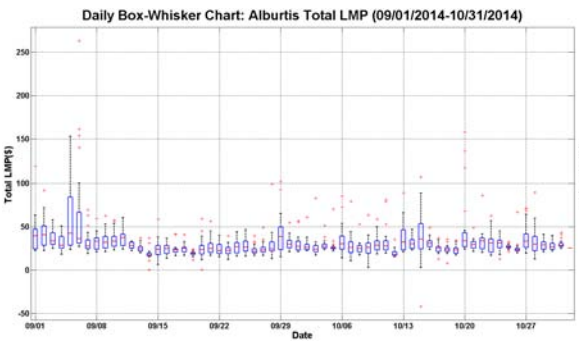
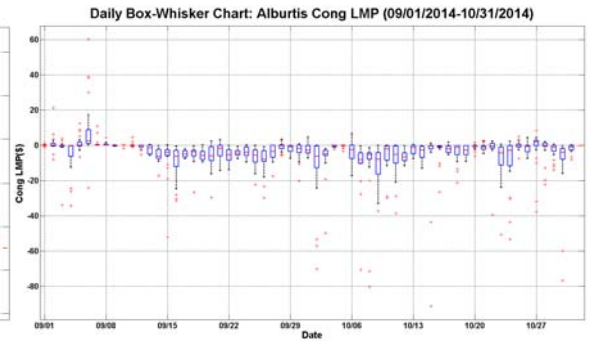



**Figure 12:** Example Plot: Three Components of LMP PJM Alburtis bus

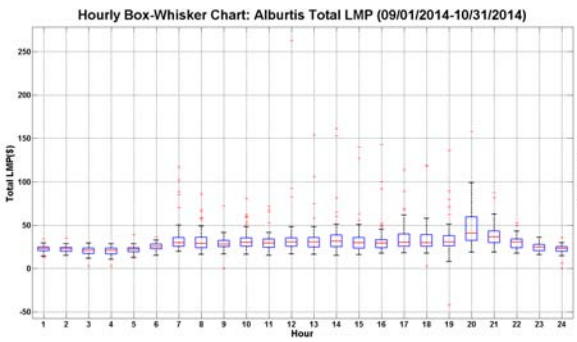
The Table 11 is the congestion LMP statistics of individual bus. NYISO and ISONE LMP data have been processed to hourly average in these statistics (the sampling rate of the original LMP data receiving from PJM and MISO is 1 data per hour, and receiving from NYISO and ISONE is 1 data per 5-minutes). Dominant positions (congestion LMP is negative, positive or zero) for each location are highlighted in red. In 15 locations, 9 locations have negative congestion LMP as dominant, 3 locations have positive congestion LMP as dominant, and 3 locations with zero congestion LMP at most of time. Based on the formula LMP = generation marginal cost + congestion cost + cost of marginal losses, when the negative congestion cost occurred, this location may have lower total LMP.



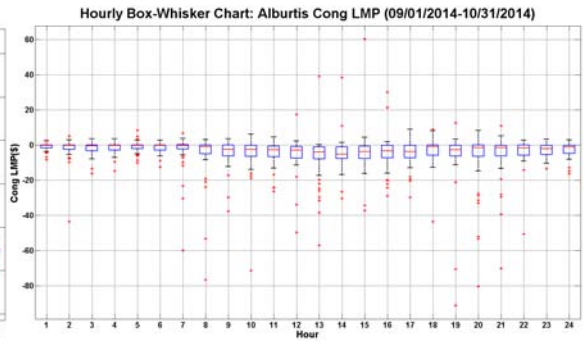

**(a)** Daily Total LMP




**(b)** Daily Congestion LMP




**(c)** Hourly Total LMP




**(d)** Hourly Congestion LMP

**Figure 13:** Daily and Hourly Box-whisker charts of Total LMP and Congestion LMP - PJM Alburtis

**Table 11:** Individual Congestion LMP Statistics of Period from 09/01/2014 to 10/31/2014

| Area | Location | Congestion LMP Minimum | Congestion LMP Maximum | Congestion LMP Range | Congestion LMP<0 (Percentage) | Congestion LMP=0 (Percentage) | Congestion LMP>0 Percentage) |
|---|---|---|---|---|---|---|---|
| PJM | Alburtis | -91.19 | 60.25 | 151.44 | 78.76% | 6.08% | 15.16% |
| | Goodings | -71.57 | 42.65 | 114.22 | 47.54% | 5.94% | 46.52% |
| | Jacksons Ferry | -31.98 | 149.33 | 181.31 | 33.88% | 6.08% | 60.04% |
| | Canton Centr. | -52.89 | 45.36 | 98.25 | 40.44% | 6.69% | 52.87% |
| MISO | Arcadian | -88.87 | 111.73 | 200.60 | 61.54% | 4.17% | 34.29% |
| | Cumberland | -117.03 | 26.95 | 143.98 | 38.73% | 1.57% | 59.70% |
| | Hanna | -102.5 | 488.47 | 590.97 | 68.78% | 3.89% | 27.32% |
| | Labadie | -116.15 | 18.64 | 134.79 | 71.04% | 3.83% | 25.14% |
| | Monroe | -59.15 | 185.82 | 244.97 | 53.55% | 4.17% | 42.28% |
| | Palisades | -608.15 | 181.57 | 789.72 | 54.17% | 4.23% | 41.6% |
| | Raun | -93.07 | 275.23 | 368.30 | 86.48% | 3.83% | 9.70% |
| | Sub 91 | -176.62 | 75.35 | 251.97 | 82.92% | 3.83% | 13.25% |
| NYISO | Niagara | -486.67 | 38.38 | 525.05 | 34.33% | 62.66% | 3.00% |
| | Ramapo | -673.06 | 0.003 | 673.06 | 24.51% | 75.43% | 0.07% |
| ISONE | Millbury | -52.98 | 23.65 | 76.63 | 5.87% | 89.35% | 4.03% |

## 5.3 Congestion LMP Difference of Paired Buses

Transmission congestion charge is incurred when the power system is constrained by physical limits. The congestion charge for a specified path is the product of the flow along the path and the price differences between the two terminals of the path.

The Table 12 is the congestion LMP statistics of the paired bus. The price differences between two locations which are under the same area are analyzed. Same as the table of individual bus statistics, the dominant positions for each location are highlighted in red. Among 8 location pairs, 5 pairs have negative congestion LMP difference as dominant, and 3 pairs have zero congestion LMP difference at most of time. When the congestion cost difference (from A to B) is negative, it may indicate that transferring power from A to B is more encouraged at that time if the system has constraints.

**Table 12:** Paired-Bus Congestion LMP Statistics of Period from 09/01/2014 to 10/31/2014

| Area | Bus Pairs | CongLMP Diff.<0 | CongLMP Diff.=0 | CongLMP Diff.> 0 |
|---|---|---|---|---|
| PJM | Alburtis-Canton Centr. | 70.68% | 16.20% | 13.12% |
| | Alburtis-Jacksons Ferry | 63.91% | 15.38% | 20.71% |
| MISO | Hanna-Monroe | 45.39% | 33.97% | 20.64% |
| | Labadie-Cumberland | 78.06% | 7.38% | 14.56% |
| | Labadie-Hanna | 37.25% | 40.26% | 22.49% |
| | Palisades-Monroe | 7.45% | 51.26% | 41.29% |
| | Raun-Sub 91 | 53.52% | 26.79% | 19.69% |
| NYISO | Niagara-Ramapo | 16.20% | 60.77% | 23.03% |

The possible potential linear relationship was examined between congestion LMP difference and angle difference of each bus pair. The Figure 14 shows in PJM area, except the dots of congestion LMP difference equals to \$0, the more that angle difference closer to 0°, the congestion LMP differences are less. However as in Figure 15, it shows in MISO area, there is no clear linear relationship between the prices and angles. The congestion LMP difference vs. angle difference plots of all bus pairs are in Appendix 8.5.

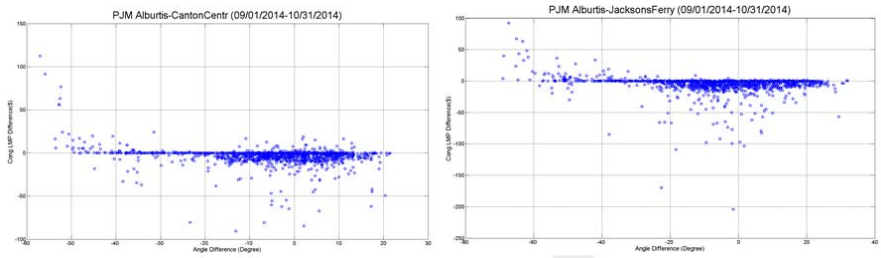



**Figure 14:** PJM Bus Pairs: Congestion LMP Difference vs. Angle Difference

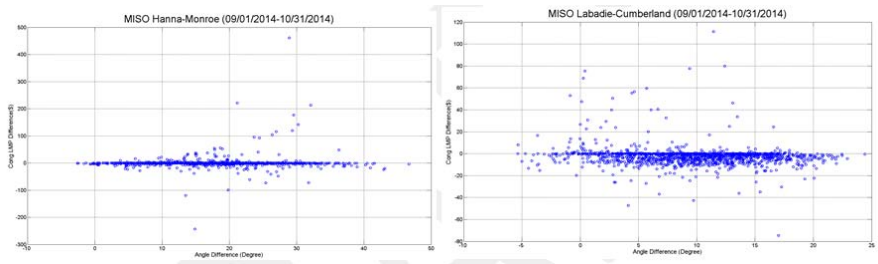



**Figure 15:** MISO Bus Pairs: Congestion LMP Difference vs. Angle Difference

Based on the congestion LMP difference plots of each bus pair (Appendix 8.6), amount \$100 and \$50 are evaluated to be the thresholds to determine price spike

for PJM and MISO areas, amount $300 and $100 are evaluated to be the thresholds to determine price spikes for NYISO area. Spike hours were captured based on these two values. During these 61 days, the price spikes are observed on different days at different locations.

The Table 13 is an example of price spikes in MISO area. Two columns are provided with $100 and $50 threshold values.

With the congestion LMP spikes hours captured, the possible correlation between angle difference and congestion LMP difference is examined. The Figure 16 is an example of the two component comparison. The congestion LMP spikes of Hanna-Monroe pair were marked in grey frame, angle pairs were tracked down. When congestion LMP spike appears, the extreme angle difference change was not observed clearly from this initial analysis. The complete two component comparison plots of all bus pairs are in Appendix 8.6. Deeper analysis will be described in following sections.

**Table 13:** Example: Congestion LMP Spikes of MISO Bus Pairs

| Bus Pair | Abs. CongLMP Diff.> $100 | Abs. CongLMP Diff.> $50 |
|---|---|---|
| Raun-Sub 91 | 09/05 14:00 | 09/05 14:00 |
| | 09/29 09:00 | 09/29 09:00 |
| | 10/15 19:00 | 10/15 19:00 |
| Hanna-Monroe | 09/17 14:00 | 09/17 14:00 |
| | 09/18 05:00 | 09/18 05:00 |
| | 09/29 09:00 | 09/29 09:00 |
| | 09/29 11:00 | 09/29 11:00 |
| | 09/29 12:00 | 09/29 12:00 |
| | 09/29 13:00 | 09/29 13:00 |
| | 09/29 14:00 | 09/29 14:00 |
| | 09/30 08:00 | 09/30 08:00 |
| | 10/01 11:00 | 10/01 11:00 |
| | 10/06 13:00 | 10/06 13:00 |
| Labadie-Cumberland | | 09/05 13:00 |
| | | 09/05 14:00 |
| | | 09/08 16:00 |
| | | 09/10 14:00 |
| | | 09/10 15:00 |
| | | 10/06 13:00 |
| | | 10/15 18:00 |
| | 10/17 13:00 | 10/17 13:00 |
| | 10/17 14:00 | 10/17 14:00 |
| | 10/17 15:00 | 10/17 15:00 |
| | | 10/18 15:00 |
| Labadie/Hanna | 09/02 15:00 | 09/02 15:00 |
| | 09/02 16:00 | 09/02 16:00 |
| | 09/17 14:00 | 09/17 14:00 |
| | 09/29 09:00 | 09/29 09:00 |
| | 09/29 11:00 | 09/29 11:00 |
| | 09/29 12:00 | 09/29 12:00 |
| | 09/29 13:00 | 09/29 13:00 |
| | 09/29 14:00 | 09/29 14:00 |
| | 09/30 08:00 | 09/30 08:00 |
| | 10/01 11:00 | 10/01 11:00 |
| Palisades-Monroe | 09/03 05:00 | 09/03 05:00 |
| | 09/18 05:00 | 09/18 05:00 |
| | 09/18 08:00 | 09/18 08:00 |
| | 09/18 12:00 | 09/18 12:00 |
| | 09/18 18:00 | 09/18 18:00 |

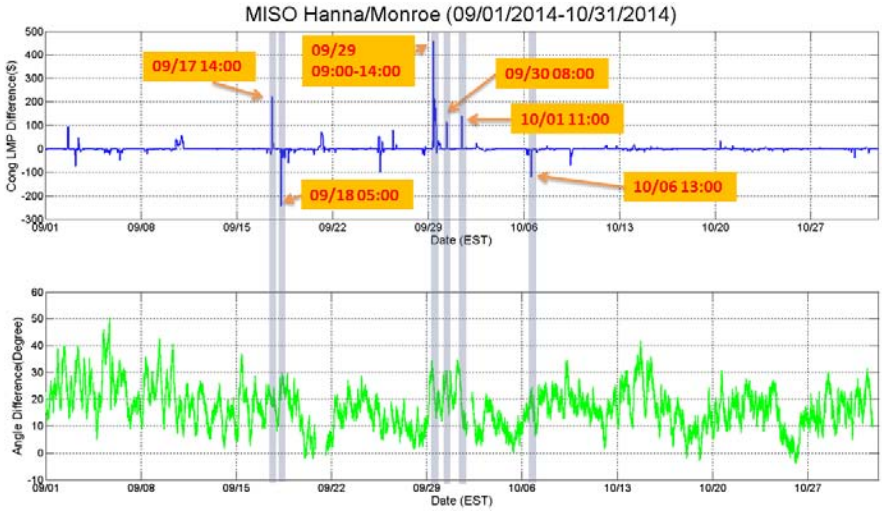



**Figure 16:** Example: MISO Hanna-Monroe Angle Difference vs. Congestion LMP Difference Spikes

## 5.4 Examine the Correlation between LMP Data and Wide-Area Angle Pair Data

Figure 17 below shows scatter plot between angle difference and total LMP price. The top left plot is for angle pair Raun-Millbury. The bottom right plot is for angle pair Alburtis-Canton Centr. Overall data shows no strong correlation between LMP and angle difference data. But from plots, it can observed there are more high LMP price spikes when angle is high which may indicate that the correlation may exist when system is in stress. Therefore, detailed case study is performed when system is in stress.

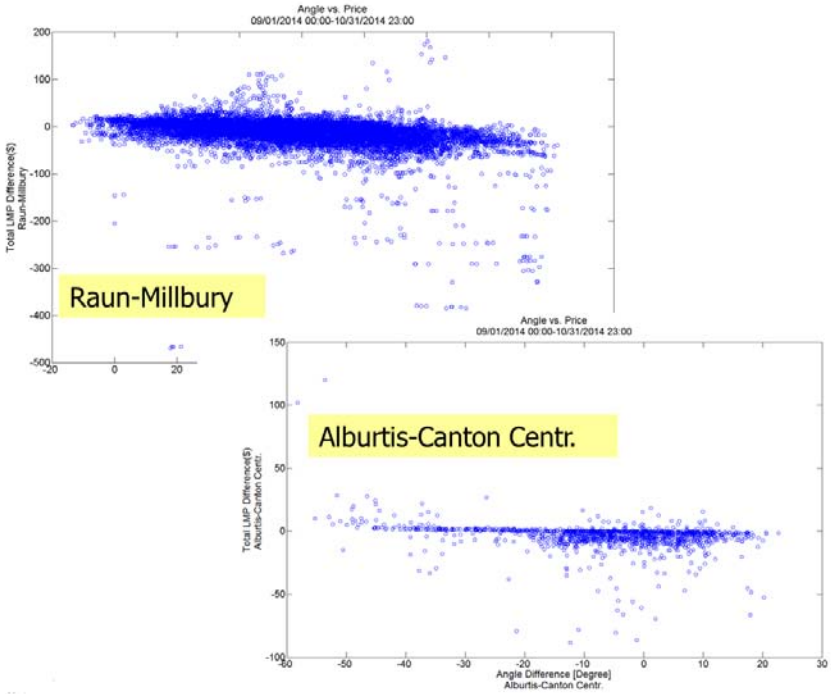



**Figure 17:** Angle Difference vs. LMP

## 5.5 Case Studies

Detailed investigation is recommended to be performed for at least five stress days. Five days are selected based on following system stress criteria:

- Wide area angle pair difference (Raun-Millbury/Arcadian-Millbury)>100°.
- Angle pair difference exceeds high/low established monitoring values.
- Price Spike> $50.

The complete study of Total LMP-Loss vs. angle difference for days angle difference exceeded high and low 0.5% data range can be found in Appendix 8.3. The complete study of price spike study can be found in Appendix 8.7.

Table 14 below lists the five selected days for case study. It also lists the reason of selection for system stress.

The detailed analysis for these selected days will be described in the following sections.

**Table 14:** Selected 5 Days for Detailed Case Study and System Stress Status

| Date | System Stress Status |
|---|---|
| 9/2/2014 | High temperature and load is high |
| 9/5/2014 | Wide area angle pair is high |
| 10/13/2014 | Severe weather in South Region in MISO |
| 10/17/2014 | ARS event in MISO |
| 10/26/2014 | Local area in stress |

### 5.5.1 September 2, 2014 Case Study

September 2, 2014 is selected because of high load in NYISO. Figure 18 shows area load trend in NYISO area from 09/01/2014 to 10/31/2014. From this figure, it can be found that area load achieved to the maximum level in area N.Y.C which is above 10000 MW during the two month period. After checking the NYISO interface information, it is learnt the interface margin between UPNY/CONED and Dysinger-East was low on 09/02/2014. Both information indicate NYISO was in stress on 09/02/2014.

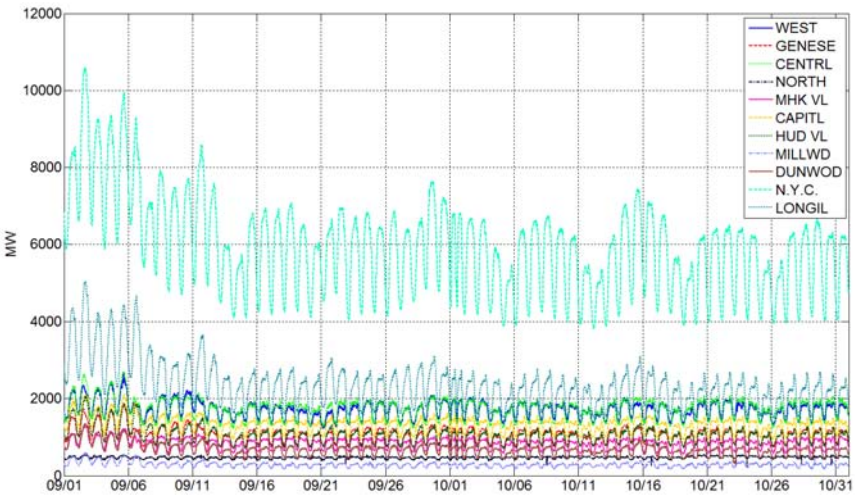



**Figure 18:** NYISO Load Trend from 09/01/2014 to 10/31/2013

Then, LMP price on 09/02/2014 is under investigation. Figure 19 shows the Total-Loss difference between Dunwoodie-Hudson in NYISO, and Total-Loss price in Hanna and Millbury. All three plots show price spike around hour 13:00 to 18:00. Figure 20 on page 36 shows Angle Difference Trend for Angle Pairs Niagara-Ramapo, Alburtis-Jacksons Ferry, Niagara-Monroe and Hanna-Canton Centr. on 9/02/2014. From these plots, it is observed that all four angle pairs difference

exceeded High/Low established reference values. Angle pair differences stayed high for hours from 12:00-18:00. Price spike and high angle difference are both observed when NYISO system is in stress.

**Figure 19:** Total-Loss Trend in Hanna and Millbury, NYISO Total-Loss Difference between Dunwoodie-Hudson

### 5.5.2 September 5, 2014 Case Study

Day 09/05/2014 is selected because of high wide area angle pair difference value. Figure 21 shows angle difference trend of wide-area angle pairs for a two month period from 09/01/2014-10/31/2014. It is observed the wide area angle pair difference is almost at its highest level for the 2-months range on 09/05/2014, which indicates the wide-area system is in stress on 9/5/2014. Figure 22 presents the Congestion component of LMP differences and angle pair differences for several listed angle pairs. It shows there are small spikes during 6AM-8AM and a big spike during 11AM-19PM. The plot at the bottom shows the angle difference for wide area angle pairs (Raun-Millbury and Arcadian-Millbury) stay at a high level (>100 degree) for almost the whole day. On 9/5/2014, wide area system stress is observed and congestion price difference spike is also found within angle stress period.

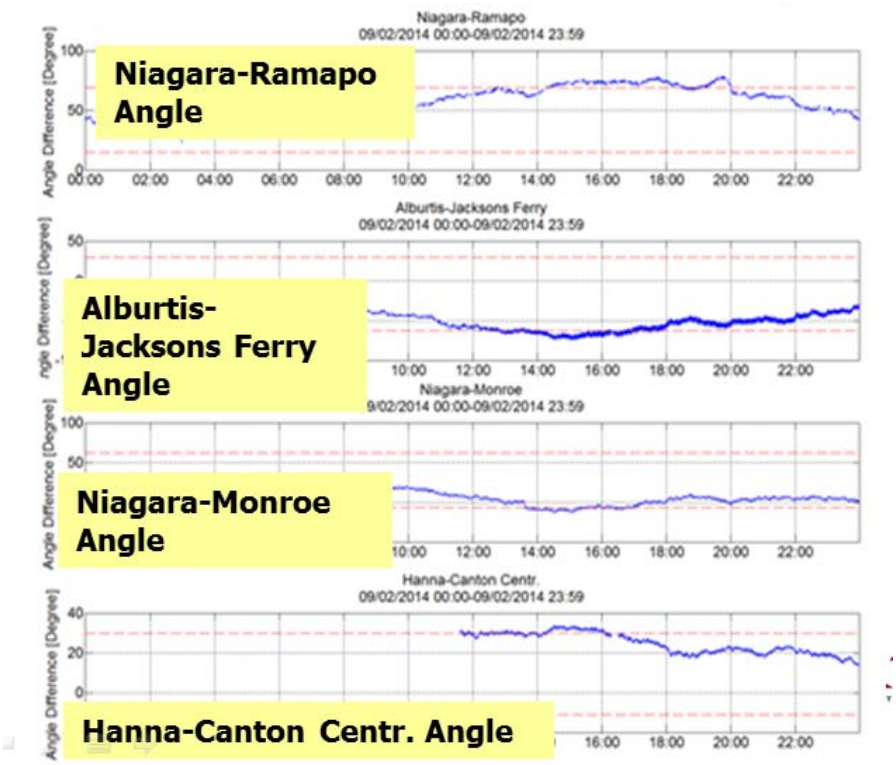



**Figure 20:** Angle Difference Trend for Angle Pairs Niagara-Ramapo, Alburtis-Jacksons Ferry, Niagara-Monroe and Hanna-Canton Centr. on 9/02/2014

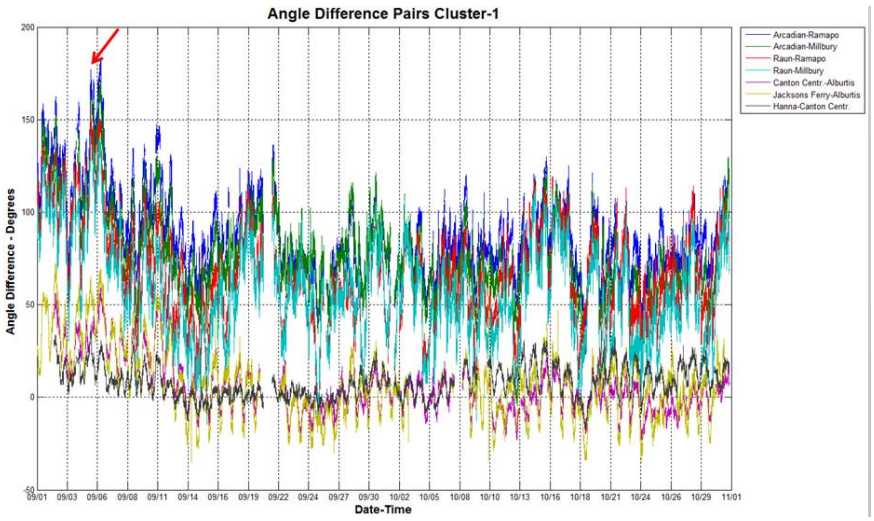



**Figure 21:** Angle Difference Trend for Wide Area Angle Pairs from 09/01/2014-10/31/2014

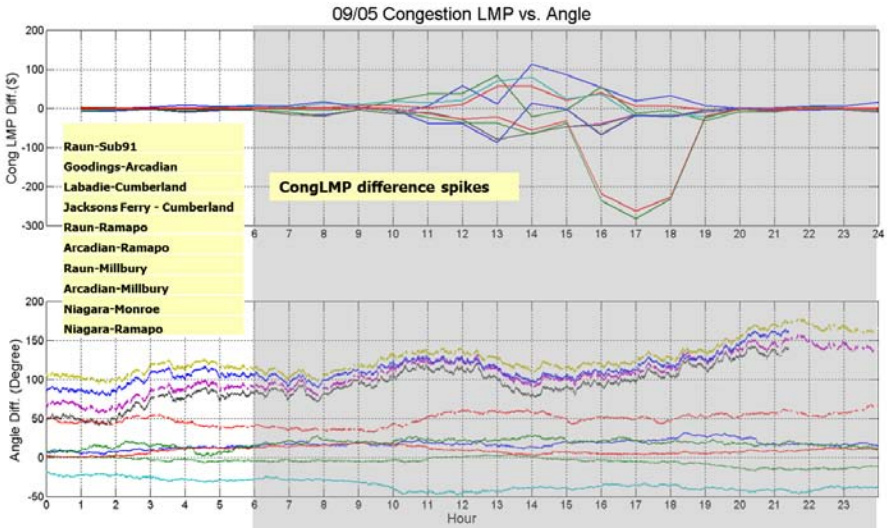



**Figure 22:** Congestion LMP and Angle Difference for Selected Wide Area Angle Pairs on 09/05/2014

### 5.5.3 October 13, 2014 Case Study

Based on system stress status provided by MISO, it is learnt there was severe weather in South Region between 9:00 to 22:00 on October 13. Top plot of Figure 23 shows the congestion component difference for all the selected angle pairs on 10/13/2015. The bottom plot shows the angle difference for all the selected angle pairs. It is observed congestion part of LMP fluctuated at 6 a.m., 9 a.m. and 12 p.m.. Angle differences start to increase around 5am, 8am and 12pm. In Figure 24, the angle difference between Hanna-Canton Centr is presented and it is observed angle value exceeding the established high reference value. According to NERC frequency working group monthly event report[2], there are three reported NERC frequency events found on 7:57:53 AM, 3:11:26 PM and 4:48:05 PM on Oct 13, 2014. All these signals indicate MISO system is in stress on Oct 13, 2014. Price spike and high angle difference are observed when MISO system is in stress on 10/13/2014.

### 5.5.4 October 17, 2014 Case Study

On 10/17/2014, several wide angle pair differences are above 100 degree based on the Figure 25. Around hour 7:00-11:00 and 13:00-17:00, congestion component price difference above $50. According to MISO event log, there was ARS event between 3:05:00 AM and 3:20:00 AM. There are two reported NERC frequency events[2] found on 4:03:22 AM, 2:31:15 PM on Oct 17, 2014. From Figure 26,

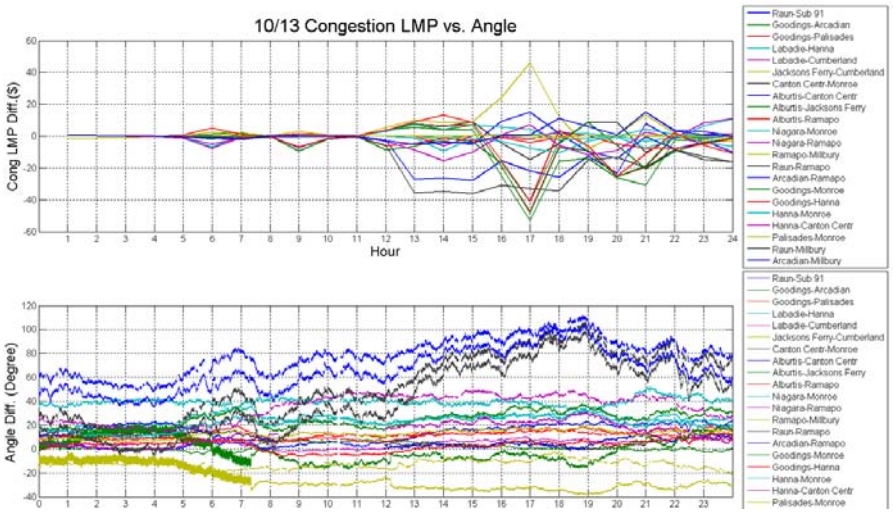



**Figure 23:** Congestion LMP and Wide Area Angle Difference on 10/13/2015

**Figure 24:** Angle Difference Trend for Wide Area Angle Pair Hanna-Canton Centr. on 10/13/2015

angle difference between Raun-Sub 91 exceeded established high reference value around 2:15 in the morning.

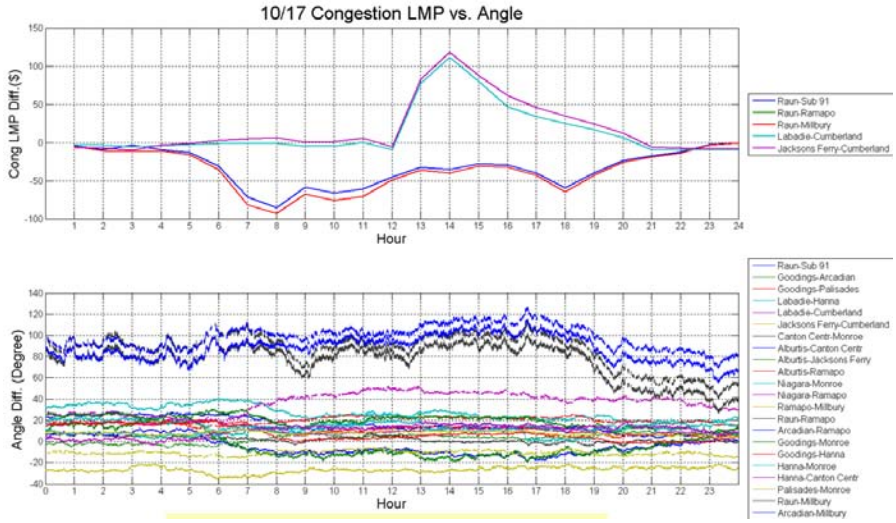



**Figure 25:** Congestion LMP and Wide Area Angle Difference on 10/17/2014

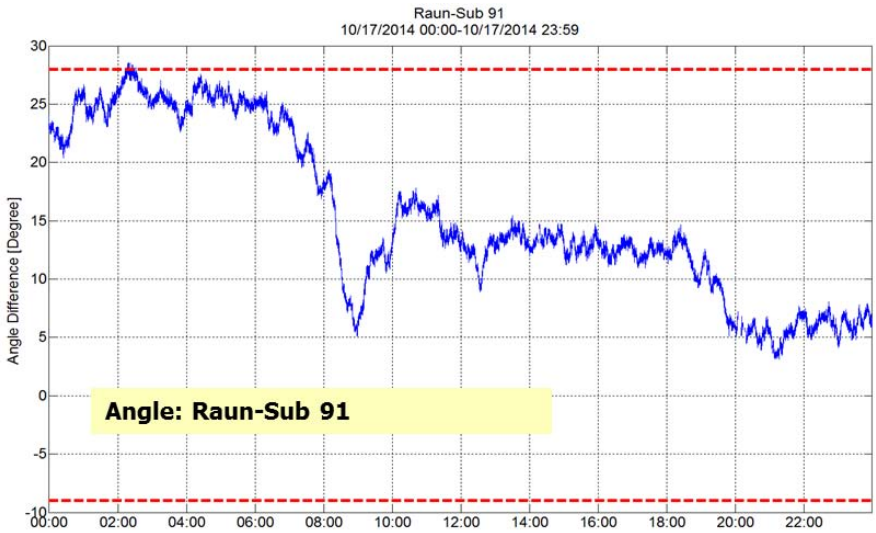



**Figure 26:** Angle Difference Trend for Wide Area Angle Pairs

### 5.5.5 October 26, 2014 Case Study

From Figure 27, it is found that angle difference between Jackson Ferry-Cumberland exceeded established high reference value. From Figure 28, the wide area angle

pairs stayed low less than 100 degrees. Congestion component differences for angle pairs Alburtis-JacksonFrerry and Jackson Ferry-Cumberlan showed spikes for several times on 10/26/2014. It means the overall wide area system was not in stress, but local area around JacksonFerry was in stress on 10/26/2014. According to PJMs interface log, it is indicated that South Interface margin level around 2:00 and 23:00 was low on 10/26/2014 which is verified what was observed in both angle pair difference and LMP data.

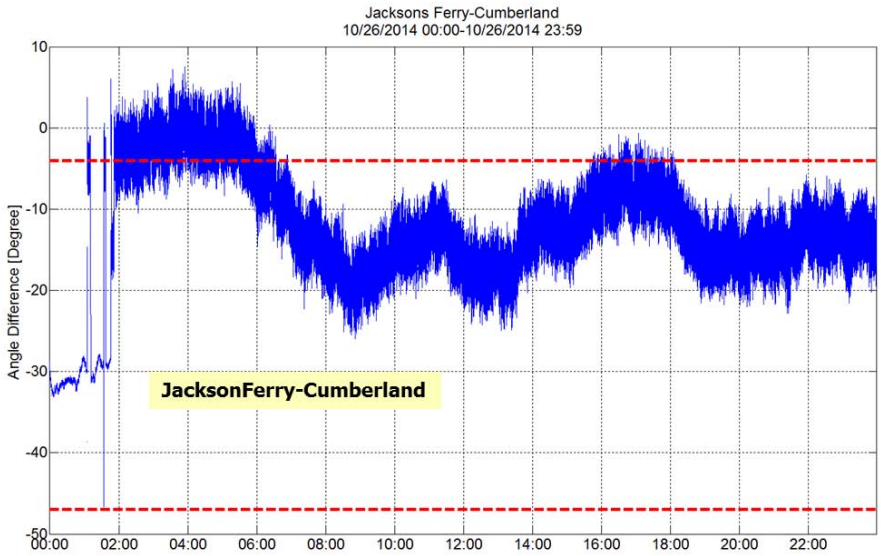



**Figure 27:** Angle Difference for Jackson Ferry-Cumberland on 10/26/2014

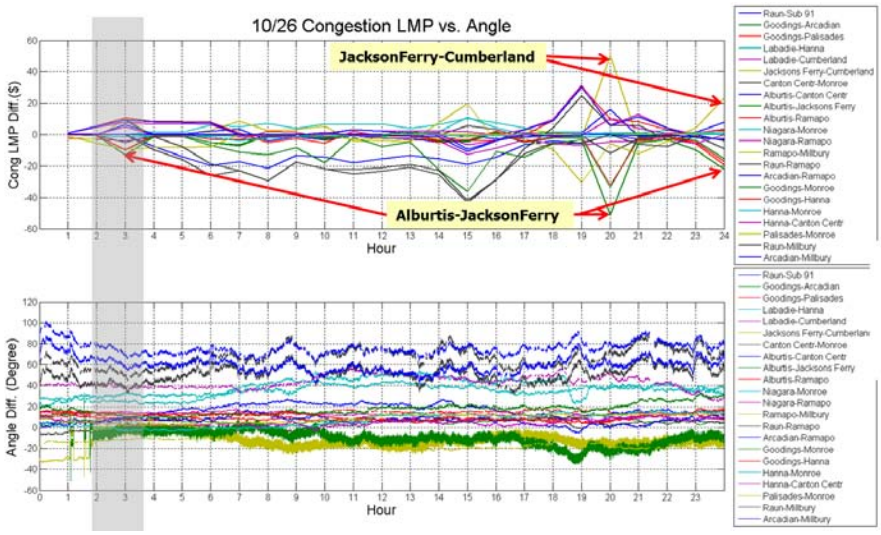



**Figure 28:** Congestion LMP and Wide Area Angle Difference on 10/26/2014

## 5.6 Conclusions and Observations

This section presents the statistical study focusing on the LMP data. The LMP data of four ISOs was provided or collected by CERTS-EPG. The statistical result for both individual node and pairs are provided. The co-relation between the angle pair differences and the Locational Marginal Price (LMP) differences has been analyzed. Overall data shows no strong correlation between LMP and angle difference, but, it is observed there are more high LMP price spikes when angle is high, which may indicate that LMP shoots up when system is in stress. The detailed study results of five stress cases confirm that LMP spike will likely happen when the system is in stress, but is much more dependent on localized stress conditions.

# 6 STUDY DEC 1-7 2014 EVENTS

During the meeting in the ISONE on Feb 5 2015, TAG members expressed desire to analyze and understand the angle pair difference behavior when system is under stress. TAG members suggested to study and analyze data from Dec 1-Dec 7 2014. During these days, there was operating challenges for operations. They agreed they will provide 1 second phasor data (and supporting power system measurements) for identified 22 sites (and surrogates) for Dec 1-7, 2014 to EPG.

## 6.1 Angle Data Availability and Quality for Dec 1-Dec 7 2014 Data

Before starting analysis, as done in previous analysis time periods, the voltage angle data from the PMU data files from all four ISOs was preprocessed to clean the data using data quality status flags. Known bad samples such as repeating 0, 120, -9999 and other stale data indicators were eliminated. Data was also cleaned by removing any data outside their typical value range. Angle difference was calculated using the clean data, and sudden abnormal data spikes were eliminated.

Status flag information was provided by MISO, PJM and ISO-NE was used to identify the details of data quality error. The Table 15 below shows the Status Flag Code in Hexadecimal, the data quality type based on the code and the number of samples for each PMU that was identified to be of that data quality type. Total number of samples for 7 days = (7 days×24 Hours×60 Minutes×60 Seconds) = 604800 samples.

**Table 15:** MISO Data Quality Statistics Based on Status Flag Code

| StatusFlagCode | 0x00000 | 0xDE030 | 0xFF030 | 0x21000 | 0x56000 | 0x56010 | 0x56020 | 0x42000 | 0x88000 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Data Quality Type | Good Data | Data Invalid | Data Invalid/ Sync Error | Sortby Arrival | PMU Error | PMU Error/ Unlocked time | PMU Error/ Sync Error | Sync Error | Test Mode | Dropout[1] | Missing[2] | Total |
| Altwrock_Ck 01 | 594352 | 71 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 591 | 9782 | 604800 |
| Ammojopa_345 01 | 590716 | 0 | 492[3] | 3221[3] | 0 | 0 | 0 | 0 | 0 | 589 | 9782 | 604800 |
| Ammolabadie 04 | 590644 | 0 | 491[3] | 3297[3] | 0 | 0 | 0 | 0 | 0 | 586 | 9782 | 604800 |
| Ammomtgy 01 | 588802 | 0 | 2686[3] | 2942[3] | 0 | 0 | 0 | 0 | 0 | 588 | 9782 | 604800 |
| Ammorush_Is 01 | 590543 | 0 | 495[3] | 3395[3] | 0 | 0 | 0 | 0 | 0 | 585 | 9782 | 604800 |
| Ammosioux 01 | 590618 | 0 | 498[3] | 3261[3] | 27 | 28 | 0 | 0 | 0 | 586 | 9782 | 604800 |
| Consargenta01 | 594319 | 108 | 4 | 0 | 0 | 0 | 0 | 5 | 0 | 582 | 9782 | 604800 |
| Conspalisad2 01 | 560893 | 33525[4] | 4 | 0 | 0 | 0 | 0 | 7 | 0 | 589 | 9782 | 604800 |
| Decomonroe401 | 0 | 594425[4] | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 589 | 9782 | 604800 |
| Decoplacid 01 | 594406 | 18 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 590 | 9782 | 604800 |
| Ipl Guion 01 | 594222 | 3 | 204 | 0 | 0 | 0 | 0 | 0 | 0 | 589 | 9782 | 604800 |
| Ipl Hannaipl 01 | 594222 | 3 | 204 | 0 | 0 | 0 | 0 | 0 | 0 | 589 | 9782 | 604800 |
| Ipl Sunnysid 01 | 594051 | 131 | 204 | 0 | 0 | 0 | 0 | 0 | 43 | 589 | 9782 | 604800 |
| Mec Cbluffs 01 | 593898 | 0 | 53 | 0 | 91 | 386 | 0 | 0 | 0 | 590 | 9782 | 604800 |
| Mec E_Molin 01 | 594010 | 0 | 416 | 0 | 0 | 0 | 0 | 0 | 0 | 592 | 9782 | 604800 |
| Mec Hills 01 | 594383 | 0 | 47 | 0 | 0 | 0 | 0 | 0 | 0 | 588 | 9782 | 604800 |
| Mec Lehigh2 01 | 584039 | 0 | 95 | 0 | 1333[5] | 6265[5] | 2700[5] | 0 | 0 | 586 | 9782 | 604800 |
| Mec Raun 01 | 0 | 0 | 594429[6] | 0 | 0 | 0 | 0 | 0 | 0 | 589 | 9782 | 604800 |
| Mec Raun 02 | 0 | 0 | 594435[6] | 0 | 0 | 0 | 0 | 0 | 0 | 583 | 9782 | 604800 |
| Wauesiouxcy 01 | 593917 | 98 | 396 | 0 | 0 | 0 | 0 | 0 | 0 | 607 | 9782 | 604800 |
| Wec Arcadn 01 | 583460 | 0 | 10954 | 0 | 0 | 0 | 0 | 0 | 10 | 594 | 9782 | 604800 |

1 Dropout in the above table indicates missing data numbers for timestamps in file indicated by 'NaN'.

2 Missing data is the number of data points which do not have timestamp in the data files. This is the difference of expected data points (604800) and available data points.

3 PMUs from AMMO have most errors due to Time Sync and Sort by Arrival indicating possible clock/ communication issue.

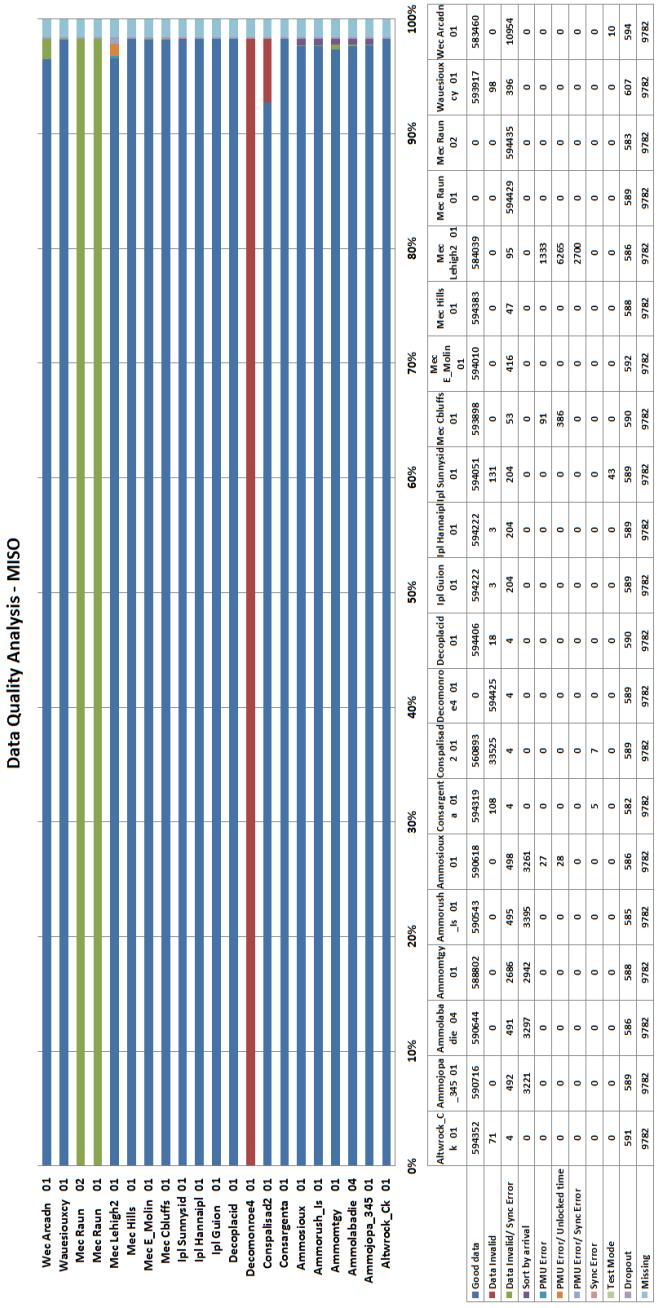
4 PMUs from Palisades and Monroe have mostly Data Invalid error indicating possible device failure.

5 PMU from Lehigh experienced PMU error including configuration error indicating possible device/clock failure.

6 PMUs from Raun have mostly Data Invalid/Sync error indicating non-operational PMU.

The Figure 29 below displays graphically the data quality distribution for each PMU.

The analysis was repeated for PMUs from PJM which can be found in Table 16 and Figure 30, for ISONE which can be found in Table 17 and Figure 31.




| | Altwrock_Ck 01 | Ammojopa_345 01 | Ammolabadie 04 | Ammomtgy 01 | Ammoruch_Is 01 | Ammosioux 01 | Consargenta 01 | Conspalisad2 01 | Decomonroe4 01 | Decoplacid 01 | Ipl Guion 01 | Ipl Hannaipl 01 | Ipl Sumnyid 01 | Mec Cbluffs 01 | Mec E_Molin 01 | Mec Hills 01 | Mec Lehigh2 01 | Mec Raun 01 | Mec Raun 02 | Wauesiouxcy 01 | Wec Arcadn 01 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Good data | 594352 | 590716 | 590644 | 588802 | 590643 | 590618 | 594319 | 560893 | 0 | 594406 | 594222 | 594222 | 594051 | 593898 | 594010 | 594383 | 584039 | 0 | 0 | 593917 | 583460 |
| Data Invalid | 71 | 0 | 0 | 0 | 0 | 0 | 108 | 33525 | 594425 | 18 | 3 | 3 | 131 | 0 | 0 | 0 | 0 | 0 | 0 | 98 | 0 |
| Data Invalid/ Sync Error | 4 | 492 | 491 | 2686 | 495 | 498 | 4 | 4 | 4 | 4 | 204 | 204 | 204 | 53 | 416 | 47 | 95 | 594429 | 594435 | 396 | 10954 |
| Sort by arrival | 0 | 3221 | 3297 | 2942 | 3395 | 3261 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| PMU Error | 0 | 0 | 0 | 0 | 0 | 27 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 91 | 0 | 0 | 1333 | 0 | 0 | 0 | 0 |
| PMU Error/ Unlocked time | 0 | 0 | 0 | 0 | 0 | 28 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 386 | 0 | 0 | 6265 | 0 | 0 | 0 | 0 |
| PMU Error/ Sync Error | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2700 | 0 | 0 | 0 | 0 |
| Sync Error | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Test Mode | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 43 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 |
| Dropout | 591 | 589 | 586 | 588 | 585 | 586 | 582 | 589 | 589 | 590 | 589 | 589 | 589 | 590 | 592 | 588 | 586 | 589 | 583 | 607 | 594 |
| Missing | 9782 | 9782 | 9782 | 9782 | 9782 | 9782 | 9782 | 9782 | 9782 | 9782 | 9782 | 9782 | 9782 | 9782 | 9782 | 9782 | 9782 | 9782 | 9782 | 9782 | 9782 |

**Figure 29:** Data Quality Analysis Distribution Chart for MISO

**Table 16:** PJM Data Quality Statistics Based on Status Flag Code

| StatusFlagCode | 0x0000 | 0xf030 | 0xe030 | 0x2000 | 0x2010 | 0x2020 | 0x2030 | |
|---|---|---|---|---|---|---|---|---|
| Data Quality Type | Good Data | Data Invalid/ PMU Error/ Sync Error/ Sort by Arrival | Data Invalid/ PMU Error/ Sync Error | Sync Error | Sync Error/ Unlocked 10s | Sync Error/ Unlocked 100s | Sync Error/ Unlocked 1000s | Total |
| AA 05CANTNC 01 | 486300 | 118091[1] | 0 | 407[2] | 2[2] | 0[2] | 0[2] | 604800 |
| AA 05CANTNC 02 | 484662 | 119718[1] | 0 | 415[2] | 5[2] | 0[2] | 0[2] | 604800 |
| AA 05CANTNC 03 | 492564 | 111623[1] | 0 | 11[2] | 42[2] | 380[2] | 180[2] | 604800 |
| AA 05CANTNC 04 | 484683 | 119746[1] | 0 | 371[2] | 0[2] | 0[2] | 0[2] | 604800 |
| AA 05CANTNC 05 | 491992 | 112184[1] | 0 | 11[2] | 41[2] | 405[2] | 167[2] | 604800 |
| AA 05CANTNC 06 | 492618 | 111566[1] | 0 | 11[2] | 40[2] | 386[2] | 179[2] | 604800 |
| AA 05J FERR 02 | 492101 | 112699[1] | 0 | 0 | 0 | 0 | 0 | 604800 |
| AA 05J FERR 03 | 491965 | 112835[1] | 0 | 0 | 0 | 0 | 0 | 604800 |
| AA 05J FERR 04 | 497980 | 106820[1] | 0 | 0 | 0 | 0 | 0 | 604800 |
| AA 05J FERR 05 | 491996 | 112804[1] | 0 | 0 | 0 | 0 | 0 | 604800 |
| AA 05J FERR 06 | 363878 | 240922[1] | 0 | 0 | 0 | 0 | 0 | 604800 |
| AA 05J FERR 07 | 363878 | 240922[1] | 0 | 0 | 0 | 0 | 0 | 604800 |
| CE GOODI;2R 11 | 601228 | 966[3] | 2598[3] | 8[3] | 0 | 0 | 0 | 604800 |
| CE GOODI;4B 12 | 603811 | 964[3] | 0[3] | 25[3] | 0 | 0 | 0 | 604800 |
| PL ALBURTIS 51 | 592831 | 8479[4] | 3490[4] | 0 | 0 | 0 | 0 | 604800 |
| PL ALBURTIS 52 | 592831 | 8479[4] | 3490[4] | 0 | 0 | 0 | 0 | 604800 |
| PL ALBURTIS 53 | 592831 | 8479[4] | 3490[4] | 0 | 0 | 0 | 0 | 604800 |
| PL ALBURTIS 54 | 596321 | 8479[4] | 0[4] | 0 | 0 | 0 | 0 | 604800 |
| PL ALBURTIS 55 | 596321 | 8479[4] | 0[4] | 0 | 0 | 0 | 0 | 604800 |
| PL ALBURTIS 56 | 596321 | 8479[4] | 0[4] | 0 | 0 | 0 | 0 | 604800 |

1 PMUs from AA have primarily have Data Invalid/PMU Error/Sync Error/Sort by arrival error indicating data communication issues from AA.

2 In addition to above, PMUs from Central Canton also have Sync Error indicating clock issue.

3 PMUs from CE (Goodings) have moderate Data invalid and Sync error.

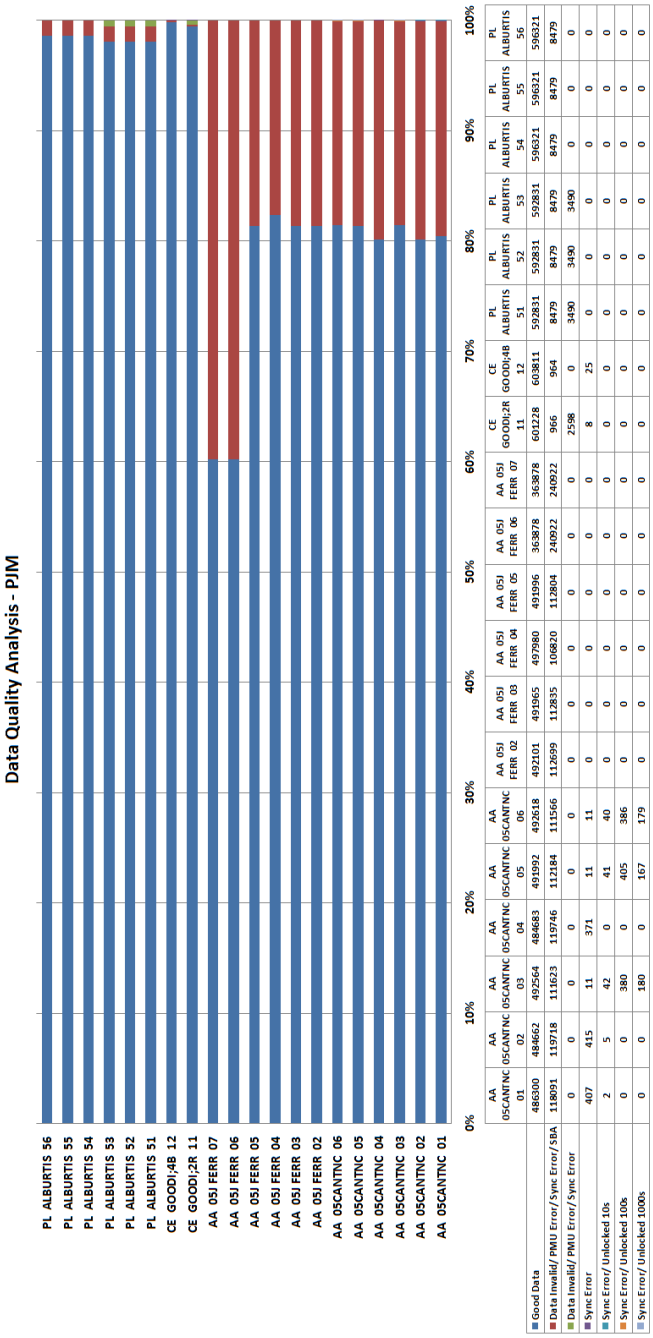
4 PMUs from PL (Alburtis) have some data invalid and additional sync error with possible communication/clock issue.

**Table 17:** ISONE Data Quality Statistics Based on Status Flag Code

| Status Flag Code | 00 00 | E0 00 | 80 00 | 40 00 | |
|---|---|---|---|---|---|
| Data Quality Type | Good[1] | Data Invalid/ PMU Error/ Sync Error | Data Invalid[2] | PMU Error | Total |
| BH_ORRINGTON_A | 600241 | 6 | 4331 | 222 | 604800 |
| NE_MILLBURY_3A | 604407 | 6 | 165 | 222 | 604800 |
| NE_SANDYPOND_A | 604091 | 6 | 481 | 222 | 604800 |

1 Overall Best PMU data quality with few errors.

2 PMU from Orrington has high Data Invalid error compared to others indicating possible device failure.




| | AA 05CANTNC 01 | AA 05CANTNC 02 | AA 05CANTNC 03 | AA 05CANTNC 04 | AA 05CANTNC 05 | AA 05CANTNC 06 | AA 05J FERR 02 | AA 05J FERR 03 | AA 05J FERR 04 | AA 05J FERR 05 | AA 05J FERR 06 | AA 05J FERR 07 | CE GOODj2R 11 | CE GOODj4B 12 | PL ALBURTIS 51 | PL ALBURTIS 52 | PL ALBURTIS 53 | PL ALBURTIS 54 | PL ALBURTIS 55 | PL ALBURTIS 56 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Good Data | 486300 | 484662 | 492564 | 484683 | 491992 | 492618 | 492101 | 491965 | 497980 | 491996 | 363878 | 363878 | 601228 | 603811 | 592831 | 592831 | 592831 | 596321 | 596321 | 596321 |
| Data Invalid/ PMU Error/ Sync Error/ SBA | 118091 | 119718 | 111623 | 119746 | 112184 | 111566 | 112699 | 112835 | 106820 | 112804 | 240922 | 240922 | 966 | 964 | 8479 | 8479 | 8479 | 8479 | 8479 | 8479 |
| Data Invalid/ PMU Error/ Sync Error | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2598 | 0 | 3490 | 3490 | 3490 | 0 | 0 | 0 |
| Sync Error | 407 | 415 | 11 | 371 | 11 | 11 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 25 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sync Error/ Unlocked 10s | 2 | 5 | 42 | 0 | 41 | 40 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sync Error/ Unlocked 100s | 0 | 0 | 380 | 0 | 405 | 386 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sync Error/ Unlocked 1000s | 0 | 0 | 180 | 0 | 167 | 179 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Figure 30:** Data Quality Analysis Distribution Chart for PJM

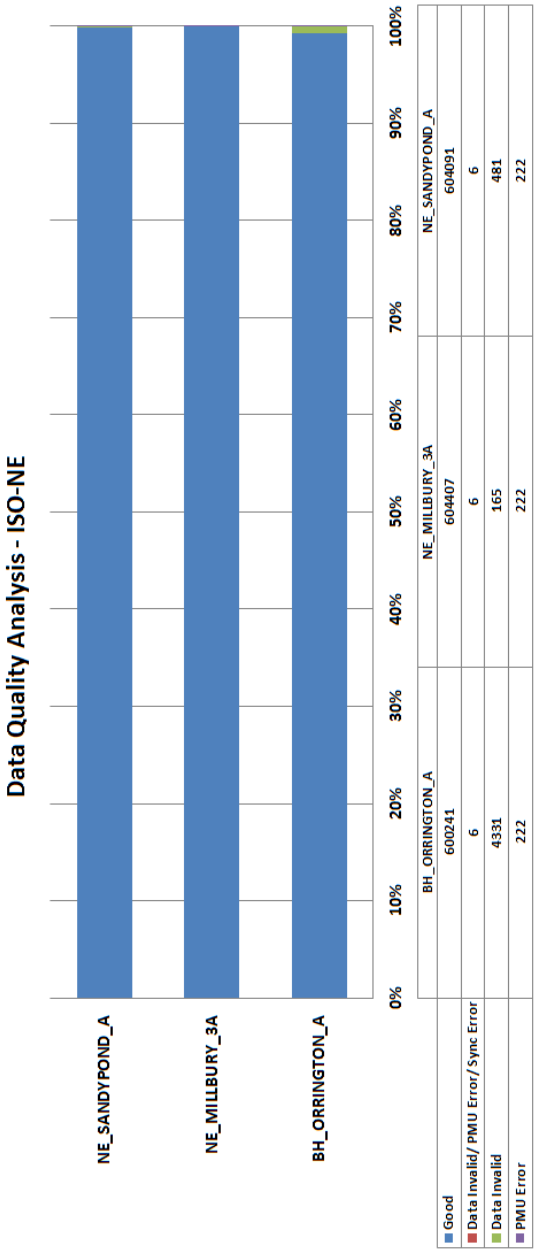



**Figure 31:** Data Quality Analysis Distribution Chart for ISONE

After each signal data is cleaned, good data quality and data availability percentage is calculated by dividing the number of good quality data points by total number of expected data points. Alternative replacement PMUs with good data quality were identified and used for analysis instead of PMU data that do not have good data quality. For Dec-1-7, 2014 dataset, two additional PMUs were

used (Orrington and Sandypond) from ISO-NE to help with event identification and analysis. The PMUs used for analysis, their replacements (if needed) with good data availability are listed in Table 18.

**Table 18:** PMU and Substation Mapping with Data Availability for Dec 1-7, 2014

| Index | Substation | Alternative | PMU/Signal Name | Data Provider | Good Data % |
|---|---|---|---|---|---|
| 1 | Alburtis 500kV | | PL ALBURTIS 51.L500BRANCHBG | PJM | 97.9 |
| 2 | Arcadian 345kV | | Wec Arcadn 01-B345_1 | MISO | 96.5 |
| 3 | Canton Centr. 345kV | | AA 05CANTNC 01.L34505SCANTO | PJM | 80.4 |
| 4 | Cumberland 500kV* | Joppa | Ammojopa_345 01-L34546 | MISO | 98.2 |
| 5 | Goodings 345kV | | CE GOODI;2R 11.L345GOODI;2R | PJM | 99.4 |
| 6 | Hanna 345kV | | Ipl Hannaipl 01-L345C | MISO | 98.3 |
| 7 | Jacksons Ferry 765kV | | AA 05J FERR 02.L76505BROADF | PJM | 81.4 |
| 8 | Labadie 345kV | | Ammolabadie 04-L3451 | MISO | 98.2 |
| 9 | Millbury 345kV | | NE_MILLBURY_3A.L345 | ISO-NE | 99.9 |
| 10 | Monroe 345kV* | Placid | Decoplacid 01-L345B2 | MISO | 98.3 |
| 11 | Niagara 345kV | | NIAGARA345.N345_NS1_V1 | NYISO | 98.3 |
| 12 | Palisades 345kV | | Conspalisad2 01-L3451F | MISO | 92.7 |
| 13 | Ramapo 500kV | | RAM.V1VPM | NYISO | 99.0 |
| 14 | Raun 345kV* | Lehigh | Mec Lehigh2 01-L3453020 | MISO | 96.6 |
| 15 | Sub 91 345kV | | Altwrock_Ck 01-L345799 | MISO | 98.3 |
| 16 | Orrington 345kV | | BH_ORRINGTON_A.B345 | ISO-NE | 99.2 |
| 17 | Sandypond 345kV | | NE_SANDYPOND_A.L345 | ISO-NE | 99.9 |

*Alternative PMU data is used

After calculating the angle difference, statistical analysis was performed on these angle difference data and summary results (such as Max, Min, Mean, Median, and Percent positive) were calculated and reported. The High and Low range values were estimated by eliminating top and bottom 0.5% of data. This was done to eliminate any data spikes and other noisy data that may have escaped the data cleaning process. The angle difference pairs with Arcadian and PMUs from ISO-NE (Millbury, Arrington and Sandy Pond) were adjusted by 120 degrees. These statistical summary results are presented in Table 19 below:

**Table 19:** Summary of Statistical Analysis Results Using Angle Difference Data for Dec 1, 2014 - Dec 7, 2014

| Index | From bus | To bus | Adj | Good % | Min 0.5% | Max 0.5% | Range | Min | Max | Media | Mean | Positive % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Raun | Sub 91 | | 94 | -10 | 25 | 35 | -13 | 27 | 10 | 9 | 79 |
| 2 | Goodings | Arcadian | +120 | 94 | -8 | 10 | 18 | -10 | 12 | -1 | -1 | 39 |
| 3 | Goodings | Palisades | | 92 | 3 | 25 | 22 | 0 | 27 | 17 | 17 | 100 |
| 4 | Labadie | Hanna | | 96 | 22 | 56 | 34 | 17 | 61 | 38 | 38 | 100 |
| 5 | Labadie | Cumberland | | 96 | -4 | 20 | 24 | -5 | 21 | 7 | 7 | 96 |
| 6 | JacksonsFerry | Cumberland | | 78 | -52 | -26 | 26 | -54 | -20 | -40 | -39 | 0 |
| 7 | CantonCentr. | Monroe | | 77 | 3 | 29 | 26 | 0 | 31 | 14 | 15 | 100 |
| 8 | Alburtis | CantonCentr. | | 75 | -23 | 5 | 28 | -25 | 6 | -8 | -8 | 10 |
| 9 | Alburtis | JacksonsFerry | | 76 | -33 | 11 | 44 | -38 | 14 | -14 | -14 | 6 |
| 10 | Alburtis | Ramapo | | 93 | 0 | 35 | 35 | -1 | 37 | 21 | 20 | 98 |
| 11 | Niagara | Monroe | | 74 | 1 | 51 | 50 | -2 | 55 | 29 | 28 | 100 |
| 12 | Niagara | Ramapo | | 98 | 22 | 55 | 33 | 18 | 58 | 40 | 39 | 100 |
| 13 | Ramapo | Millbury | -120 | 99 | -10 | 19 | 29 | -11 | 22 | 1 | 2 | 60 |
| 14 | Raun | Ramapo | | 93 | 34 | 142 | 108 | 25 | 151 | 97 | 92 | 100 |
| 15 | Arcadian | Ramapo | -120 | 93 | 15 | 87 | 72 | 11 | 93 | 58 | 54 | 100 |
| 16 | Goodings | Monroe | | 95 | 20 | 55 | 35 | 17 | 57 | 42 | 41 | 100 |
| 17 | Goodings | Hanna | | 95 | -3 | 29 | 32 | -4 | 31 | 11 | 12 | 96 |
| 18 | Hanna | Monroe | | 96 | 10 | 45 | 35 | 8 | 49 | 30 | 28 | 100 |
| 19 | Hanna | CantonCentr. | | 77 | -1 | 30 | 31 | -4 | 32 | 15 | 14 | 98 |
| 20 | Palisades | Monroe | | 93 | 14 | 36 | 22 | 13 | 38 | 24 | 24 | 100 |
| 21 | Raun | Millbury | -120 | 94 | 34 | 148 | 114 | 29 | 159 | 98 | 94 | 100 |
| 22 | Arcadian | Millbury | +120 | 93 | 11 | 101 | 90 | 4 | 108 | 59 | 57 | 100 |
| 23 | Raun | Orrington | -120 | 93 | 12 | 155 | 143 | 6 | 167 | 89 | 84 | 100 |
| 24 | Arcadian | Orrington | +120 | 93 | -9 | 117 | 126 | -16 | 129 | 45 | 47 | 97 |
| 25 | Ramapo | Orrington | -120 | 98 | -31 | 37 | 68 | -34 | 44 | -11 | -8 | 24 |
| 26 | Raun | Sandy Pond | -120 | 93 | 31 | 148 | 117 | 26 | 157 | 97 | 93 | 100 |
| 27 | Arcadian | Sandy Pond | +120 | 93 | 8 | 104 | 96 | 1 | 112 | 57 | 55 | 100 |
| 28 | Ramapo | Sandy Pond | -120 | 99 | -12 | 23 | 35 | -14 | 26 | -1 | 1 | 45 |

The High (0.5% max), Low (0.5% min) and median values from the period of Dec 1-7, 2014 are compared with both the study periods (Winter 2014 and Fall 2014) and are listed in Table 20 for comparison. Also listed are the High and Low values from the State Estimator data study for March 2011 as reference.

**Table 20:** Comparison of High, Median, and Low Values for the Different Study Periods

| Index | From bus | To bus | SE Data | | PMU Data (Winter) | | | PMU Data (Fall) | | | PMU Data (Event) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mar-11 | | 12/15/2013-2/15/2014 | | | 9/1/2014-10/31/2014 | | | Dec 1-7, 2014 | | |
| | | | Low | High | Low | Median | High | Low | Median | High | Low | Median | High |
| 1 | Raun | Sub 91 | -13 | 48 | -30 | 5 | 30 | -9 | 10 | 28 | -10 | 10 | 25 |
| 2 | Goodings | Arcadian | -8 | 14 | -14 | -2 | 18 | -12 | 2 | 15 | -8 | -1 | 10 |
| 3 | Goodings | Palisades | 7 | 29 | -6 | 15 | 28 | -5 | 10 | 23 | 3 | 17 | 25 |
| 4 | Labadie | Hanna | 23 | 57 | 12 | 41 | 63 | 0 | 29 | 48 | 22 | 38 | 56 |
| 5 | Labadie | Cumberland | 9 | 35 | -11 | 25 | 47 | -4 | 10 | 22 | -4 | 7 | 20 |
| 6 | JacksonsFerry | Cumberland | -47 | -19 | -54 | -32 | -4 | -47 | -28 | -4 | -52 | -40 | -26 |
| 7 | CantonCentr. | Monroe | -10 | 12 | -34 | -6 | 17 | -9 | 9 | 27 | 3 | 14 | 29 |
| 8 | Alburtis | CantonCentr. | -46 | -10 | -61 | -35 | 8 | -52 | -5 | 20 | -23 | -8 | 5 |
| 9 | Alburtis | JacksonsFerry | -60 | -12 | -76 | -42 | 11 | -63 | -6 | 29 | -33 | -14 | 11 |
| 10 | Alburtis | Ramapo | 2 | 18 | -3 | 27 | 49 | -2 | 12 | 26 | 0 | 21 | 35 |
| 11 | Niagara | Monroe | -26 | 12 | -49 | -7 | 50 | -7 | 31 | 62 | 1 | 29 | 51 |
| 12 | Niagara | Ramapo | 9 | 57 | 22 | 55 | 88 | 15 | 41 | 69 | 22 | 40 | 55 |
| 13 | Ramapo | Millbury | -26 | 17 | -36 | 3 | 24 | -25 | -10 | 11 | -10 | 1 | 19 |
| 14 | Raun | Ramapo | 66 | 154 | 19 | 119 | 208 | 7 | 67 | 142 | 34 | 97 | 142 |
| 15 | Arcadian | Ramapo | 39 | 109 | 19 | 91 | 159 | 43 | 89 | 168 | 15 | 58 | 87 |
| 16 | Goodings | Monroe | 22 | 54 | -6 | 29 | 51 | -1 | 21 | 46 | 20 | 42 | 55 |
| 17 | Goodings | Hanna | 0 | 23 | -21 | 8 | 27 | -16 | 5 | 22 | -3 | 11 | 29 |
| 18 | Hanna | Monroe | 11 | 46 | -18 | 21 | 46 | -1 | 17 | 40 | 10 | 30 | 45 |
| 19 | Hanna | CantonCentr. | 13 | 42 | -5 | 26 | 48 | -11 | 8 | 30 | -1 | 15 | 30 |
| 20 | Palisades | Monroe | 8 | 29 | -3 | 13 | 27 | 0 | 11 | 27 | 14 | 24 | 36 |
| 21 | Raun | Millbury | 26 | 117 | 8 | 125 | 213 | 0 | 56 | 128 | 34 | 98 | 148 |
| 22 | Arcadian | Millbury | 51 | 159 | 2 | 93 | 165 | 27 | 78 | 154 | 11 | 59 | 101 |

The Appendix 8.8 provides the charts graphically display the High-Median-Low values for each of the phasor data analysis periods in 2014. The State Estimator High and Low values for March 2011 is also included as reference.

## 6.2 Explore and Develop Method for Identifying System Events Using Angle Pair Differences

After extracting, cleaning and combining the data, EPG looked for events during Dec 1-7 2014. According to [2], there are three major NERC events reported in this period. Figure 32 shows the geographic map of these three major NERC events. The detail of each event is described in the figure.

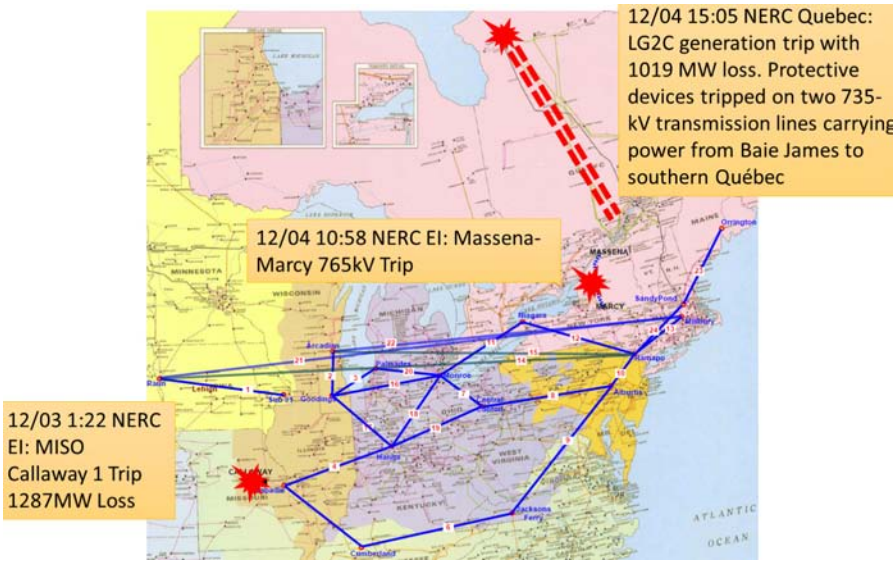



**Figure 32:** Identified 3 NERC Events from Dec 1 to Dec 7, 2014

The method used to identify the events is based on the change range of angle pair difference in 1-minute time window and it is well known as control chart used to determine if a manufacturing or business process is in a state of statistical control[5]. If the 1-minute data change range falls outside of the established upper control limit (**UCL**), it indicates that the monitored process is not in control. There are three steps involved in this method.

- Identifying the maximum and minimum values in 1-minute time window.
- Calculating 1-minute the data change range=maximum- minimum.
- Comparing the 1-minute change range with upper control limit(**UCL**).

Figures 33, 34 and 35 show the process step by step.

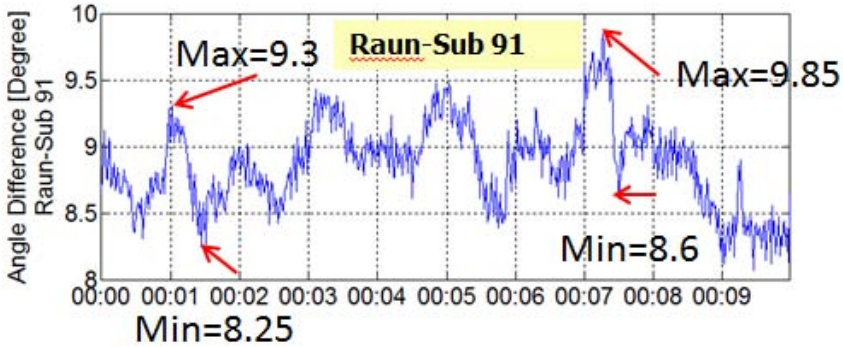



**Figure 33:** Control Plot Step 1: Find Max and Min Point in 1-Min Time Window

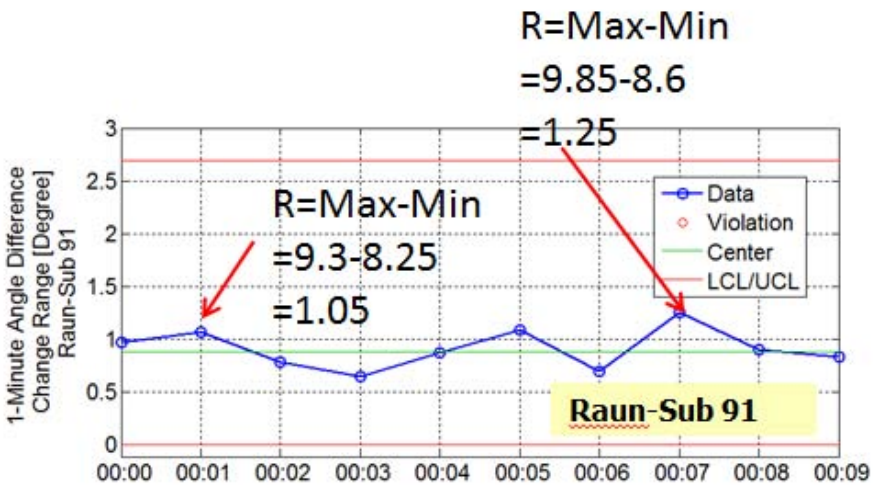



**Figure 34:** Control Plot Step 2: Calculate the Range Value

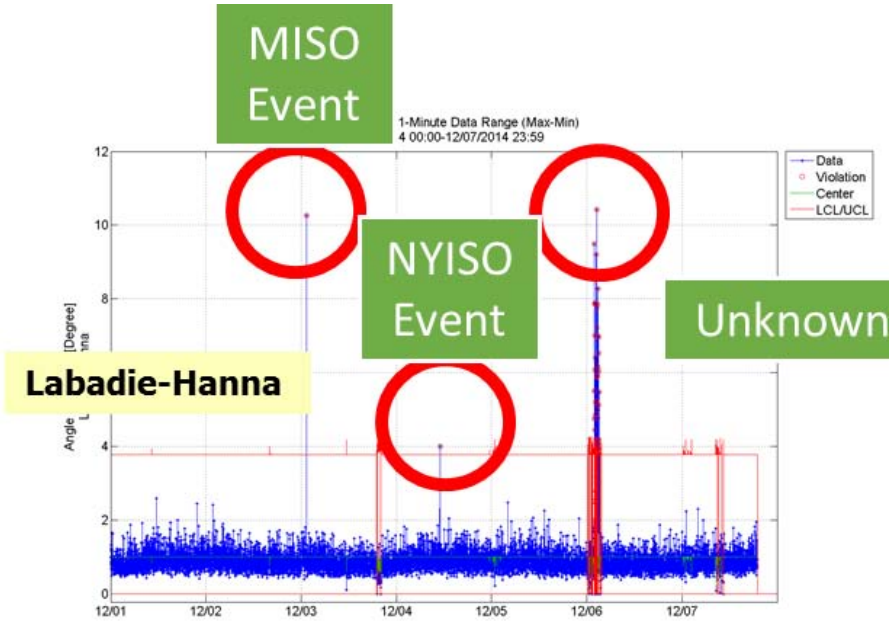



**Figure 35:** Control Plot Step 3: Compare the Range with Upper Control Limit

The UCL is calculated by using the following formula:

$$UCL_i = \overline{R} + nSigma\frac{\sigma}{\sqrt{n_i}} \tag{1}$$

$$\overline{R} = \frac{\sum R}{K} \tag{2}$$

$$\sigma = \frac{\overline{R}}{d_2} \tag{3}$$

Where:

$n_i$ : subgroup size
$d_2$ : control chart constants that depend on subgroup size
$nSigma$ : is the number of sigma multiples from the center line to a control limit
$K$ : number os subgroup

The default value for the nSigma is 3. In order to find the extreme event, we recommend to use of $nSigma = 20$. Lower nSigma values identify more events, higher values may miss some events. Figure 35 shows there are three events identified by the control plot method for the angle pair Labadie-Hanna with $nSigma = 20$. Two events are known NERC major events and one is unknown local event. The

unknown local event is later identified by MISO representative as generation trip located near Hanna in Indianapolis area. In Appendix 8.9 provides control plots for all the selected angle pairs with $nSigma = 20$.

Table 21 below summarizes all the identified events detected by all selected angle pairs with $nSigma = 20$. Table columns provide the date/time of the detected events and table rows list all selected angle pairs. The cells with red color indicate there is an event detected by the a specific angle pair. Two known NERC major events are detected by seven and more selected angle pairs, and twelve local events are found by three and less than three selected angle pairs. The details of the identified local events were provided by TAG members based on their operation log described in Table 21.

There are some local events detected by two angle pairs, Ramapo-Millbury and Ramapo-Sandy Pond as shown in Table 22. Many angle change spikes are observed in Figure 36 and 37. It means this event detection method may be not appropriate to use for these two angle pairs. It is suspected it is result from phase angle regulator installed on Ramapo. But, this behavior is not observed for the other angle pairs involving Ramapo.

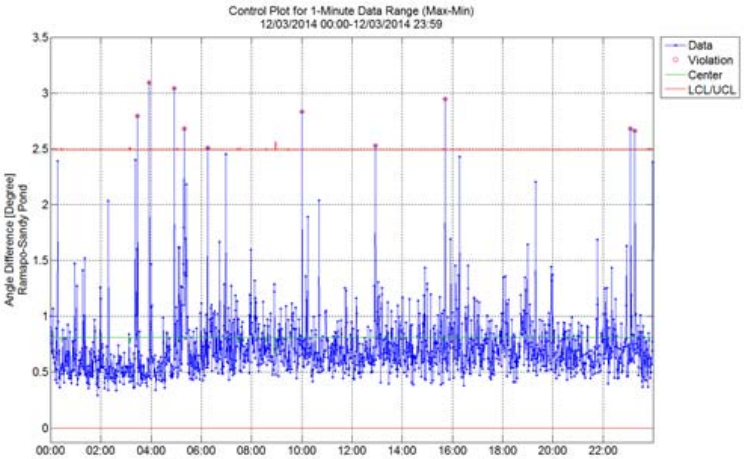



**Figure 36:** Angle Pair Difference for Ramapo-Sandy Pond on December 3, 2014

If $nSigma$ is reduced to 15, there are a total of 36 events detected as shown in Table 23 and 24. Besides two known NERC events which is also identified by $nSigma = 20$, the third 12/4 15:05 NERC major event located in Hydro Quebec can be detected by angle pair SandyPond-Orrington.

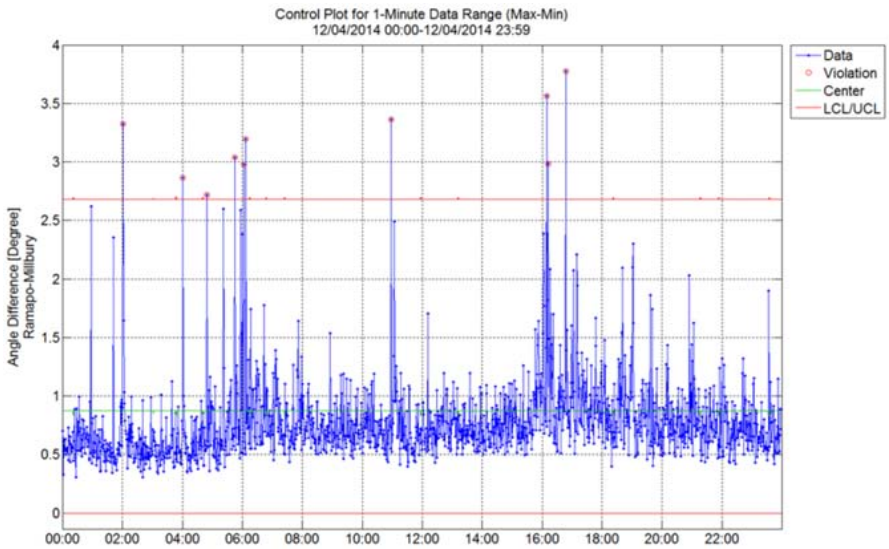



**Figure 37:** Angle Pair Difference for Ramapo-Millbury on December 4, 2014

**Table 21:** Detected Events Summary for Dec 1 to Dec 7, 2014 (nSigma=20)

| FromBus | ToBus | UCL | 12/01 1:02 | 12/01 10:28 | 12/01 11:12 | 12/01 11:47 | 12/01 15:44 | 12/01 11:09 | 12/01 11:33 | 12/03 1:22 | 12/4 10:58 | 12/5 4:59 | 12/5 13:22 | 12/5 18:08 | 12/6 1:52 -12/6 3:02 | 12/7 15:26 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Raun | Sub 91 | 3.3 | | | | | | | | | | | | | | |
| Goodings | Arcadian | 2.04 | | | | | | | | | | | | | | |
| Goodings | Palisades | 2.69 | | | | | | | | | | | | | | |
| Labadie | Hanna | 3.78 | | | | | | | | | | | | | 5 | |
| Labadie | Cumberland | 1.72 | | | | | | | | | | | | | | |
| Jacks.Ferry. | Cumberland | 3.69 | | | | | | | 2 | | | | 3 | | 5 | |
| CantonCtr. | Monroe | 3.17 | | | | | | 2 | | | | | | | | |
| Alburtis | CantonCtr. | 4.34 | | | | | | | | | | | | | | 6 |
| Alburtis | Jacks.Ferry. | 6.02 | | | | | | | | | | | | | | |
| Alburtis | Ramapo | 2.4 | | | | | | | | | | 7 | | | | |
| Niagara | Monroe | 5.88 | | | | | | | | | | | | | | |
| Niagara | Ramapo | 4.43 | | | | | | | | | | | | | | |
| Raun | Ramapo | 11.71 | | | | | | | | | | | | | | |
| Arcadian | Ramapo | 10.06 | | | | | | | | | | | | | | |
| Goodings | Monroe | 5.24 | | | | | | | | | | | | | | |
| Goodings | Hanna | 3.23 | | | | | | | | | | | | | | |
| Hanna | Monroe | 4.15 | | | | | | | 2 | | | | 3 | | | |
| Hanna | CantonCtr. | 4.29 | | | | | | 2 | 2 | | | | 3 | | | |
| Palisades | Monroe | 2.92 | | | | | | | | | | | | 4 | | |
| Raun | Millbury | 12.76 | | | | | | | | | | | | | | |
| Arcadian | Millbury | 11.25 | | | | | | | | | | | | | | |
| Sandy Pond | Orrington | 3.99 | 1 | 1 | 1 | 1 | 1 | | | | | | | | | |

1 ISONE: system impact was small and no equipment tripping messages.

2 MISO: Outages in MISO North Region led to Phase Shifter bypassed and Manitoba→MISO import limit imposed.

3 MISO: Line restored in North Region led to Phase Shifter restored and Manitoba→MISO import limit removed.

4 MISO: Two 345 lines restored in Michigan near Monroe.

5 MISO: Gen trip near Hanna (Indianapolis area).

6 PJM: went off-cost for reactive transfers at 12/07/2014 15:34.

7 PJM: unknown. Ask NYISO check from their side (Ramapo)

**Table 22:** Detected Events Summary for Dec 1 to Dec 7, 2014 for Angle Pairs in Question

| FromBus | ToBus | UCL | 12/01 15:44 | 12/02 5:06 | 12/02 23:17 | 12/03 3:56 | 12/03 4:55 | 12/4 2:01 | 12/4 5:45 | 12/4 6:03 | 12/4 6:07 | 12/4 10:58 | 12/4 16:09 | 12/4 16:12 | 12/4 16:47 | 12/5 1:17 | 12/5 16:16 | 12/6 7:41 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ramapo* | Millbury | 2.93 | | | | | | | | | | | | | | | | |
| Ramapo* | SandyPond | 3.09 | | | | | | | | | | | | | | | | |

*Phase angle regulator installed on Ramapo

**Table 23:** Detected Events Summary for Dec 1 to Dec 7, 2014 (nSigma=15)

| From | To | UCL | 12/01 1:02 | 12/01 5:54 | 12/01 10:28 | 12/01 10:30 | 12/01 11:09 | 12/01 11:12 | 12/01 11:33 | 12/01 11:47 | 12/01 15:44 | 12/03 1:22 | 12/03 3:56 | 12/03 10:41 | 12/03 15:43 | 12/03 17:08 | 12/04 8:29 | 12/04 10:58 | 12/04 11:03 | 12/04 13:40 | 12/04 15:05 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Raun | Sub 91 | 2.7 | | | | | | | | | | | | | | | | | | | |
| Goodings | Arcadian | 1.67 | | | | | | | | | | | | | | | | | | | |
| Goodings | Palisades | 2.2 | | | | | | | | | | | | | | | | | | | |
| Labadie | Hanna | 3.09 | | | | | | | | | | | | | | | | | | | |
| Labadie | Cumberland | 1.41 | | | | | | | | | | | | | | | | | | | |
| Jacks.Ferry | Cumberland | 3.02 | | | | | | | | | | | | | | | | | | | |
| CantonCtr. | Monroe | 2.58 | | | | | | | | | | | | | | | | | | | |
| Alburtis | CantonCtr. | 3.54 | | | | | | | | | | | | | | | | | | | |
| Alburtis | Jacks.Ferry | 4.91 | | | | | | | | | | | | | | | | | | | |
| Alburtis | Ramapo | 1.96 | | | | | | | | | | | | | | | | | | | |
| Niagara | Monroe | 4.8 | | | | | | | | | | | | | | | | | | | |
| Niagara | Ramapo | 3.61 | | | | | | | | | | | | | | | | | | | |
| Raun | Ramapo | 9.56 | | | | | | | | | | | | | | | | | | | |
| Arcadian | Ramapo | 8.21 | | | | | | | | | | | | | | | | | | | |
| Goodings | Monroe | 4.28 | | | | | | | | | | | | | | | | | | | |
| Goodings | Hanna | 2.64 | | | | | | | | | | | | | | | | | | | |
| Hanna | Monroe | 3.39 | | | | | | | | | | | | | | | | | | | |
| Hanna | CantonCtr. | 3.5 | | | | | | | | | | | | | | | | | | | |
| Palisades | Monroe | 2.38 | | | | | | | | | | | | | | | | | | | |
| Raun | Millbury | 10.42 | | | | | | | | | | | | | | | | | | | |
| Arcadian | Millbury | 9.19 | | | | | | | | | | | | | | | | | | | |
| SandyPond | Orrington | 3.25 | | | | | | | | | | | | | | | | | | | |

**Table 24:** Detected Events Summary for Dec 1 to Dec 7, 2014 (nSigma=15) (cont'd)

| From | To | UCL | 12/04 15:56 | 12/04 17:03 | 12/04 22:26 | 12/04 22:49 | 12/05 1:13 | 12/05 2:15 | 12/05 4:04 | 12/05 4:59 | 12/05 6:57 | 12/05 6:58 | 12/05 13:22 | 12/05 18:08 | 12/06 0:09 | 12/05 1:52 -12/6 3:02 | 12/06 6:55 | 12/06 7:37 | 12/07 15:26 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Raun | Sub 91 | 2.7 | | | | | | | | | | | | | | | | | |
| Goodings | Arcadian | 1.67 | | | | | | | | | | | | | | | | | |
| Goodings | Palisades | 2.2 | | | | | | | | | | | | | | | | | |
| Labadie | Hanna | 3.09 | | | | | | | | | | | | | | | | | |
| Labadie | Cumberland | 1.41 | | | | | | | | | | | | | | | | | |
| Jacks.Ferry | Cumberland | 3.02 | | | | | | | | | | | | | | | | | |
| CantonCtr. | Monroe | 2.58 | | | | | | | | | | | | | | | | | |
| Alburtis | CantonCtr. | 3.54 | | | | | | | | | | | | | | | | | |
| Alburtis | Jacks.Ferry | 4.91 | | | | | | | | | | | | | | | | | |
| Alburtis | Ramapo | 1.96 | | | | | | | | | | | | | | | | | |
| Niagara | Monroe | 4.8 | | | | | | | | | | | | | | | | | |
| Niagara | Ramapo | 3.61 | | | | | | | | | | | | | | | | | |
| Raun | Ramapo | 9.56 | | | | | | | | | | | | | | | | | |
| Arcadian | Ramapo | 8.21 | | | | | | | | | | | | | | | | | |
| Goodings | Monroe | 4.28 | | | | | | | | | | | | | | | | | |
| Goodings | Hanna | 2.64 | | | | | | | | | | | | | | | | | |
| Hanna | Monroe | 3.39 | | | | | | | | | | | | | | | | | |
| Hanna | CantonCtr. | 3.5 | | | | | | | | | | | | | | | | | |
| Palisades | Monroe | 2.38 | | | | | | | | | | | | | | | | | |
| Raun | Millbury | 10.42 | | | | | | | | | | | | | | | | | |
| Arcadian | Millbury | 9.19 | | | | | | | | | | | | | | | | | |
| SandyPond | Orrington | 3.25 | | | | | | | | | | | | | | | | | |

Figure 38 below shows the geographic map for 12/03 1:22 Callaway 1 trip with 1287 MW loss located in MISO area. There are 7 angle pairs that detected this event with $nSigma = 20$. Three angle pairs are local angle pairs and four wide area angle pairs. It is observed that the angle pairs located close to the event location can detected events. The angle pairs that are far away from the event location can't detect the event. The bus voltage with highest change are indication with red star in the map. Figure 39 shows the voltage change for all buses during the event. Two buses, Lehigh and Joppa, have the highest voltage change. The weak buses with highest change during the event are close to the event location.

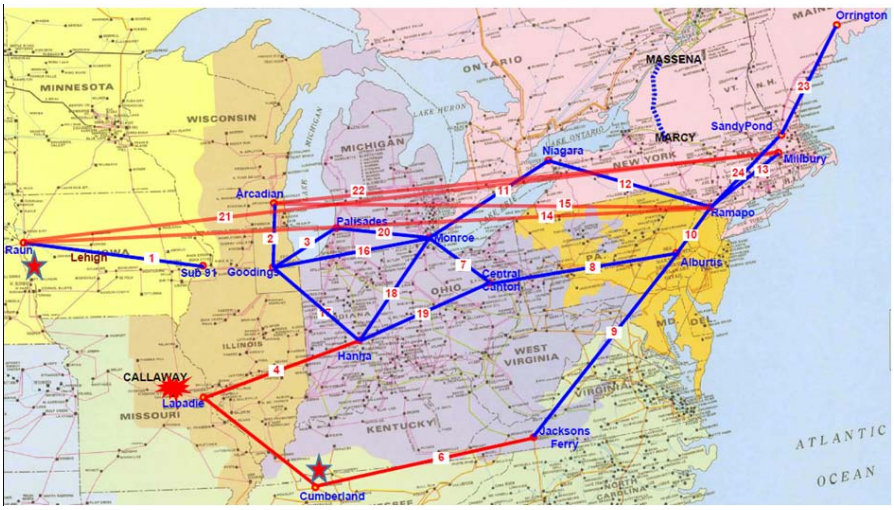



**Figure 38:** Geographic Map for 12/03 1:22 Event: 7 Angle Pairs Detected Event

Figure 40 shows the geographic map for 12/04 10:58 Massena-Marcy 765kV trip located in NYISO area. There are 16 angle pairs detected this event with $nSigma = 20$. The angle pairs located close to the event location can detect events. The angle pairs that are far away from the event location can't detect the event. The bus voltage with highest change are indication with red star in the map. Figure 41 shows the voltage change for all buses during the event. Three buses, Alburtis, Niagara and Orrington, have the highest voltage change. The weak buses with highest change during the event are close to the event location.

Figure 42 shows the geographic map for 12/04 15:05 LG2C generation trip with 1019 MW loss and two 735 kV Lines trip located in Hydro Quebec area. There is no angle pair detected for this event with $nSigma = 20$. Only one angle pair, Sandy Pond-Orrington, can detect this event with $nSigma = 15$. This angle pair is located close to the event location. The bus voltage with highest change is indication with red star in the map. Figure 43 shows the voltage change for all buses during the event. Only one buses, Orrington, has the highest voltage

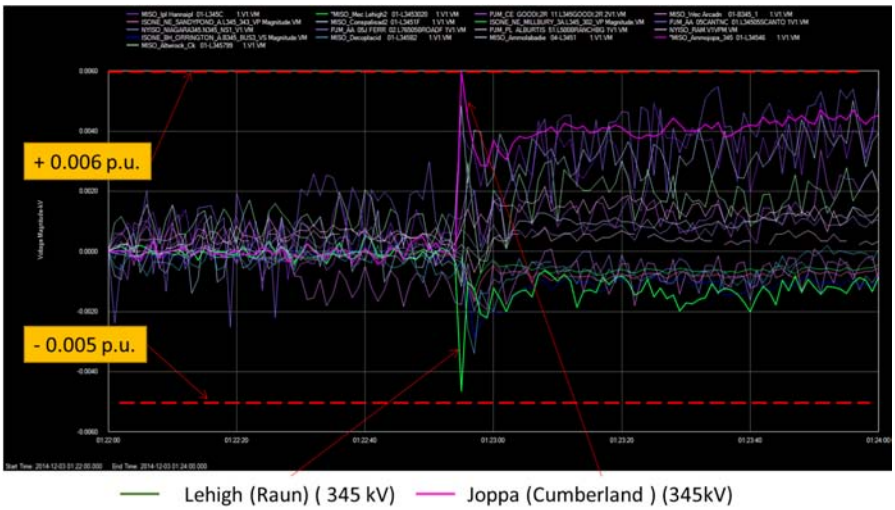



**Figure 39:** Change in Bus Voltage p.u for 12/03 1:22 Event

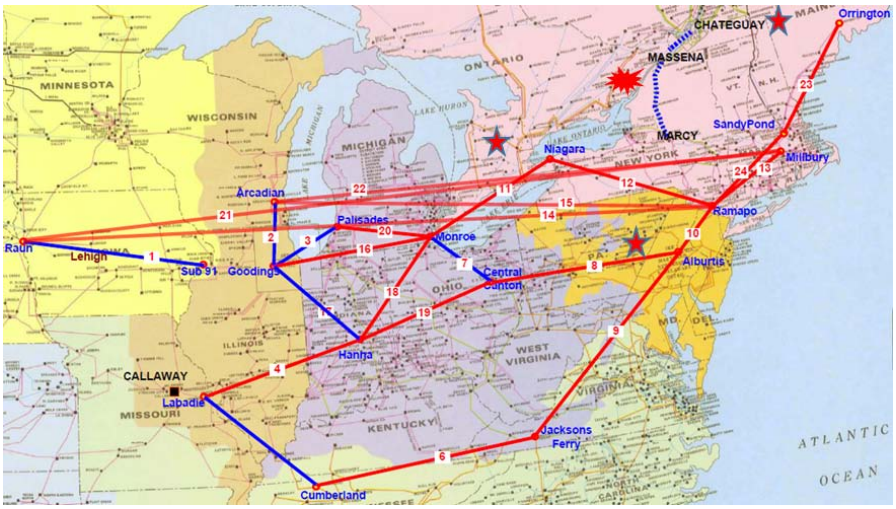



**Figure 40:** Geographic Map for 12/04/2014 10:58: 16 Angle Pairs Detected Event

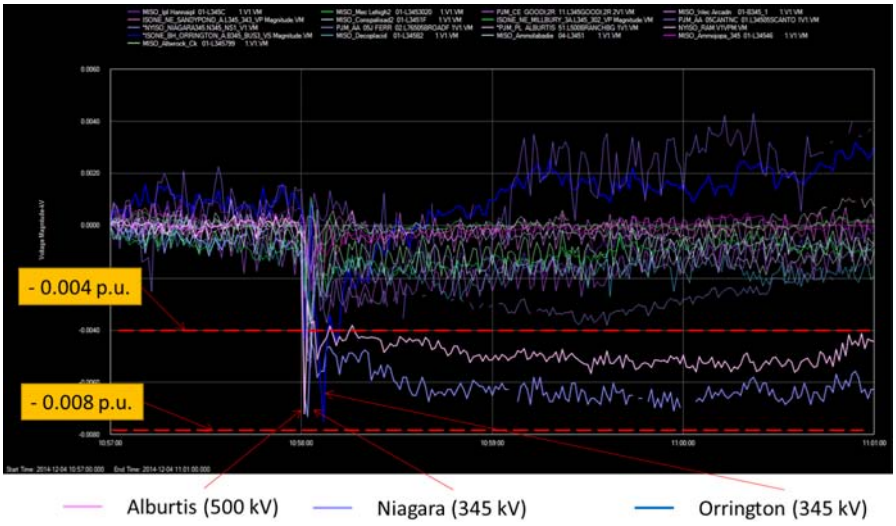



**Figure 41:** Change in Bus Voltage p.u for 12/04/2014 10:58 Event

change. This weak bus with highest change during the event is close to the event location.

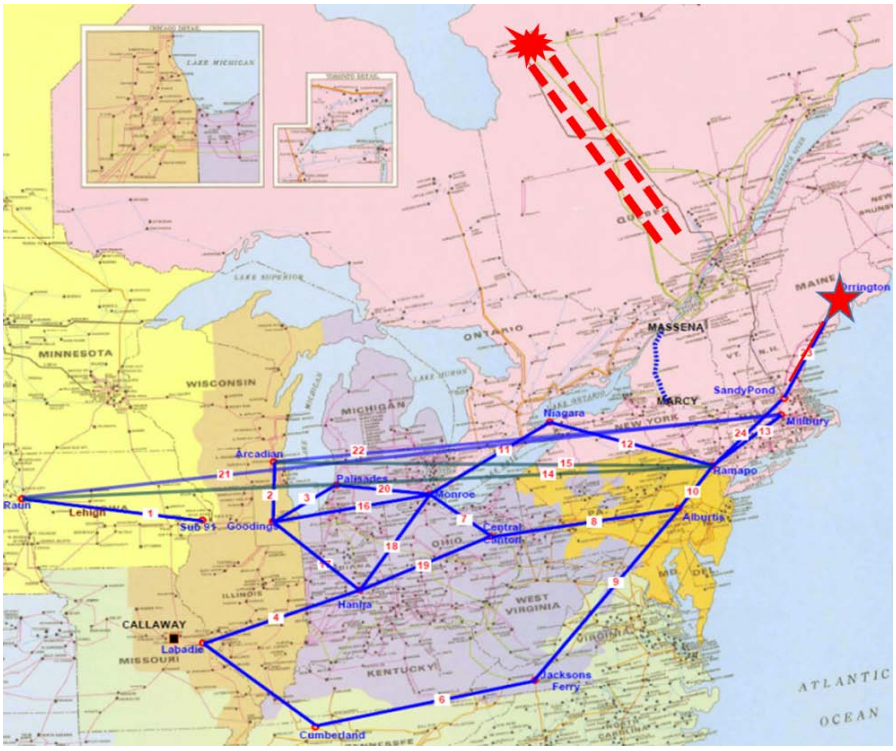



**Figure 42:** Geographic Map for 12/04 15:05: 1 Angle Pair Detected Event

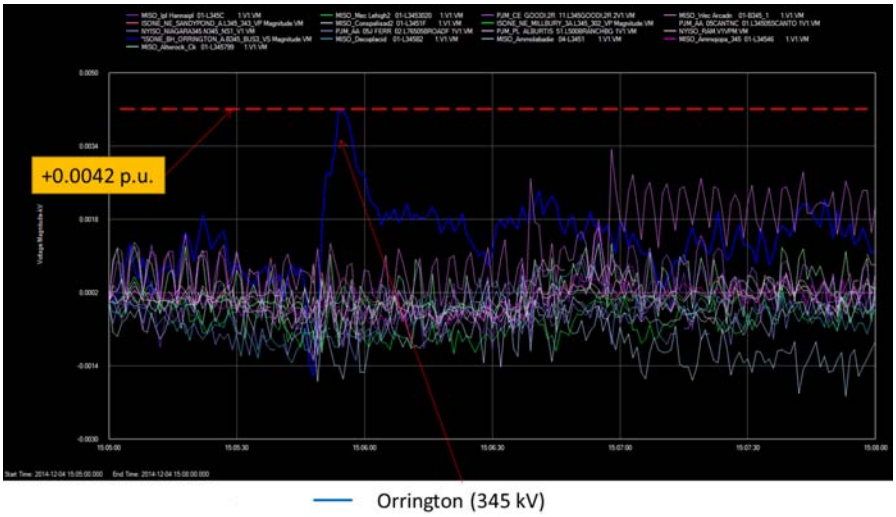



**Figure 43:** Change in Bus Voltage p.u for 12/04 15:05 Event

Angle pair difference behavior during system stress period is studied. Figure 44 is an example for angle pair difference trend for angle pair Alburtis-Ramapo from December 1-December 7 2014. The reference is established based on 2-month 2014 fall data. The blue dot in the figure is the hourly mean value calculated based on 2-month fall data. The blue vertical lines with high/low bars gives the 99.9% prediction hourly interval established based on fall data. The red line is the actual angle pair difference trend for angle pair Alburtis-Ramapo from December 1-December 7 2014. Angle pair Alburtis-Ramapo started increasing around 7:00 AM on 12/03/2014 and it exceeded the prediction interval around 10:00 AM during the 12/04/2014 10:58 event located NYISO area and stayed high.

Figure 45 is another example for angle pair difference trend for angle pair Ramapo-Millbury from December 1-December 7 2014. The angle pair showed stress around 10:00 AM on 12/04/2014 during the 12/04/2014 10:58 event located NYISO area and stayed high. It exceeded the prediction interval around 18:00 on 12/04/2014 after event 12/04 15:05 located in Hydro Quebec.

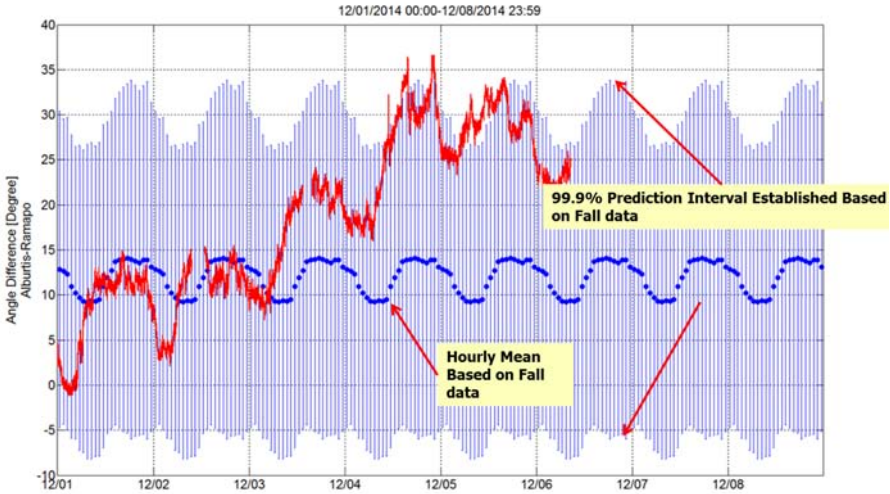



**Figure 44:** Alburtis-Ramapo Compared with Established Reference for Dec 1 to Dec 7, 2014

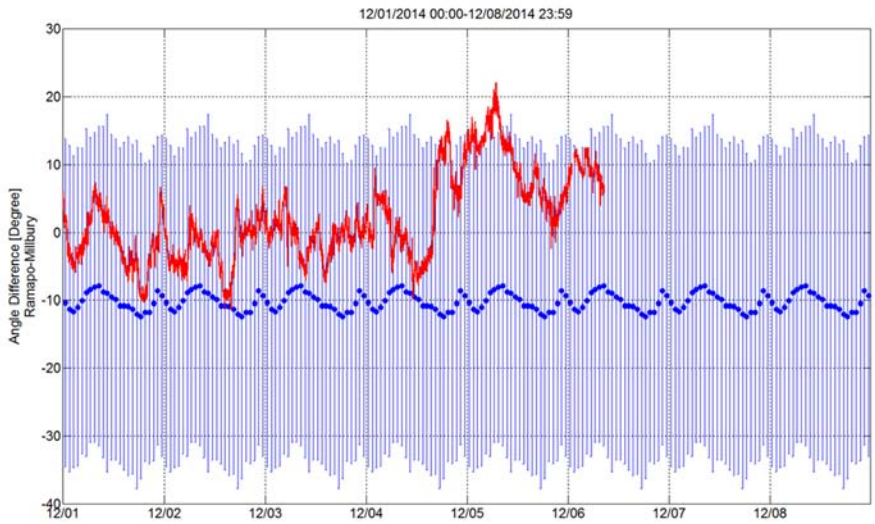
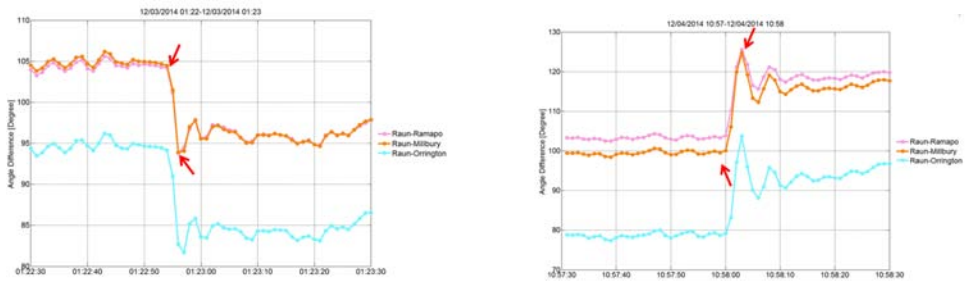



**Figure 45:** Ramapo-Millbury Compared with Established Reference for Dec 1 to Dec 7, 2014

Appendix 8.10 provides all the angle pairs difference trend for December 1-7 2014 compared with the reference range. It can be observed the angle pair difference is good metrics to measure system stress. Stress levels are correlated with angle differences. When system is in stress, angle pair difference will increase.

A comparison between two events for selected wide area angle pairs difference change is provided in Table 25 and Figure 46. For the selected wide area angle pair




**(a)** 12/03 1:22 Event **(b)** 12/04 10:58 Event

**Figure 46:** Selected Wide Area Angle Pairs Difference Change Comparison

difference change before and after event, for example Raun-Ramapo, angle changed -11° for 12/03 1:22 event. Angle changed 22° for 12/04 10:58 event. The sign of the angle change is related to the direction of the power flow. 12/03 1:22 MISO Callaway 1 trip tvent caused negative change, 12/04 10:58 NYISO Massena-Marcy 765kV trip caused positive change. It indicates there is less power transferred from west to east for 12/03 1:22 event located at MISO area and more power transferred from west to east for 12/04 10:58 event located at NYISO area. The magnitude of angle change between before and after event reflects the effect of the event. It is obvious the NYISO event has more effect on the wide area system.

**Table 25:** Selected Wide Area Angle Pairs Difference Change Comparison

| Before and After Change | | |
|---|---|---|
| | 12/03 1:22 Event | 12/04 10:58 Event |
| MW Loss [MW] | 1287 | NA |
| Raun-Ramapo[°] | -11 | 22 |
| Raun-Millbury[°] | -10 | 25 |
| Raun-Orrington[°] | -12 | 25 |
| Oscillations | | |
| Frequency[Hz] | 0.2 | 0.2 |
| Damping | 30% | 30% |
| Amplitude[°] | 11 | 22 |

## 6.3 Conclusions and Observations

This section presents the statistical study focusing on the data during Dec 1-Dec 7 2014. Data availability and quality are checked. Event detection in this period are performed. The detection method of using one-minute angle difference change range is described. Three NERC events and small local events are detected. Angle pairs close to the event location can detect the event. Angle pairs that are far away from the event location cant detect the event. It is also observed that stress levels are correlated with angle differences and voltages-during events, bus with highest

voltage change is weakest bus and often closest to event.

# 7 SUMMARY OF KEY CONCLUSIONS, FINDINGS AND NEXT STEP

- Data quality is big issue-extensive data checking and filtering is time consuming.
- Phasor data can be used effectively for baselining performance - ranges and operating thresholds.
- Fall and Winter PMU data has been used to establish high/low range for different angle pairs. The ranges can be used to alert operators if system is subjected to abnormal loading situation.
- High and low limits identified for winter period may not be suitable to identify abnormal system condition for fall period and the reverse is also true. Baselining analysis performed during a particular period to identify normal system conditions is dependent on prevalent system topology during the period and seasonal loading conditions. Baselining analysis is suggested to conducted for 12-18 months of data.
- Overall the angle pairs have higher correlation with each other during winter than in fall. This observation can be attributed to higher system stress during winter.
- Correlation analysis of angle pairs with power flow on paths shows a strong correlation. Angle pair monitoring will enable the operators to assess system stress as a backup alternative to monitoring power flow from PMU data.
- Raun-Ramapo (Wide-area) has 0.2 Hz oscillatory mode and Niagara-Ramapo (Local-area) has 0.39 Hz and 0.41 Hz oscillatory modes. Detection of frequency modes higher than 0.5 Hz which may be possibly present in the data would require higher sampling data rate for analysis.
- Statistical study was performed on LMP data of four ISOs for both individual node and pairs.
- The correlation between the angle pair differences and the Locational Marginal Price (LMP) differences has been analyzed. Overall data shows no strong correlation between LMP and angle difference. More high LMP price spikes is observed when angle is high, which may indicate that system is in stress.
- Statistical control chart is used for one-minute angle difference change range to detect events. Three major events and some local events are detected.

- Angle pairs close to the event location can detect the event. Angle pairs that are far away from the event location can not detect the event.
- Stress levels are correlated with angle differences and voltages during events, bus with highest voltage change is weakest bus and often closest to event.

The control chart analysis technique successfully detected three events within a one week period in December 2014. This statistical control level technique needs to be tested over a longer period for selection of an appropriate statistical control level. In addition, the present analysis has used only angle pairs for detection of event analysis. It is recommended that additional indicators such as voltage magnitude, power flows, oscillations and sensitivities be used to screen events. Since an event can impact these other quantities, it is recommended that the impact of events be examined on these additional metrics to fully understand the events.

In general, a significant event may either be preceded by a violation or may be followed by continued violations. When an event occurs and results in range violation, it should be corrected promptly by an operator action. Lack of operator action to correct such violations in past has resulted in event escalation resulting in blackouts. Analysis of pre or post cursors such as threshold violations, trends and rate of change can be important performance indicators in avoiding such escalations.

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[3] PJM. Data Miner for Locational Marginal Pricing. https://dataminer.pjm.com/dataminerui/pages/public/lmp.jsf/. [Online; accessed 05/22/2015].

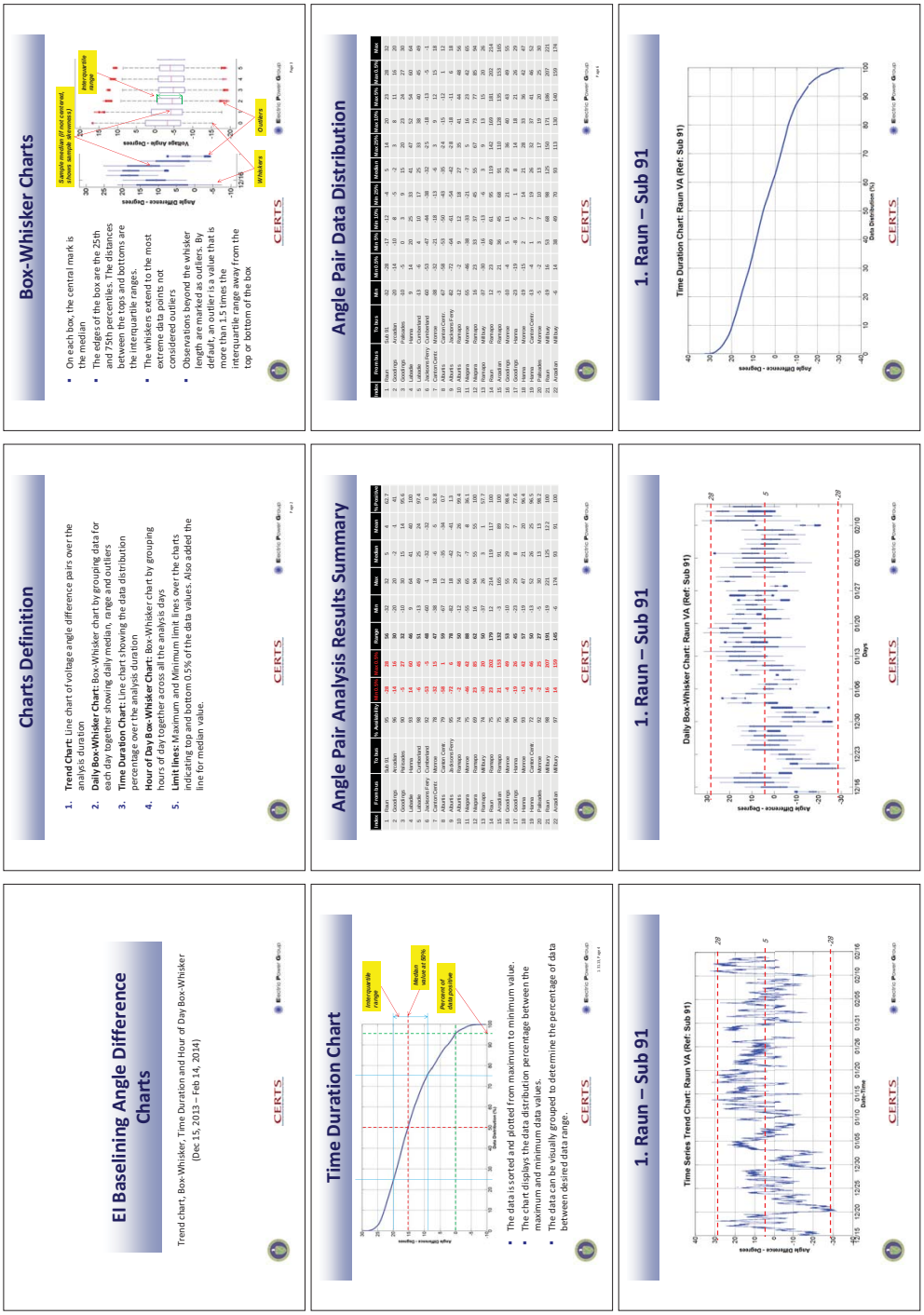
[4] PJM. Hourly Real-Time and Day-Ahead LMP. http://www.pjm.com/markets-and-operations/energy/real-time/monthlylmp.aspx/. [Online; accessed 05/22/2015].

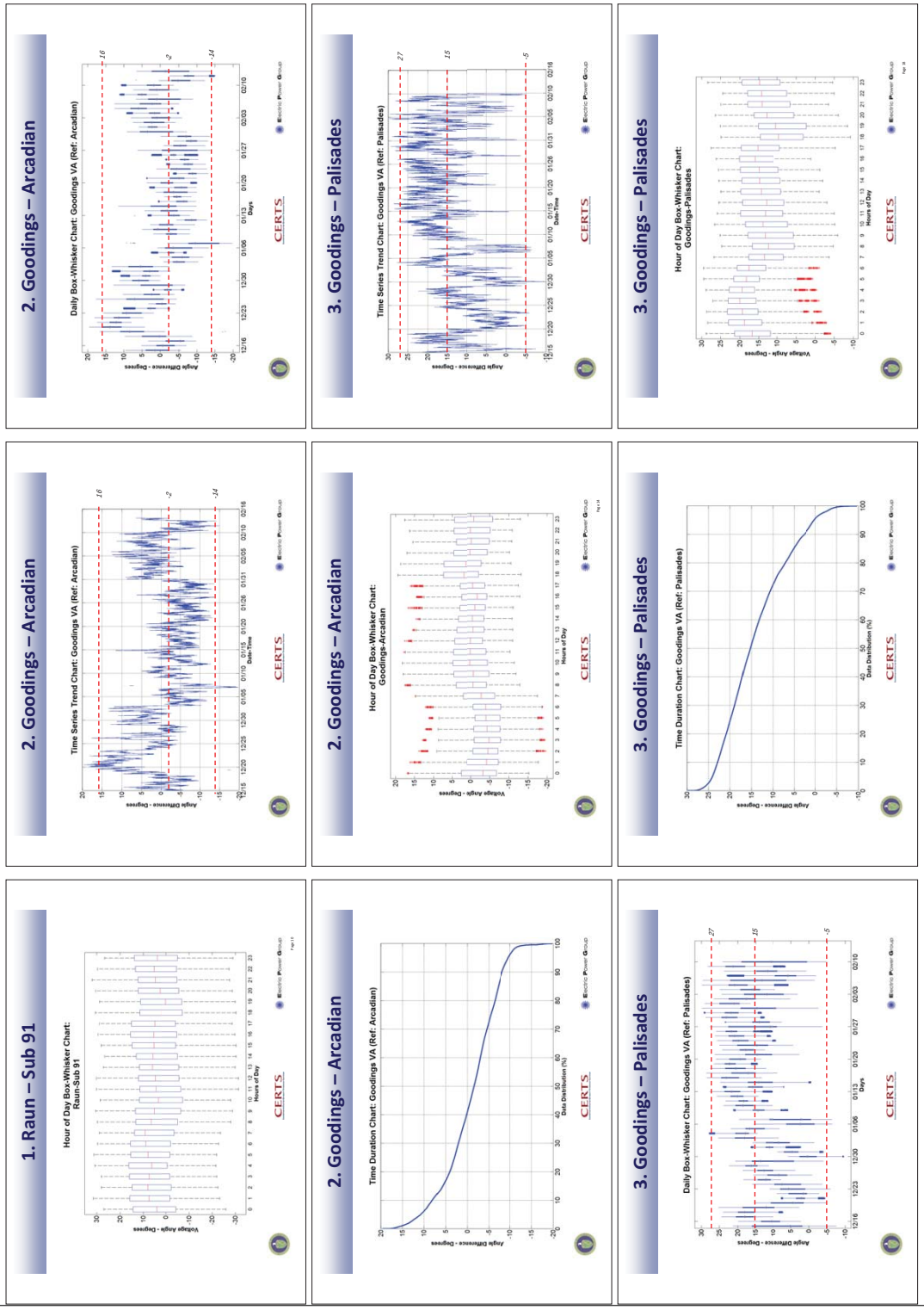
[5] Wiki. Control chart. http://en.wikipedia.org/wiki/Control_chart/. [Online; accessed 06/3/2015].

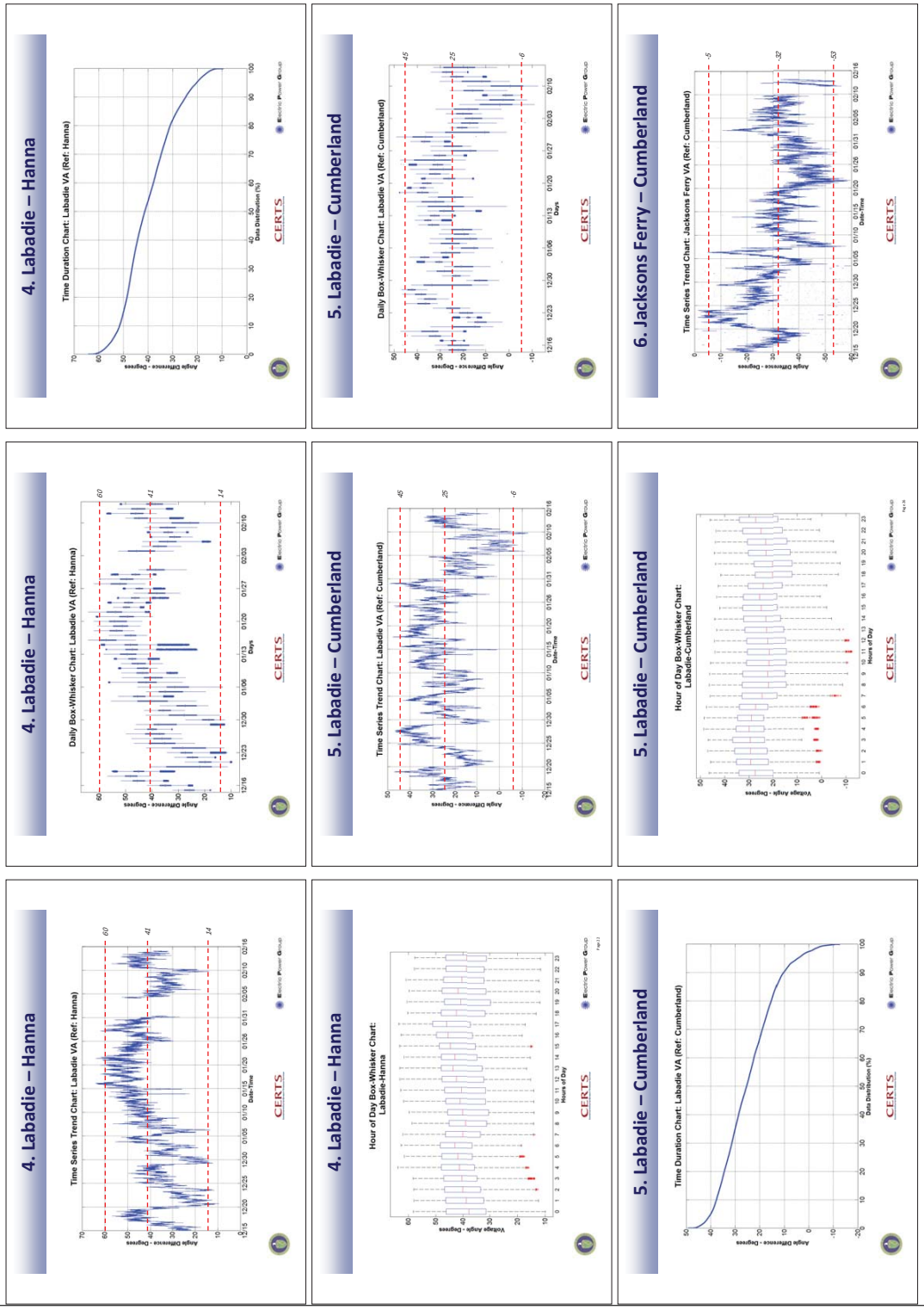
[6] Song Xue and Bharat Bhargava. Eastern interconnection baselining study 2013 report. Technical report, EPG, August 6, 2014.

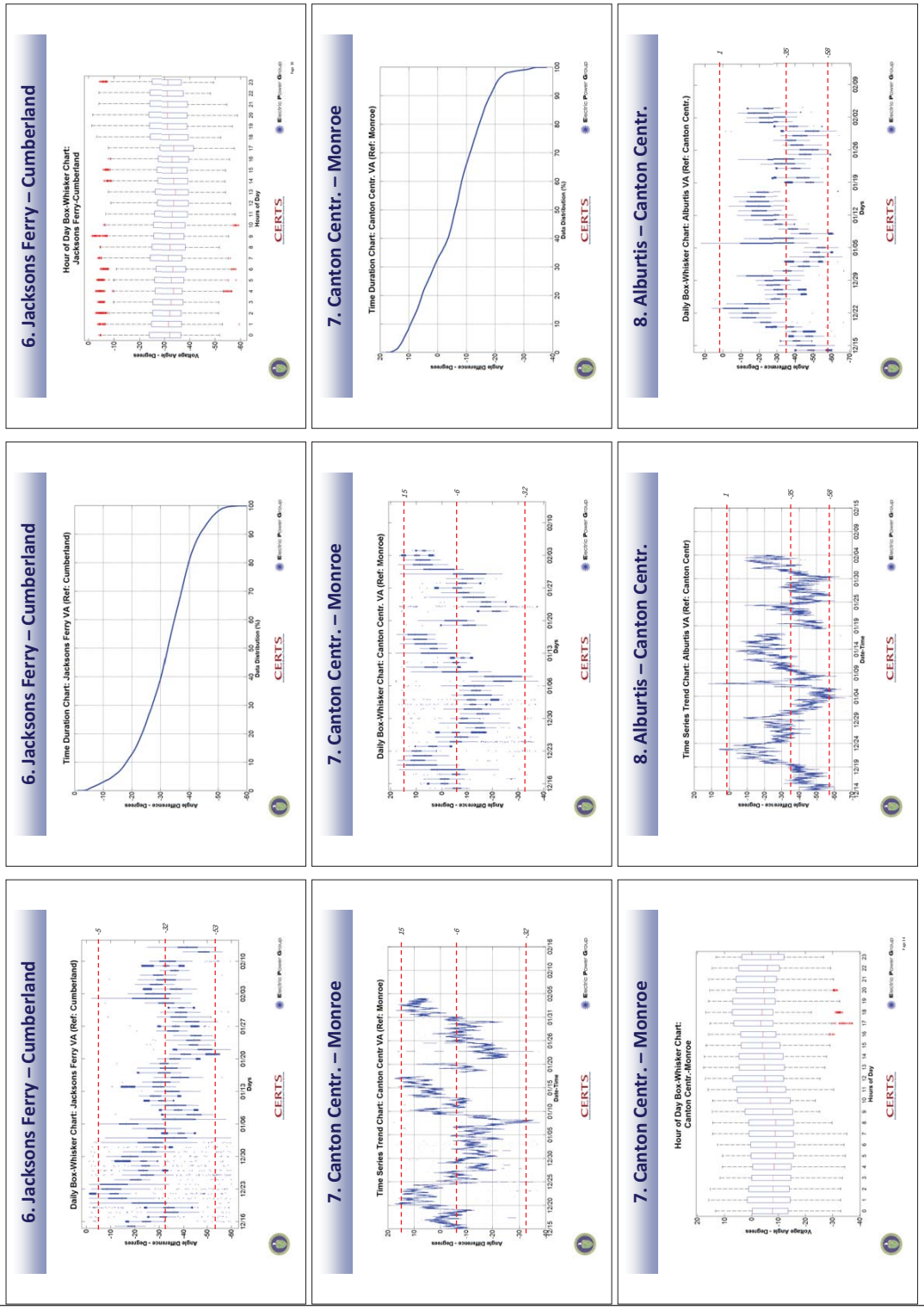
# 8 APPENDIX

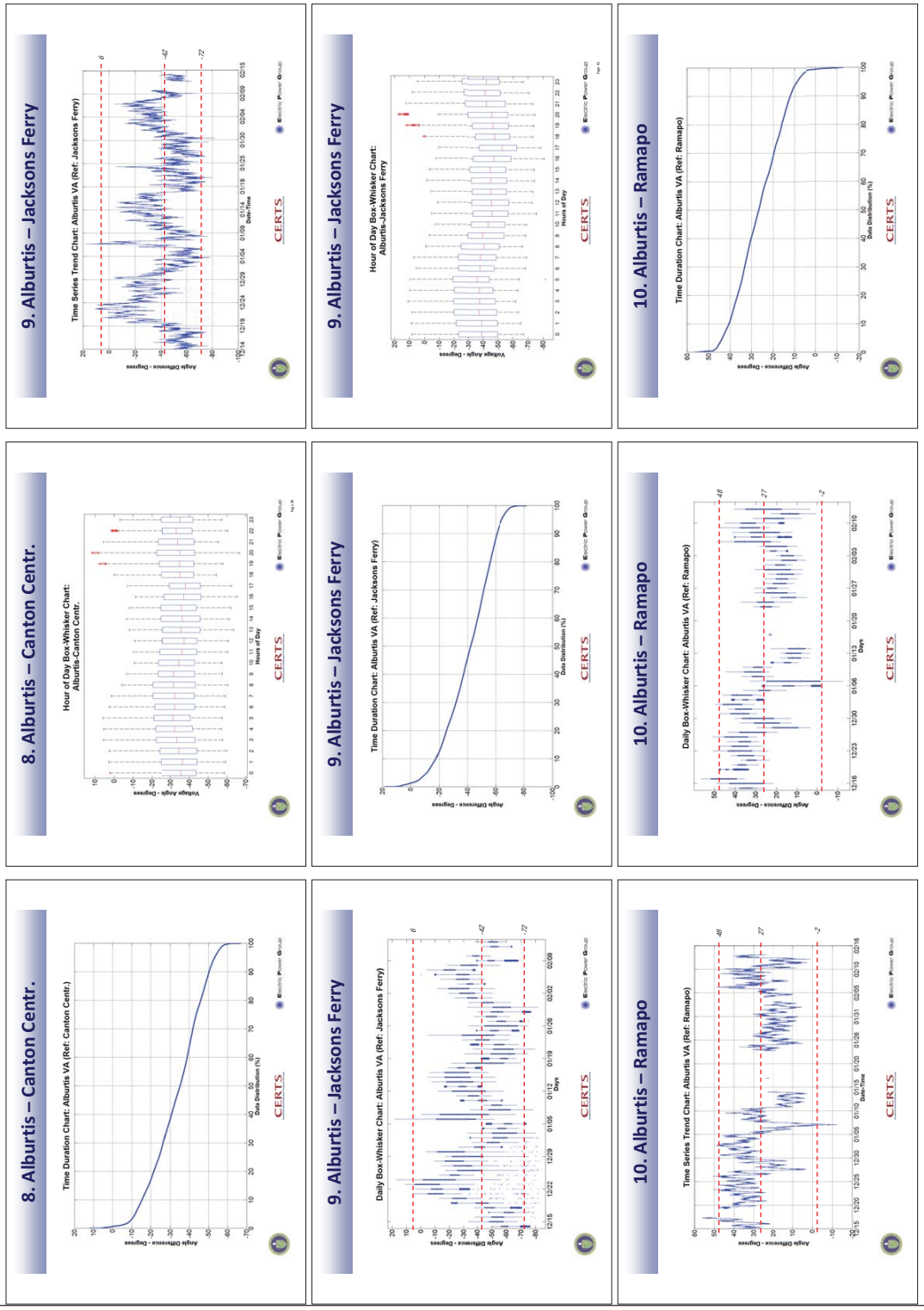
## 8.1 EI Baselining Angle Difference Charts for 2014 Winter PMU Data

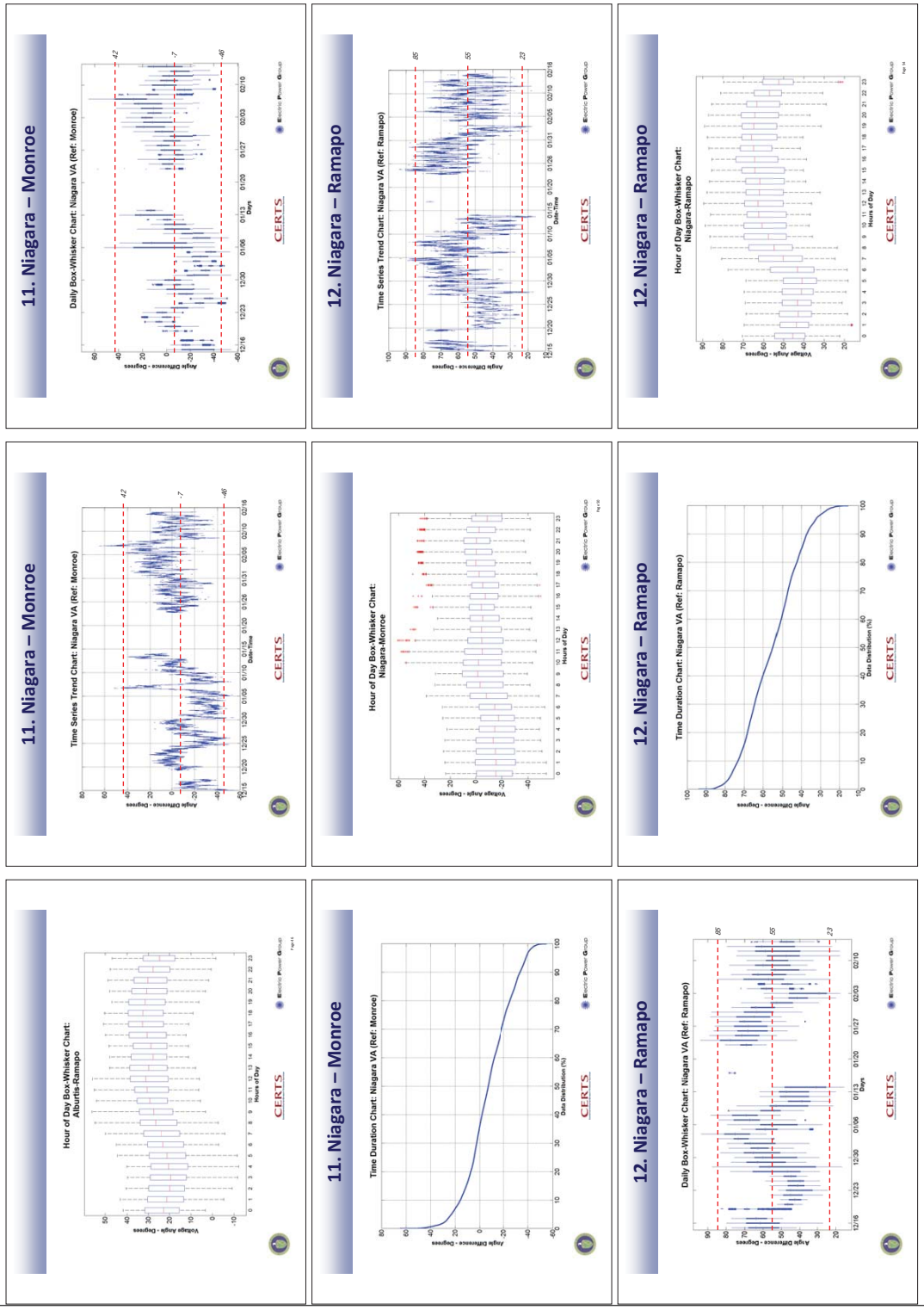


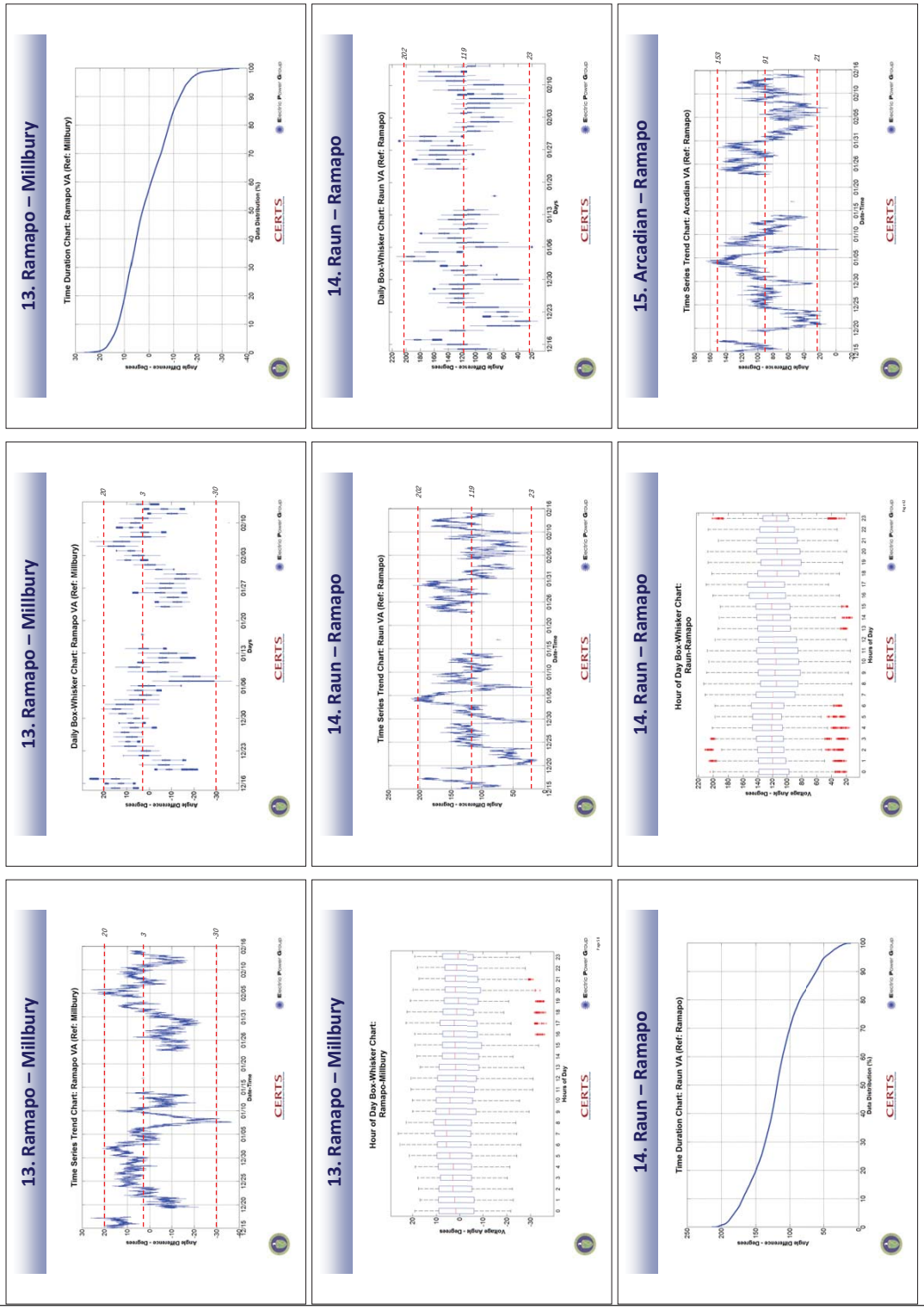

1. Raun – Sub 91
Hour of Day Box-Whisker Chart: Raun-Sub 91
Voltage Angle - Degrees
Hours of Day
CERTS
2. Goodings – Arcadian
Daily Box-Whisker Chart: Goodings VA (Ref: Arcadian)
Angle Difference - Degrees
Days
16
-2
-14
CERTS
3. Goodings – Palisades
Hour of Day Box-Whisker Chart: Goodings-Palisades
Voltage Angle - Degrees
Hours of Day
CERTS
2. Goodings – Arcadian
Time Series Trend Chart: Goodings VA (Ref: Arcadian)
Angle Difference - Degrees
Date-Time
16
-2
-14
CERTS
2. Goodings – Arcadian
Hour of Day Box-Whisker Chart: Goodings-Arcadian
Voltage Angle - Degrees
Hours of Day
CERTS
3. Goodings – Palisades
Time Duration Chart: Goodings VA (Ref: Palisades)
Angle Difference - Degrees
Data Distribution (%)
CERTS
2. Goodings – Arcadian
Time Duration Chart: Goodings VA (Ref: Arcadian)
Angle Difference - Degrees
Data Distribution (%)
CERTS
3. Goodings – Palisades
Daily Box-Whisker Chart: Goodings VA (Ref: Palisades)
Angle Difference - Degrees
Days
27
-15
-5
CERTS
3. Goodings – Palisades
Time Series Trend Chart: Goodings VA (Ref: Palisades)
Angle Difference - Degrees
Date-Time
27
-15
-5
CERTS

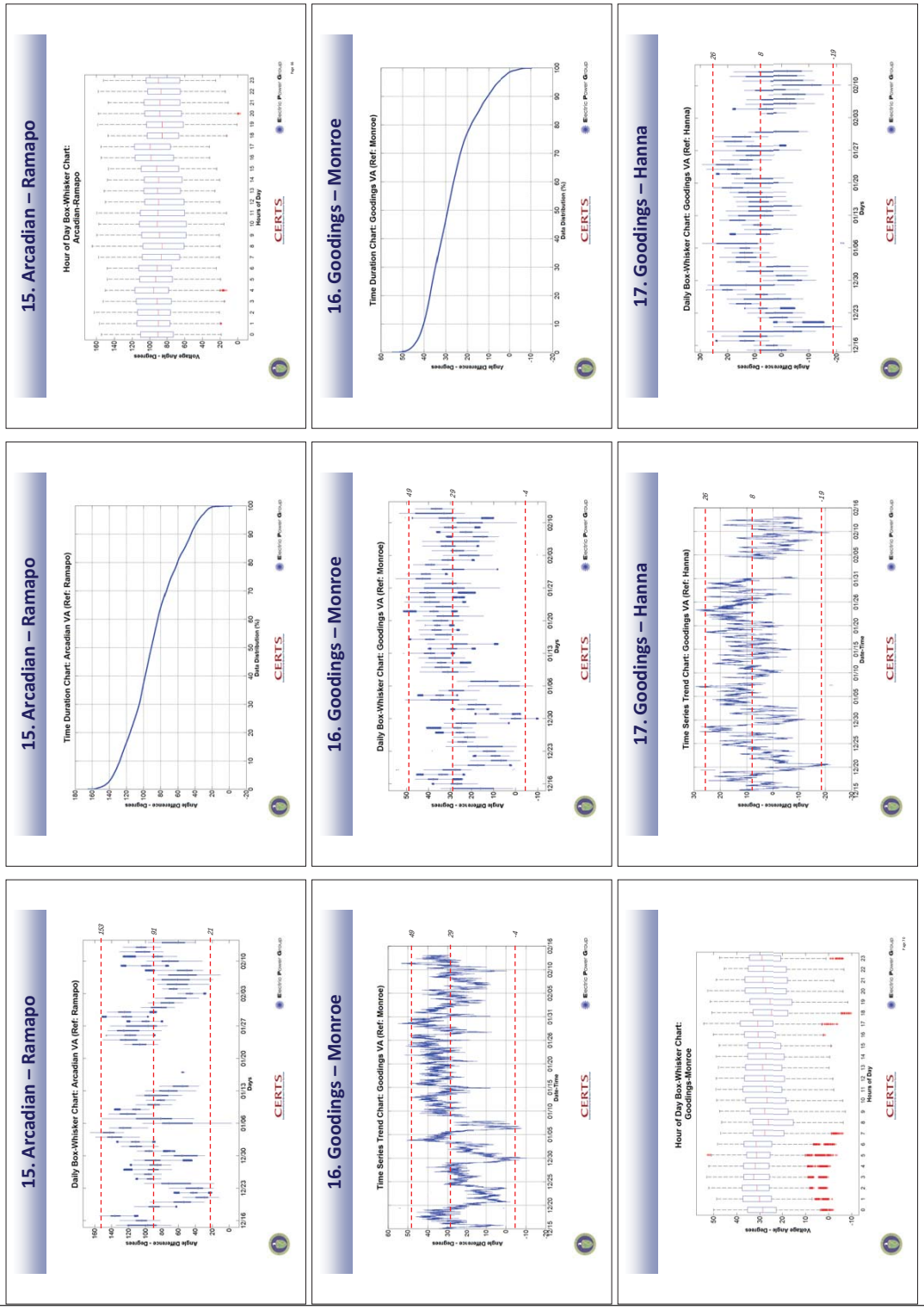

4. Labadie – Hanna
Time Duration Chart: Labadie VA (Ref: Hanna)
Angle Difference - Degrees
Data Distribution (%)
CERTS
4. Labadie – Hanna
Daily Box-Whisker Chart: Labadie VA (Ref: Hanna)
Angle Difference - Degrees
Days
CERTS
4. Labadie – Hanna
Time Series Trend Chart: Labadie VA (Ref: Hanna)
Angle Difference - Degrees
Date-Time
CERTS
5. Labadie – Cumberland
Daily Box-Whisker Chart: Labadie VA (Ref: Cumberland)
Angle Difference - Degrees
Days
CERTS
5. Labadie – Cumberland
Time Series Trend Chart: Labadie VA (Ref: Cumberland)
Angle Difference - Degrees
Date-Time
CERTS
6. Jacksons Ferry – Cumberland
Time Series Trend Chart: Jacksons Ferry VA (Ref: Cumberland)
Angle Difference - Degrees
Date-Time
CERTS
4. Labadie – Hanna
Hour of Day Box-Whisker Chart:
Labadie-Hanna
Voltage Angle - Degrees
Hours of Day
CERTS
5. Labadie – Cumberland
Hour of Day Box-Whisker Chart:
Labadie-Cumberland
Voltage Angle - Degrees
Hours of Day
CERTS
5. Labadie – Cumberland
Time Duration Chart: Labadie VA (Ref: Cumberland)
Angle Difference - Degrees
Data Distribution (%)
CERTS

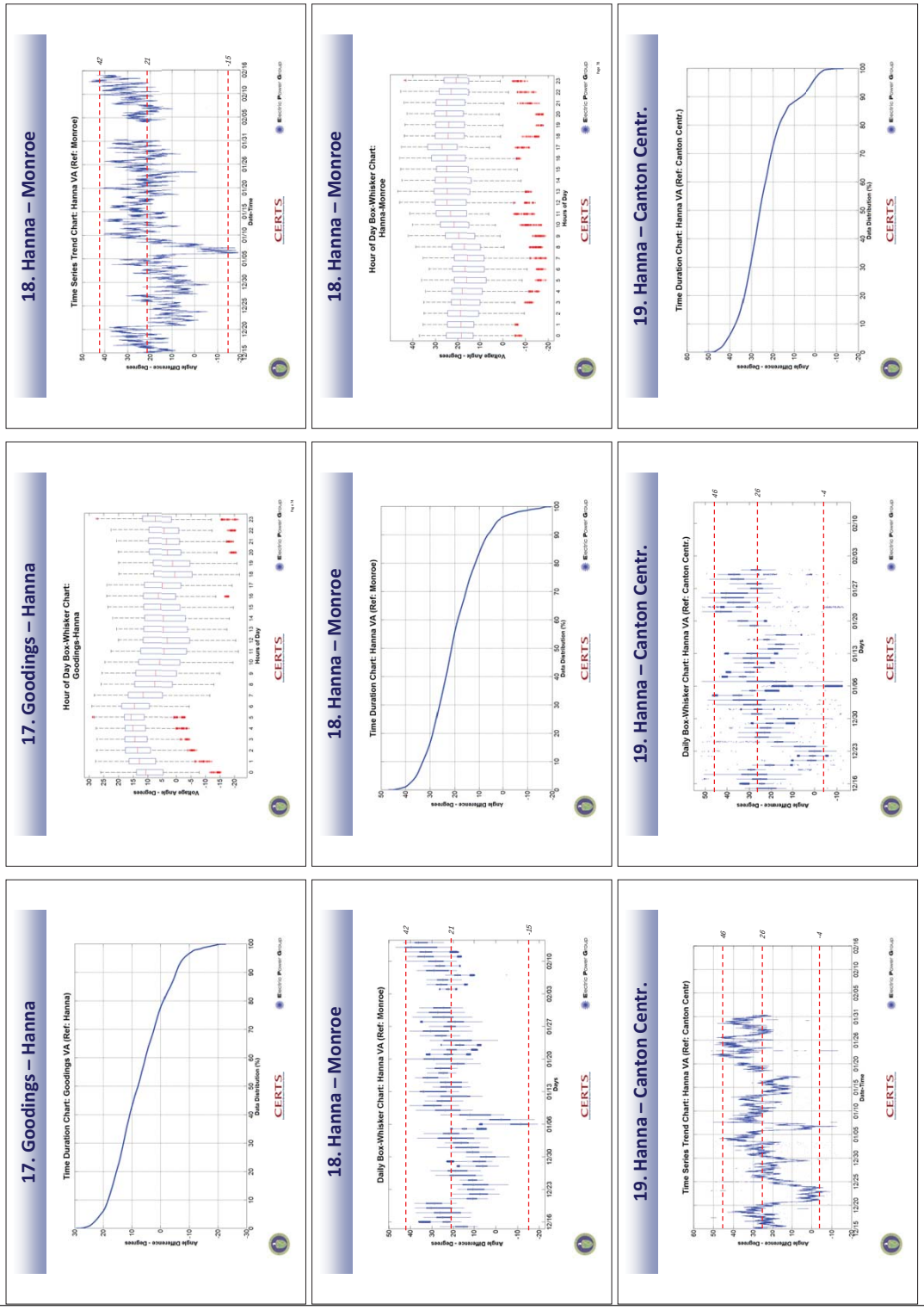

6. Jacksons Ferry – Cumberland
Hour of Day Box-Whisker Chart: Jacksons Ferry-Cumberland
Voltage Angle - Degrees
Hours of Day
CERTS
6. Jacksons Ferry – Cumberland
Time Duration Chart: Jacksons Ferry VA (Ref: Cumberland)
Angle Difference - Degrees
Data Duration (%)
CERTS
6. Jacksons Ferry – Cumberland
Daily Box-Whisker Chart: Jacksons Ferry VA (Ref: Cumberland)
Angle Difference - Degrees
Days
CERTS
7. Canton Centr. – Monroe
Time Duration Chart: Canton Centr. VA (Ref: Monroe)
Angle Difference - Degrees
Data Duration (%)
CERTS
7. Canton Centr. – Monroe
Daily Box-Whisker Chart: Canton Centr. VA (Ref: Monroe)
Angle Difference - Degrees
Days
CERTS
7. Canton Centr. – Monroe
Time Series Trend Chart: Canton Centr VA (Ref: Monroe)
Angle Difference - Degrees
Date-Time
CERTS
8. Alburtis – Canton Centr.
Daily Box-Whisker Chart: Alburtis VA (Ref: Canton Centr.)
Angle Difference - Degrees
Days
CERTS
8. Alburtis – Canton Centr.
Time Series Trend Chart: Alburtis VA (Ref: Canton Centr)
Angle Difference - Degrees
Date-Time
CERTS
7. Canton Centr. – Monroe
Hour of Day Box-Whisker Chart: Canton Centr.-Monroe
Voltage Angle - Degrees
Hours of Day
CERTS

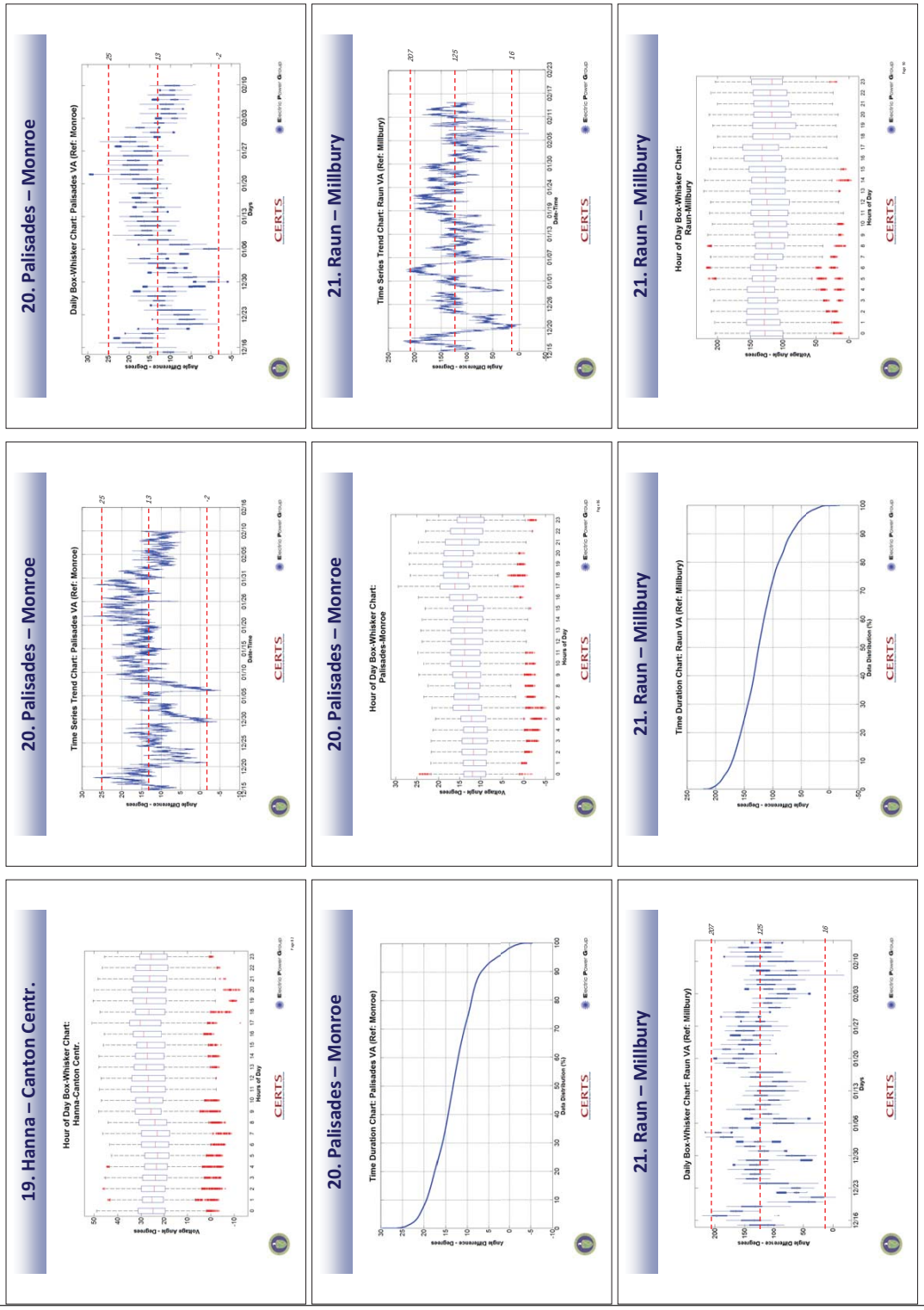

8. Alburtis – Canton Centr.
Time Duration Chart: Alburtis VA (Ref: Canton Centr.)
Angle Difference - Degrees
Data Distribution (%)
CERTS
8. Alburtis – Canton Centr.
Hour of Day Box-Whisker Chart: Alburtis-Canton Centr.
Voltage Angle - Degrees
Hours of Day
CERTS
9. Alburtis – Jacksons Ferry
Time Series Trend Chart: Alburtis VA (Ref: Jacksons Ferry)
Angle Difference - Degrees
Date-Time
6
-42
-72
CERTS
9. Alburtis – Jacksons Ferry
Time Duration Chart: Alburtis VA (Ref: Jacksons Ferry)
Angle Difference - Degrees
Data Distribution (%)
CERTS
9. Alburtis – Jacksons Ferry
Hour of Day Box-Whisker Chart: Alburtis-Jacksons Ferry
Voltage Angle - Degrees
Hours of Day
CERTS
9. Alburtis – Jacksons Ferry
Daily Box-Whisker Chart: Alburtis VA (Ref: Jacksons Ferry)
Angle Difference - Degrees
Days
6
-42
-72
CERTS
10. Alburtis – Ramapo
Time Series Trend Chart: Alburtis VA (Ref: Ramapo)
Angle Difference - Degrees
Date-Time
48
27
-2
CERTS
10. Alburtis – Ramapo
Time Duration Chart: Alburtis VA (Ref: Ramapo)
Angle Difference - Degrees
Data Distribution (%)
CERTS
10. Alburtis – Ramapo
Daily Box-Whisker Chart: Alburtis VA (Ref: Ramapo)
Angle Difference - Degrees
Days
48
27
-2
CERTS

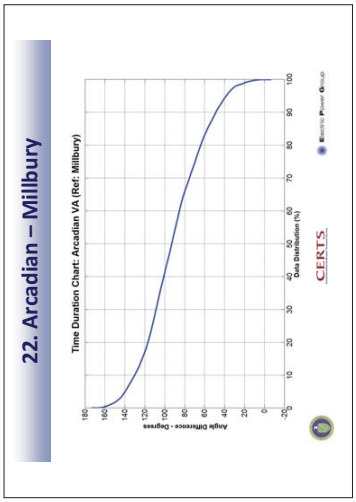

11. Niagara – Monroe
Daily Box-Whisker Chart: Niagara VA (Ref: Monroe)
Angle Difference - Degrees
Days
CERTS
11. Niagara – Monroe
Time Series Trend Chart: Niagara VA (Ref: Monroe)
Angle Difference - Degrees
Date-Time
CERTS
Hour of Day Box-Whisker Chart: Alburtis-Ramapo
Voltage Angle - Degrees
Hours of Day
CERTS
11. Niagara – Monroe
Hour of Day Box-Whisker Chart: Niagara-Monroe
Voltage Angle - Degrees
Hours of Day
CERTS
11. Niagara – Monroe
Time Duration Chart: Niagara VA (Ref: Monroe)
Angle Difference - Degrees
Data Distribution (%)
CERTS
12. Niagara – Ramapo
Time Series Trend Chart: Niagara VA (Ref: Ramapo)
Angle Difference - Degrees
Date-Time
CERTS
12. Niagara – Ramapo
Hour of Day Box-Whisker Chart: Niagara-Ramapo
Voltage Angle - Degrees
Hours of Day
CERTS
12. Niagara – Ramapo
Time Duration Chart: Niagara VA (Ref: Ramapo)
Angle Difference - Degrees
Data Distribution (%)
CERTS
12. Niagara – Ramapo
Daily Box-Whisker Chart: Niagara VA (Ref: Ramapo)
Angle Difference - Degrees
Days
CERTS

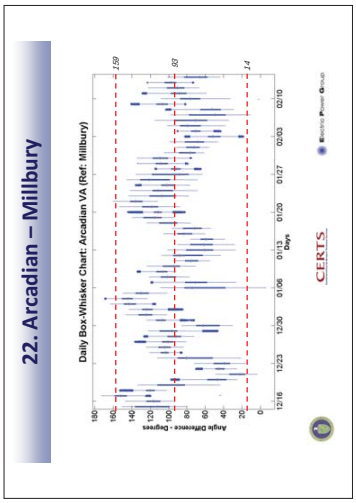

13. Ramapo – Millbury
Time Duration Chart: Ramapo VA (Ref: Millbury)
Angle Difference - Degrees
Data Distribution (%)
CERTS
13. Ramapo – Millbury
Daily Box-Whisker Chart: Ramapo VA (Ref: Millbury)
Angle Difference - Degrees
Days
20
3
-30
CERTS
13. Ramapo – Millbury
Time Series Trend Chart: Ramapo VA (Ref: Millbury)
Angle Difference - Degrees
Date-Time
20
3
-30
CERTS
14. Raun – Ramapo
Daily Box-Whisker Chart: Raun VA (Ref: Ramapo)
Angle Difference - Degrees
Days
202
119
23
CERTS
14. Raun – Ramapo
Time Series Trend Chart: Raun VA (Ref: Ramapo)
Angle Difference - Degrees
Date-Time
202
119
23
CERTS
14. Raun – Ramapo
Hour of Day Box-Whisker Chart:
Raun-Ramapo
Voltage Angle - Degrees
Hours of Day
CERTS
13. Ramapo – Millbury
Hour of Day Box-Whisker Chart:
Ramapo-Millbury
Voltage Angle - Degrees
Hours of Day
CERTS
14. Raun – Ramapo
Time Duration Chart: Raun VA (Ref: Ramapo)
Angle Difference - Degrees
Data Distribution (%)
CERTS
15. Arcadian – Ramapo
Time Series Trend Chart: Arcadian VA (Ref: Ramapo)
Angle Difference - Degrees
Date-Time
153
91
21
CERTS

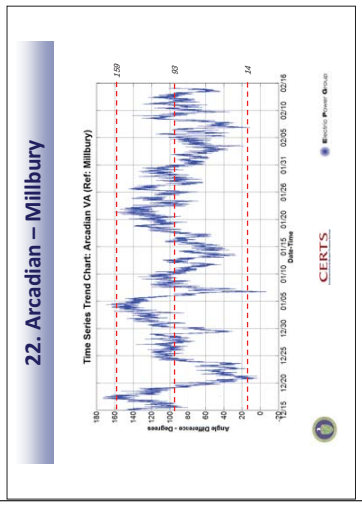

15. Arcadian – Ramapo
Hour of Day Box-Whisker Chart: Arcadian-Ramapo
Voltage Angle - Degrees
Hours of Day
CERTS
15. Arcadian – Ramapo
Time Duration Chart: Arcadian VA (Ref: Ramapo)
Angle Difference - Degrees
Data Duration (%)
CERTS
15. Arcadian – Ramapo
Daily Box-Whisker Chart: Arcadian VA (Ref: Ramapo)
153
101
21
Angle Difference - Degrees
Days
CERTS
16. Goodings – Monroe
Time Duration Chart: Goodings VA (Ref: Monroe)
Angle Difference - Degrees
Data Duration (%)
CERTS
16. Goodings – Monroe
Daily Box-Whisker Chart: Goodings VA (Ref: Monroe)
49
29
-4
Angle Difference - Degrees
Days
CERTS
16. Goodings – Monroe
Time Series Trend Chart: Goodings VA (Ref: Monroe)
49
29
-4
Angle Difference - Degrees
Date-Time
CERTS
17. Goodings – Hanna
Daily Box-Whisker Chart: Goodings VA (Ref: Hanna)
26
8
-19
Angle Difference - Degrees
Days
CERTS
17. Goodings – Hanna
Time Series Trend Chart: Goodings VA (Ref: Hanna)
26
8
-19
Angle Difference - Degrees
Date-Time
CERTS
Hour of Day Box-Whisker Chart: Goodings-Monroe
Voltage Angle - Degrees
Hours of Day
CERTS

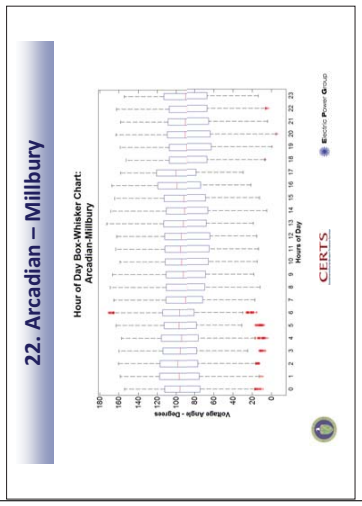

17. Goodings – Hanna
Time Duration Chart: Goodings VA (Ref: Hanna)
Angle Difference - Degrees
Data Distribution (%)
CERTS
17. Goodings – Hanna
Hour of Day Box-Whisker Chart: Goodings-Hanna
Voltage Angle - Degrees
Hours of Day
CERTS
18. Hanna – Monroe
Time Series Trend Chart: Hanna VA (Ref: Monroe)
Angle Difference - Degrees
Date-Time
42
21
-15
CERTS
18. Hanna – Monroe
Daily Box-Whisker Chart: Hanna VA (Ref: Monroe)
Angle Difference - Degrees
Days
42
21
-15
CERTS
18. Hanna – Monroe
Time Duration Chart: Hanna VA (Ref: Monroe)
Angle Difference - Degrees
Data Distribution (%)
CERTS
18. Hanna – Monroe
Hour of Day Box-Whisker Chart: Hanna-Monroe
Voltage Angle - Degrees
Hours of Day
CERTS
19. Hanna – Canton Centr.
Time Series Trend Chart: Hanna VA (Ref: Canton Centr)
Angle Difference - Degrees
Date-Time
46
26
-4
CERTS
19. Hanna – Canton Centr.
Daily Box-Whisker Chart: Hanna VA (Ref: Canton Centr.)
Angle Difference - Degrees
Days
46
26
-4
CERTS
19. Hanna – Canton Centr.
Time Duration Chart: Hanna VA (Ref: Canton Centr.)
Angle Difference - Degrees
Data Distribution (%)
CERTS


19. Hanna – Canton Centr.
Hour of Day Box-Whisker Chart: Hanna-Canton Centr.
Voltage Angle - Degrees
Hours of Day
CERTS
20. Palisades – Monroe
Time Series Trend Chart: Palisades VA (Ref: Monroe)
Angle Difference - Degrees
Date-Time
CERTS
20. Palisades – Monroe
Daily Box-Whisker Chart: Palisades VA (Ref: Monroe)
Angle Difference - Degrees
Days
CERTS
20. Palisades – Monroe
Hour of Day Box-Whisker Chart: Palisades-Monroe
Voltage Angle - Degrees
Hours of Day
CERTS
20. Palisades – Monroe
Time Duration Chart: Palisades VA (Ref: Monroe)
Angle Difference - Degrees
Data Distribution (%)
CERTS
21. Raun – Millbury
Time Duration Chart: Raun VA (Ref: Millbury)
Angle Difference - Degrees
Data Distribution (%)
CERTS
21. Raun – Millbury
Hour of Day Box-Whisker Chart: Raun-Millbury
Voltage Angle - Degrees
Hours of Day
CERTS
21. Raun – Millbury
Time Series Trend Chart: Raun VA (Ref: Millbury)
Angle Difference - Degrees
Date-Time
CERTS
21. Raun – Millbury
Daily Box-Whisker Chart: Raun VA (Ref: Millbury)
Angle Difference - Degrees
Days
CERTS

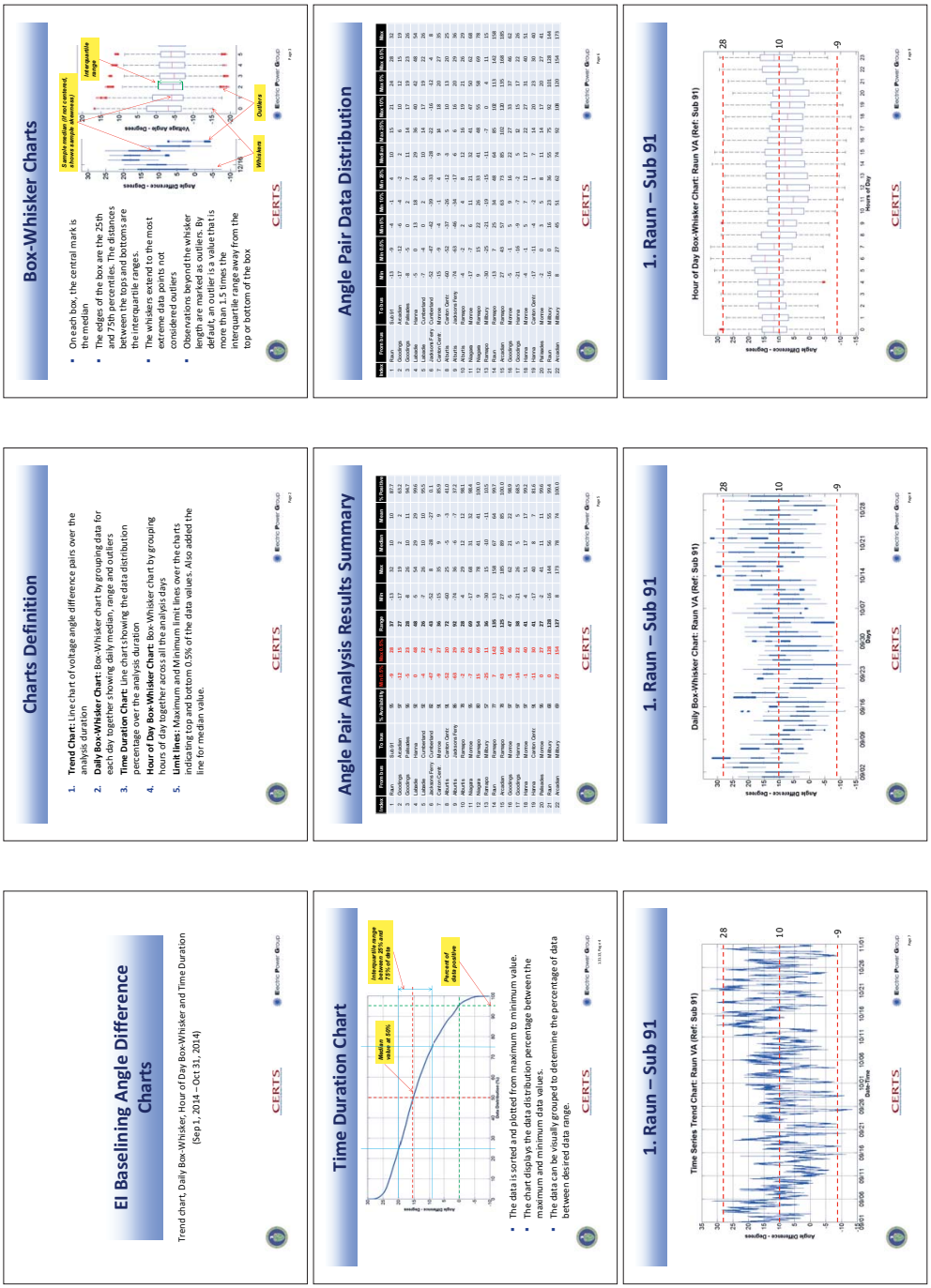

22. Arcadian – Millbury
Time Duration Chart: Arcadian VA (Ref: Millbury)
Angle Difference - Degrees
Time Duration (%)
CERTS
Electric Power Group

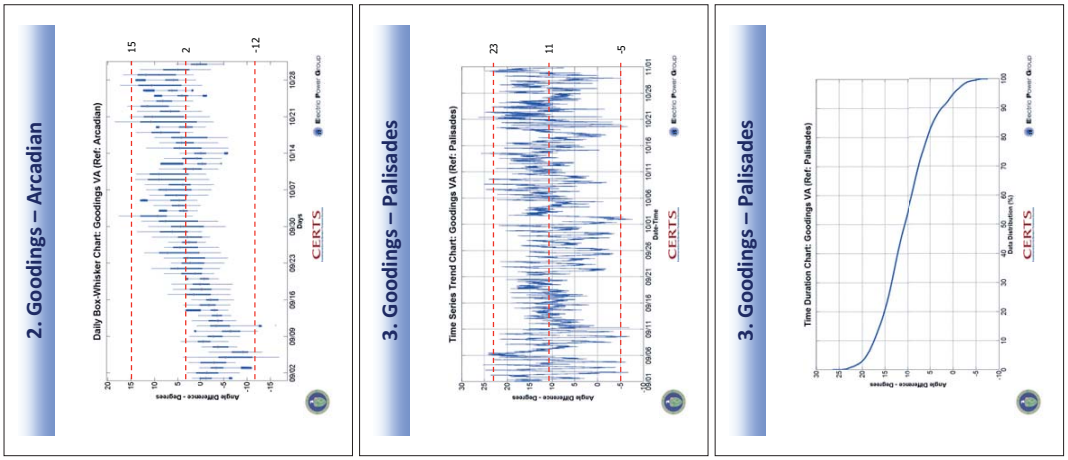

22. Arcadian – Millbury
Daily Box-Whisker Chart: Arcadian VA (Ref: Millbury)
Angle Difference - Degrees
Days
1.59
.63
.14
CERTS
Electric Power Group

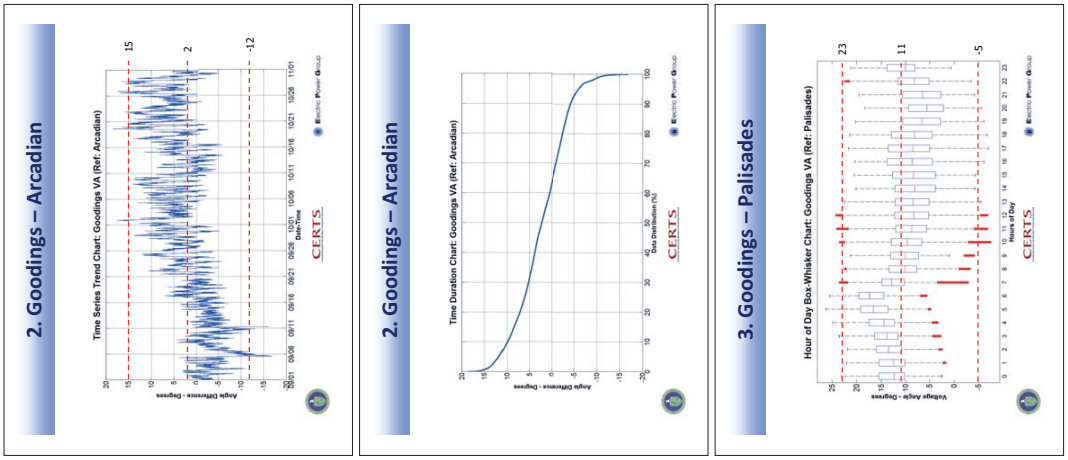

22. Arcadian – Millbury
Time Series Trend Chart: Arcadian VA (Ref: Millbury)
Angle Difference - Degrees
Date-Time
1.59
.63
.14
CERTS
Electric Power Group

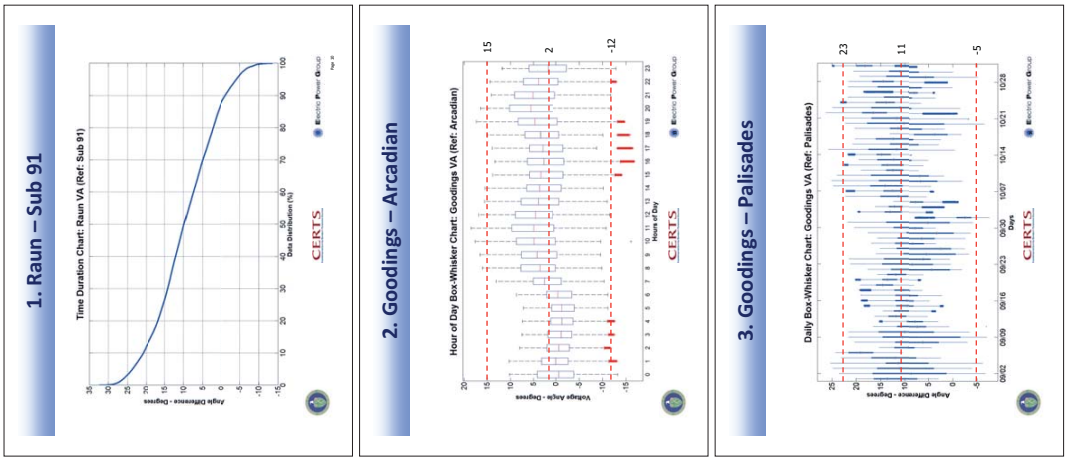

22. Arcadian – Millbury
Hour of Day Box-Whisker Chart:
Arcadian-Millbury
Voltage Angle - Degrees
Hours of Day
CERTS
Electric Power Group

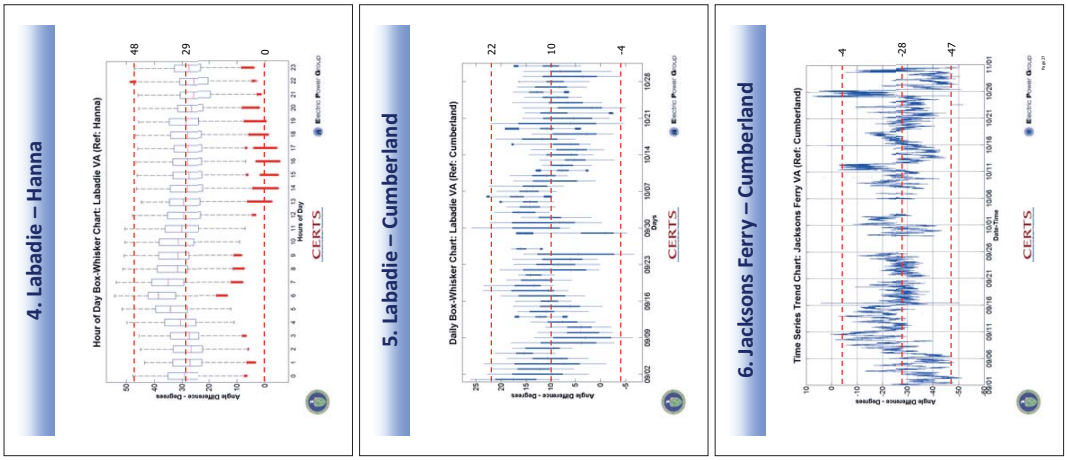
## 8.2 EI Baselining Angle Difference Charts for 2014 Fall PMU Data

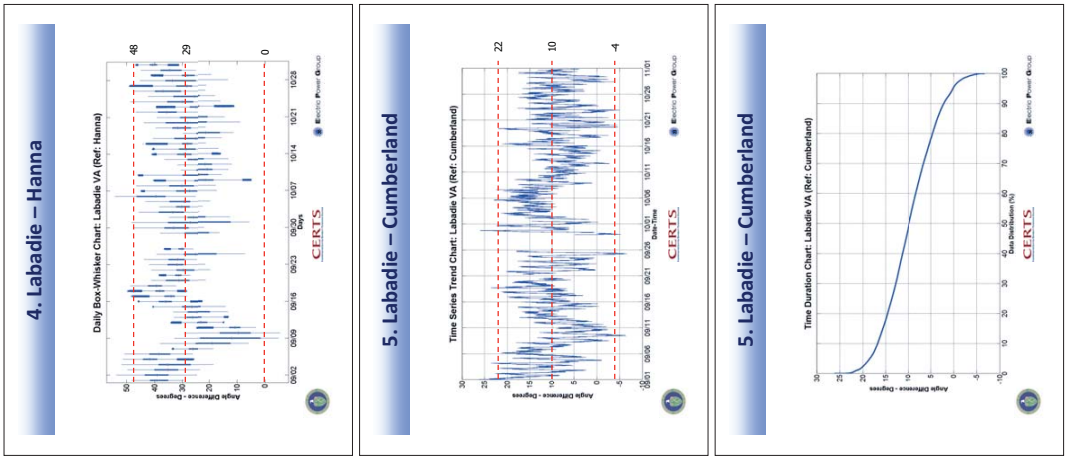


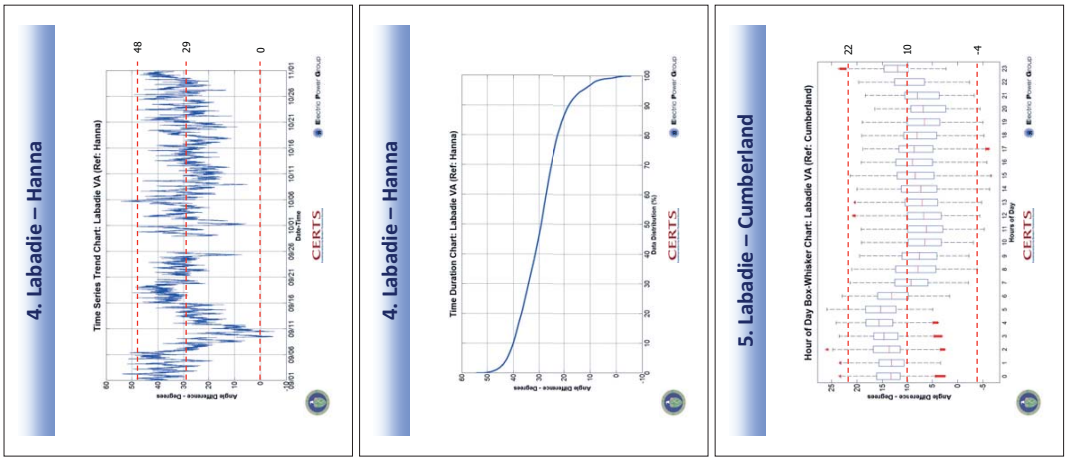

2. Goodings – Arcadian
Daily Box-Whisker Chart: Goodings VA (Ref: Arcadian)
15
2
-12
Angle Difference - Degrees
Days
CERTS
3. Goodings – Palisades
Time Series Trend Chart: Goodings VA (Ref: Palisades)
23
11
-5
Angle Difference - Degrees
Date-Time
CERTS
3. Goodings – Palisades
Time Duration Chart: Goodings VA (Ref: Palisades)
Angle Difference - Degrees
Data Distribution (%)
CERTS

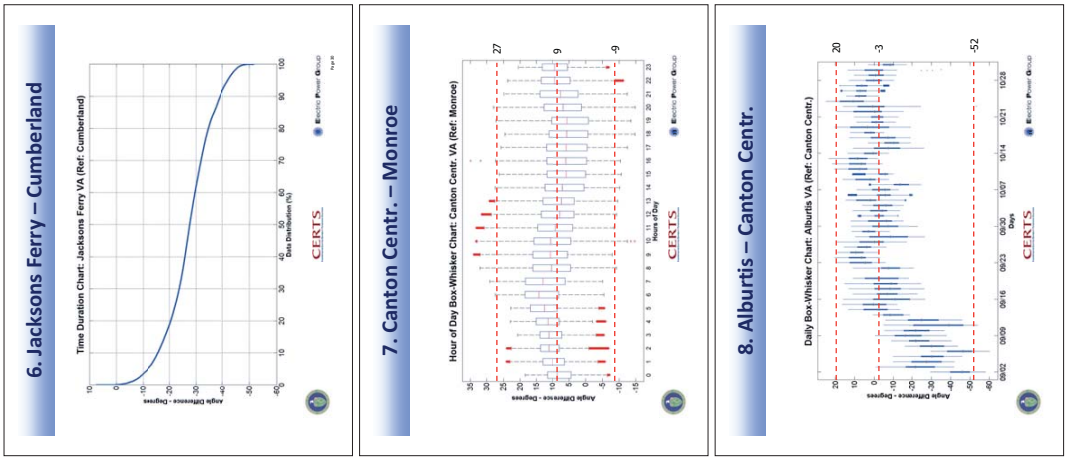

2. Goodings – Arcadian
Time Series Trend Chart: Goodings VA (Ref: Arcadian)
15
2
-12
Angle Difference - Degrees
Date-Time
CERTS
2. Goodings – Arcadian
Time Duration Chart: Goodings VA (Ref: Arcadian)
Angle Difference - Degrees
Data Distribution (%)
CERTS
3. Goodings – Palisades
Hour of Day Box-Whisker Chart: Goodings VA (Ref: Palisades)
23
11
-5
Voltage Angle - Degrees
Hours of Day
CERTS

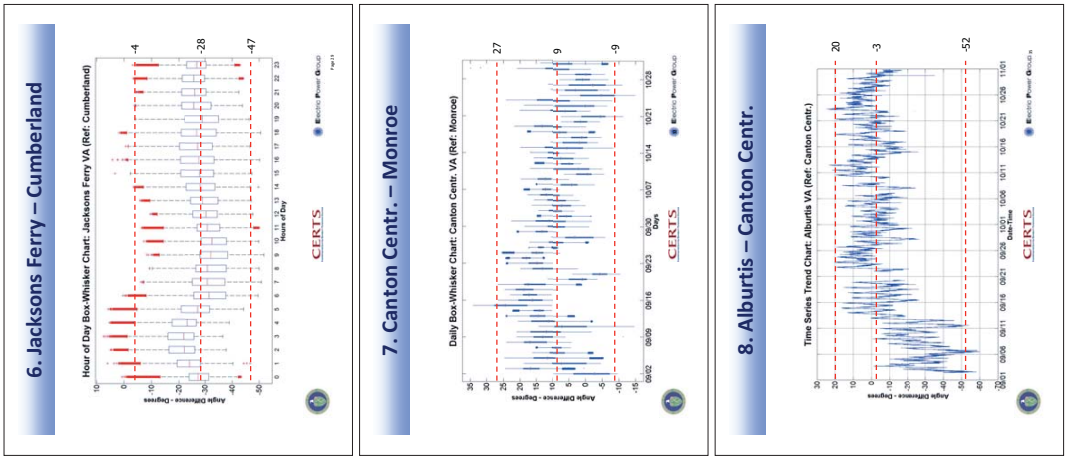

1. Raun – Sub 91
Time Duration Chart: Raun VA (Ref: Sub 91)
Angle Difference - Degrees
Data Distribution (%)
CERTS
2. Goodings – Arcadian
Hour of Day Box-Whisker Chart: Goodings VA (Ref: Arcadian)
15
2
-12
Voltage Angle - Degrees
Hours of Day
CERTS
3. Goodings – Palisades
Daily Box-Whisker Chart: Goodings VA (Ref: Palisades)
23
11
-5
Angle Difference - Degrees
Days
CERTS

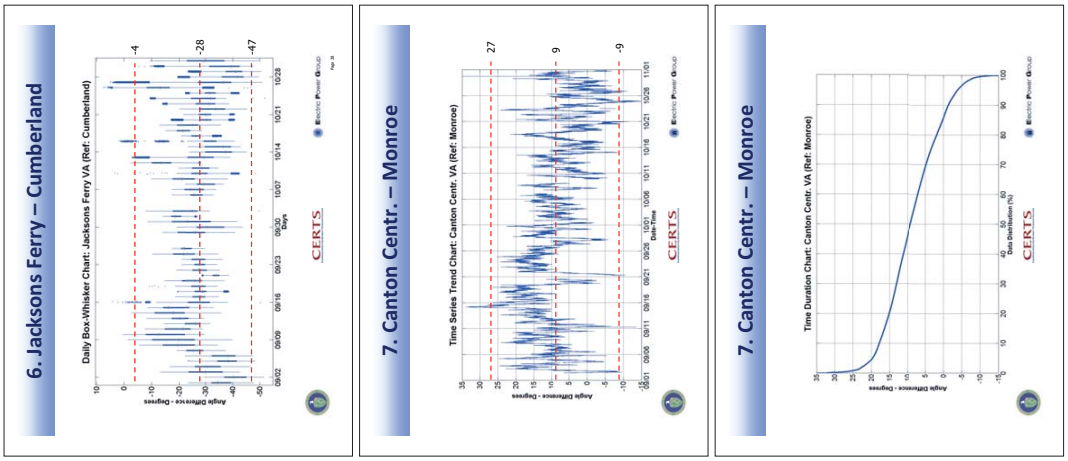

4. Labadie – Hanna
Hour of Day Box-Whisker Chart: Labadie VA (Ref: Hanna)
Angle Difference - Degrees
Hours of Day
48
29
0
CERTS
5. Labadie – Cumberland
Daily Box-Whisker Chart: Labadie VA (Ref: Cumberland)
Angle Difference - Degrees
Days
22
10
-4
CERTS
6. Jacksons Ferry – Cumberland
Time Series Trend Chart: Jacksons Ferry VA (Ref: Cumberland)
Angle Difference - Degrees
Date-Time
-4
-28
-47
CERTS

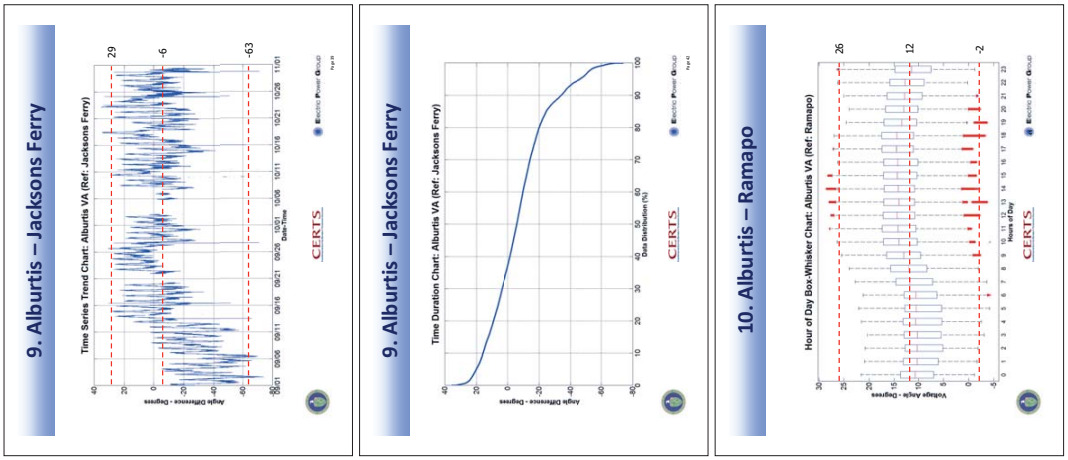

4. Labadie – Hanna
Daily Box-Whisker Chart: Labadie VA (Ref: Hanna)
Angle Difference - Degrees
Days
48
29
0
CERTS
5. Labadie – Cumberland
Time Series Trend Chart: Labadie VA (Ref: Cumberland)
Angle Difference - Degrees
Date-Time
22
10
-4
CERTS
5. Labadie – Cumberland
Time Duration Chart: Labadie VA (Ref: Cumberland)
Angle Difference - Degrees
Data Distribution (%)
CERTS

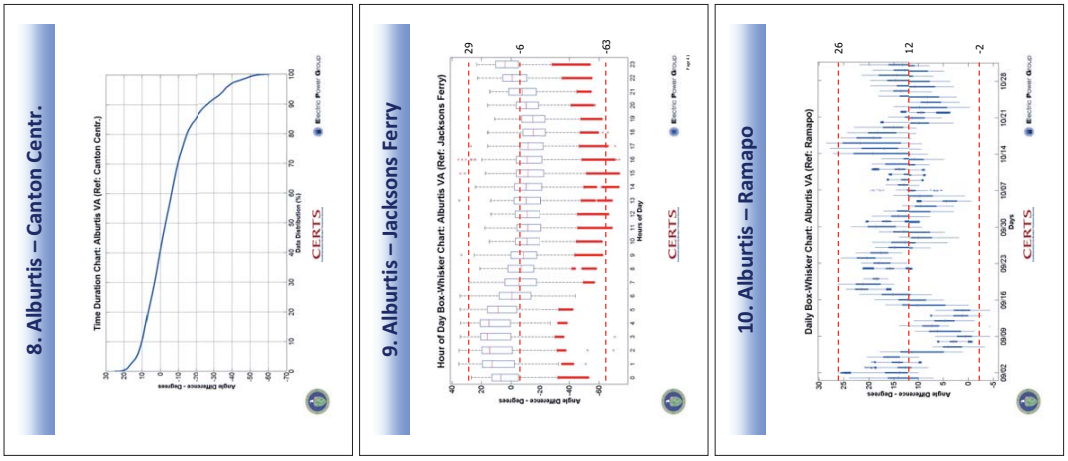

4. Labadie – Hanna
Time Series Trend Chart: Labadie VA (Ref: Hanna)
Angle Difference - Degrees
Date-Time
48
29
0
CERTS
4. Labadie – Hanna
Time Duration Chart: Labadie VA (Ref: Hanna)
Angle Difference - Degrees
Data Distribution (%)
CERTS
5. Labadie – Cumberland
Hour of Day Box-Whisker Chart: Labadie VA (Ref: Cumberland)
Angle Difference - Degrees
Hours of Day
22
10
-4
CERTS

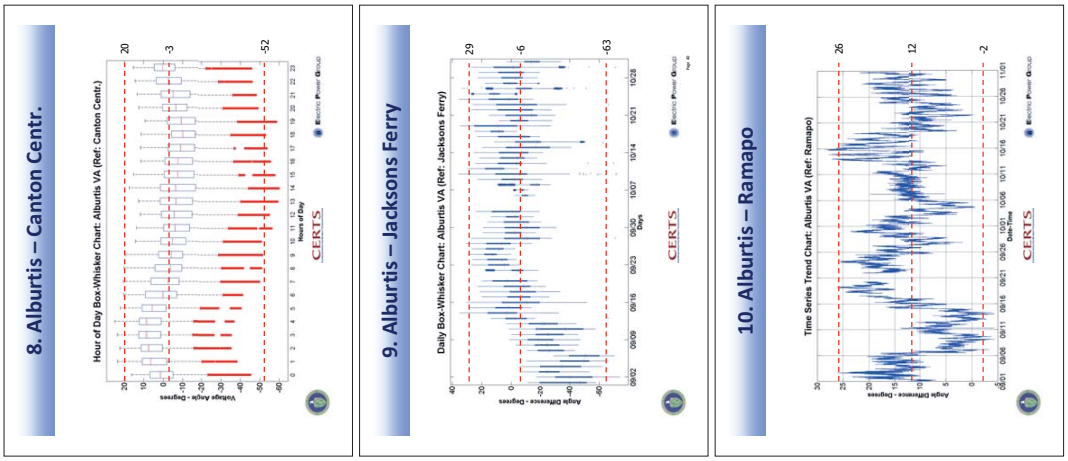

6. Jacksons Ferry – Cumberland
Time Duration Chart: Jacksons Ferry VA (Ref: Cumberland)
Angle Difference - Degrees
Data Distribution (%)
CERTS
7. Canton Centr. – Monroe
Hour of Day Box-Whisker Chart: Canton Centr. VA (Ref: Monroe)
27
9
-9
Hours of Day
8. Alburtis – Canton Centr.
Daily Box-Whisker Chart: Alburtis VA (Ref: Canton Centr.)
20
-3
-52
Days

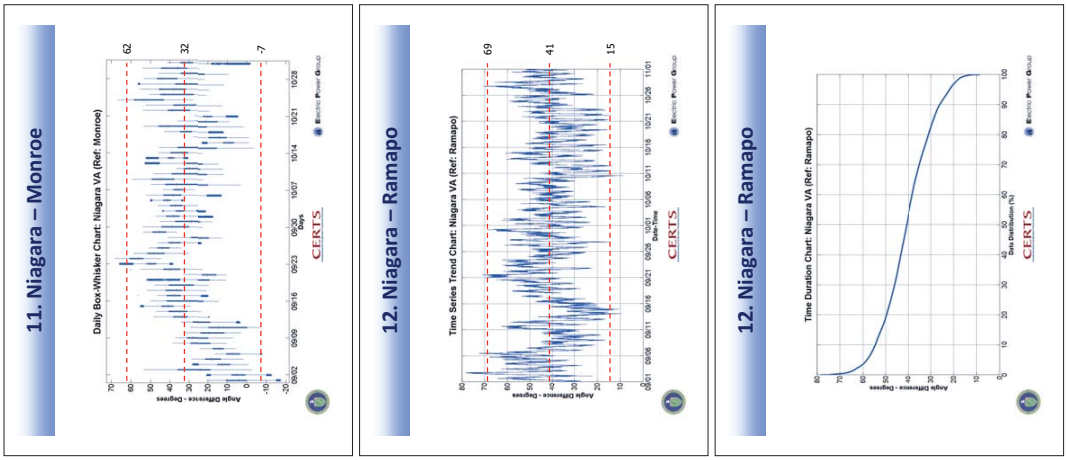

6. Jacksons Ferry – Cumberland
Hour of Day Box-Whisker Chart: Jacksons Ferry VA (Ref: Cumberland)
-4
-28
-47
Hours of Day
7. Canton Centr. – Monroe
Daily Box-Whisker Chart: Canton Centr. VA (Ref: Monroe)
27
9
-9
Days
8. Alburtis – Canton Centr.
Time Series Trend Chart: Alburtis VA (Ref: Canton Centr.)
20
-3
-52
Date-Time

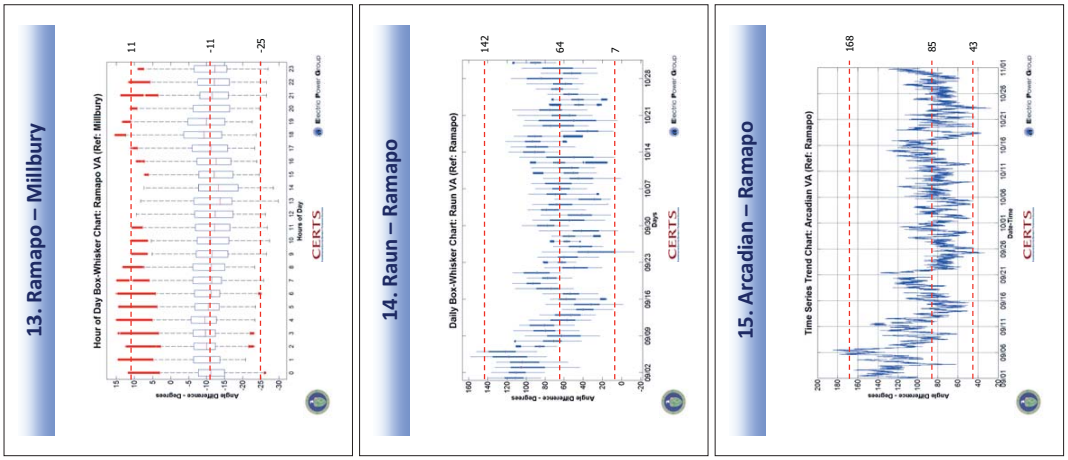

6. Jacksons Ferry – Cumberland
Daily Box-Whisker Chart: Jacksons Ferry VA (Ref: Cumberland)
-4
-28
-47
Days
7. Canton Centr. – Monroe
Time Series Trend Chart: Canton Centr. VA (Ref: Monroe)
27
9
-9
Date-Time
7. Canton Centr. – Monroe
Time Duration Chart: Canton Centr. VA (Ref: Monroe)
Angle Difference - Degrees
Data Distribution (%)

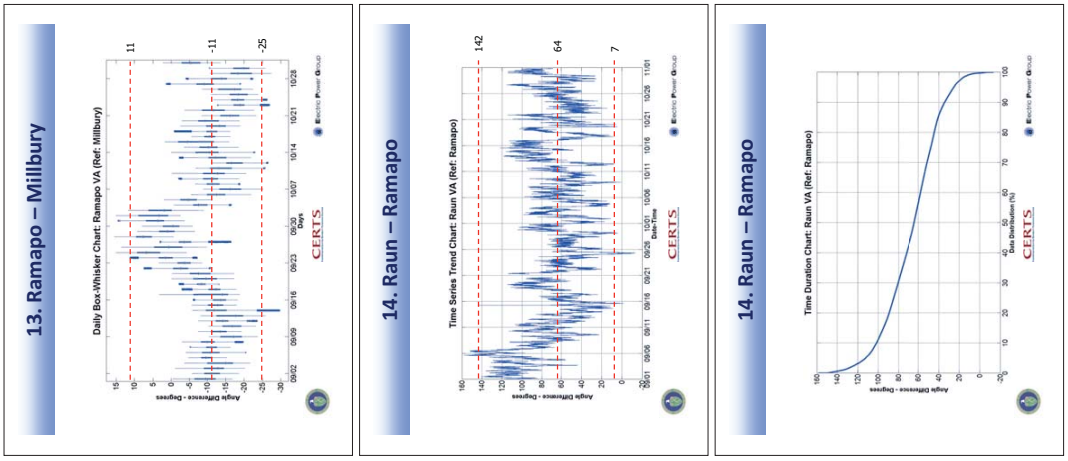

9. Alburtis – Jacksons Ferry
Time Series Trend Chart: Alburtis VA (Ref: Jacksons Ferry)
29
-6
-63
Angle Difference - Degrees
Date/Time
CERTS
Electric Power Group
9. Alburtis – Jacksons Ferry
Time Duration Chart: Alburtis VA (Ref: Jacksons Ferry)
Angle Difference - Degrees
Data Distribution (%)
CERTS
Electric Power Group
10. Alburtis – Ramapo
Hour of Day Box-Whisker Chart: Alburtis VA (Ref: Ramapo)
26
12
-2
Voltage Angle - Degrees
Hours of Day
CERTS
Electric Power Group

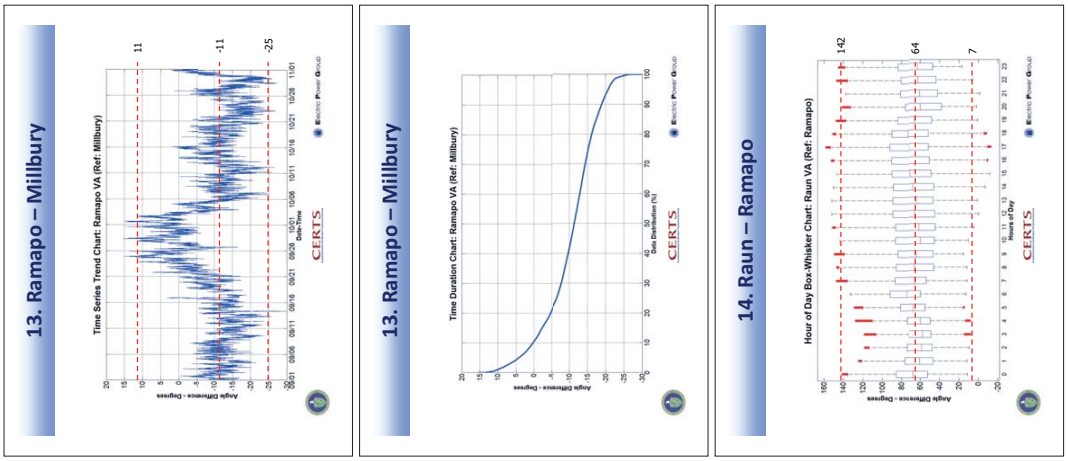

8. Alburtis – Canton Centr.
Time Duration Chart: Alburtis VA (Ref: Canton Centr.)
Angle Difference - Degrees
Data Distribution (%)
CERTS
Electric Power Group
9. Alburtis – Jacksons Ferry
Hour of Day Box-Whisker Chart: Alburtis VA (Ref: Jacksons Ferry)
29
-6
-63
Angle Difference - Degrees
Hours of Day
CERTS
Electric Power Group
10. Alburtis – Ramapo
Daily Box-Whisker Chart: Alburtis VA (Ref: Ramapo)
26
12
-2
Angle Difference - Degrees
Days
CERTS
Electric Power Group

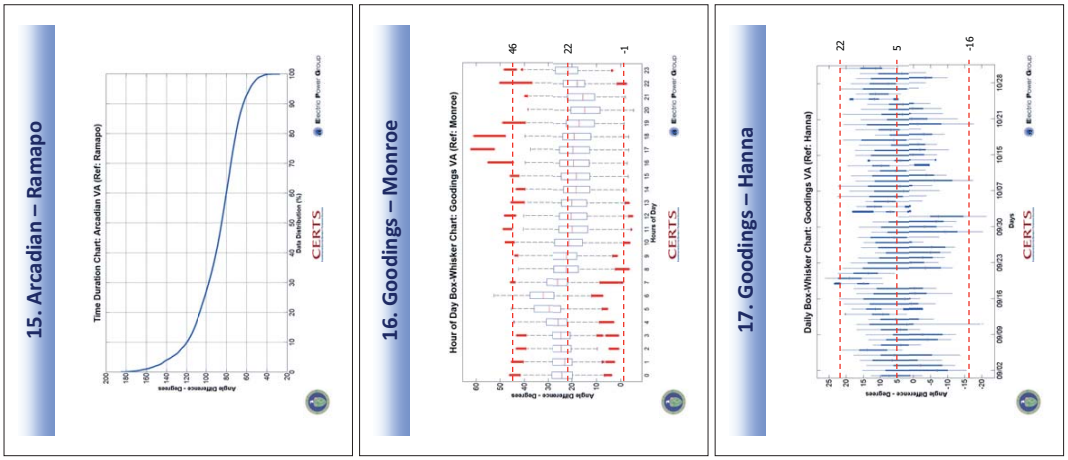

8. Alburtis – Canton Centr.
Hour of Day Box-Whisker Chart: Alburtis VA (Ref: Canton Centr.)
20
-3
-52
Voltage Angle - Degrees
Hours of Day
CERTS
Electric Power Group
9. Alburtis – Jacksons Ferry
Daily Box-Whisker Chart: Alburtis VA (Ref: Jacksons Ferry)
29
-6
-63
Angle Difference - Degrees
Days
CERTS
Electric Power Group
10. Alburtis – Ramapo
Time Series Trend Chart: Alburtis VA (Ref: Ramapo)
26
12
-2
Angle Difference - Degrees
Date/Time
CERTS
Electric Power Group

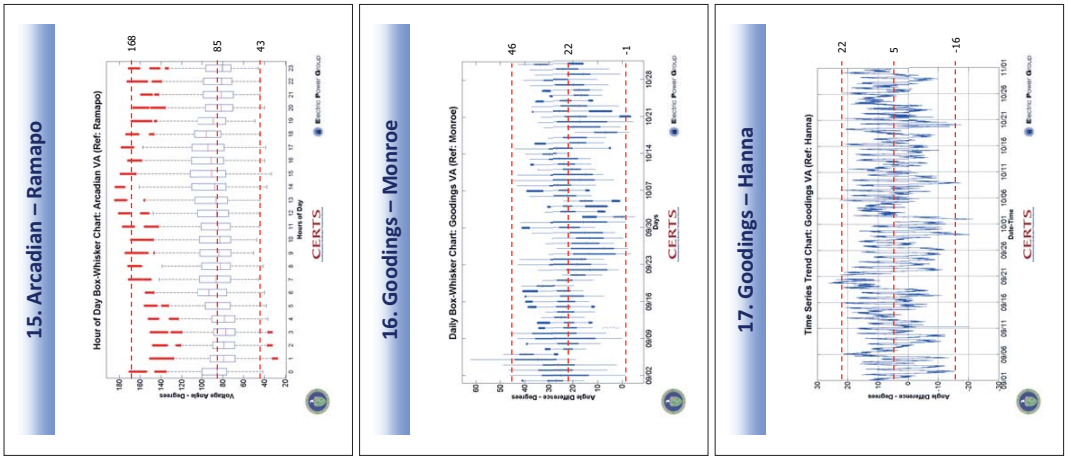

11. Niagara – Monroe
Daily Box-Whisker Chart: Niagara VA (Ref: Monroe)
Angle Difference - Degrees
Days
62
32
-7
CERTS
Electric Power Group
12. Niagara – Ramapo
Time Series Trend Chart: Niagara VA (Ref: Ramapo)
Angle Difference - Degrees
Date-Time
69
41
15
CERTS
Electric Power Group
12. Niagara – Ramapo
Time Duration Chart: Niagara VA (Ref: Ramapo)
Angle Difference - Degrees
Data Distribution (%)
CERTS
Electric Power Group
11. Niagara – Monroe
Time Series Trend Chart: Niagara VA (Ref: Monroe)
Angle Difference - Degrees
Date-Time
62
32
-7
CERTS
Electric Power Group
11. Niagara – Monroe
Time Duration Chart: Niagara VA (Ref: Monroe)
Angle Difference - Degrees
Data Distribution (%)
CERTS
Electric Power Group
12. Niagara – Ramapo
Hour of Day Box-Whisker Chart: Niagara VA (Ref: Ramapo)
Angle Difference - Degrees
Hours of Day
69
41
15
CERTS
Electric Power Group
10. Alburtis – Ramapo
Time Duration Chart: Alburtis VA (Ref: Ramapo)
Angle Difference - Degrees
Data Distribution (%)
CERTS
Electric Power Group
11. Niagara – Monroe
Hour of Day Box-Whisker Chart: Niagara VA (Ref: Monroe)
Angle Difference - Degrees
Hours of Day
62
32
-7
CERTS
Electric Power Group
12. Niagara – Ramapo
Daily Box-Whisker Chart: Niagara VA (Ref: Ramapo)
Angle Difference - Degrees
Days
69
41
15
CERTS
Electric Power Group

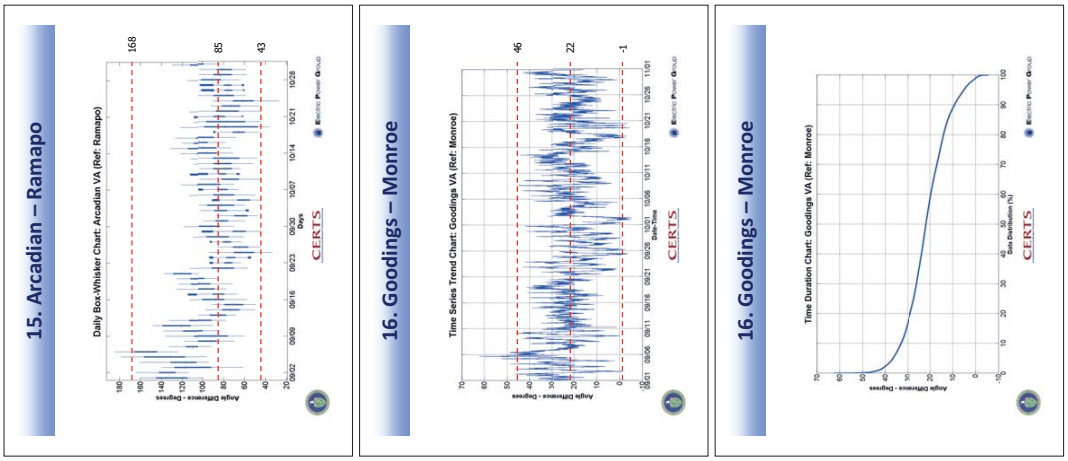

13. Ramapo – Millbury
Hour of Day Box-Whisker Chart: Ramapo VA (Ref: Millbury)
Angle Difference - Degrees
Hours of Day
11
-11
-25
CERTS
14. Raun – Ramapo
Daily Box-Whisker Chart: Raun VA (Ref: Ramapo)
Angle Difference - Degrees
Days
142
64
7
CERTS
15. Arcadian – Ramapo
Time Series Trend Chart: Arcadian VA (Ref: Ramapo)
Angle Difference - Degrees
Date-Time
168
85
-43
CERTS

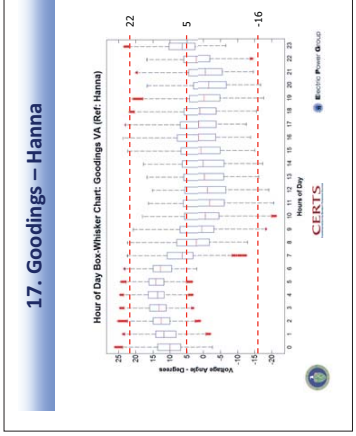

13. Ramapo – Millbury
Daily Box-Whisker Chart: Ramapo VA (Ref: Millbury)
Angle Difference - Degrees
Days
11
-11
-25
CERTS
14. Raun – Ramapo
Time Series Trend Chart: Raun VA (Ref: Ramapo)
Angle Difference - Degrees
Date-Time
142
64
7
CERTS
14. Raun – Ramapo
Time Duration Chart: Raun VA (Ref: Ramapo)
Angle Difference - Degrees
Data Distribution (%)
CERTS

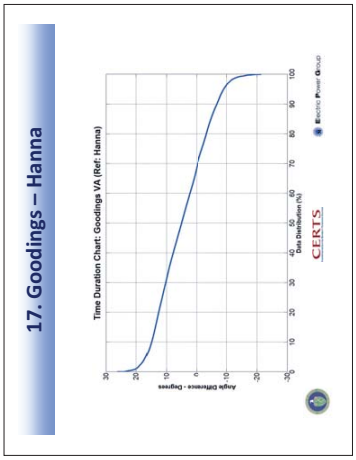

13. Ramapo – Millbury
Time Series Trend Chart: Ramapo VA (Ref: Millbury)
Angle Difference - Degrees
Date-Time
11
-11
-25
CERTS
13. Ramapo – Millbury
Time Duration Chart: Ramapo VA (Ref: Millbury)
Angle Difference - Degrees
Data Distribution (%)
CERTS
14. Raun – Ramapo
Hour of Day Box-Whisker Chart: Raun VA (Ref: Ramapo)
Angle Difference - Degrees
Hours of Day
142
64
7
CERTS

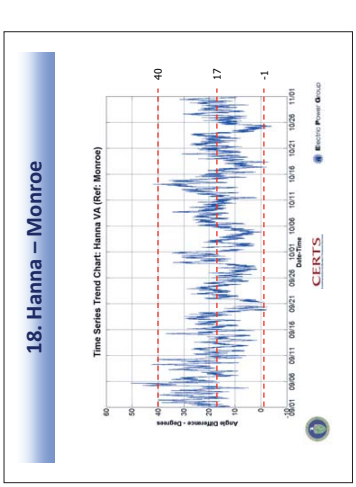

15. Arcadian – Ramapo
Time Duration Chart: Arcadian VA (Ref: Ramapo)
Angle Difference - Degrees
Time Duration (%)
CERTS
16. Goodings – Monroe
Hour of Day Box-Whisker Chart: Goodings VA (Ref: Monroe)
Angle Difference - Degrees
Hours of Day
46
22
-1
CERTS
17. Goodings – Hanna
Daily Box-Whisker Chart: Goodings VA (Ref: Hanna)
Angle Difference - Degrees
Days
22
5
-16
CERTS

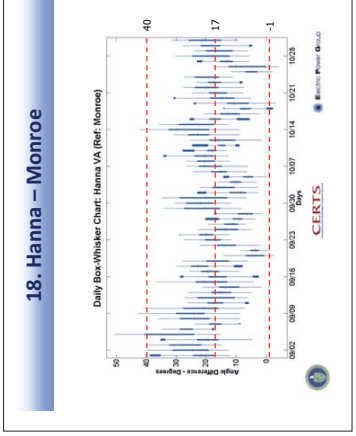

15. Arcadian – Ramapo
Hour of Day Box-Whisker Chart: Arcadian VA (Ref: Ramapo)
Voltage Angle - Degrees
Hours of Day
168
85
43
CERTS
16. Goodings – Monroe
Daily Box-Whisker Chart: Goodings VA (Ref: Monroe)
Angle Difference - Degrees
Days
46
22
-1
CERTS
17. Goodings – Hanna
Time Series Trend Chart: Goodings VA (Ref: Hanna)
Angle Difference - Degrees
Date-Time
22
5
-16
CERTS

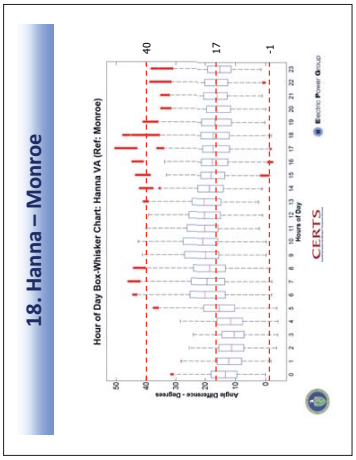

15. Arcadian – Ramapo
Daily Box-Whisker Chart: Arcadian VA (Ref: Ramapo)
Angle Difference - Degrees
Days
168
85
43
CERTS
16. Goodings – Monroe
Time Series Trend Chart: Goodings VA (Ref: Monroe)
Angle Difference - Degrees
Date-Time
46
22
-1
CERTS
16. Goodings – Monroe
Time Duration Chart: Goodings VA (Ref: Monroe)
Angle Difference - Degrees
Time Duration (%)
CERTS

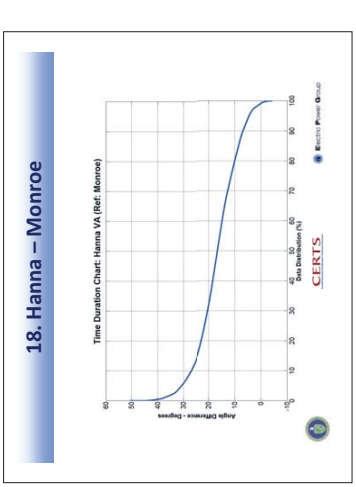

17. Goodings – Hanna
Hour of Day Box-Whisker Chart: Goodings VA (Ref: Hanna)
Voltage Angle - Degrees
Hours of Day
22
5
-16
CERTS
Electric Power Group

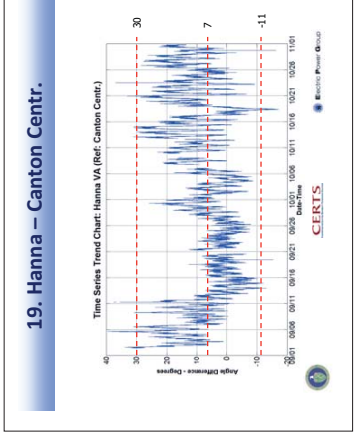

17. Goodings – Hanna
Time Duration Chart: Goodings VA (Ref: Hanna)
Angle Difference - Degrees
Data Duration (%)
CERTS
Electric Power Group

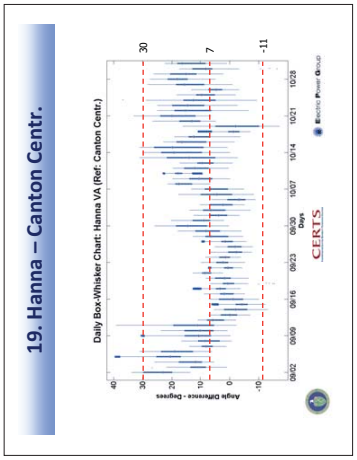

18. Hanna – Monroe
Time Series Trend Chart: Hanna VA (Ref: Monroe)
Angle Difference - Degrees
Date Time
40
17
-1
CERTS
Electric Power Group

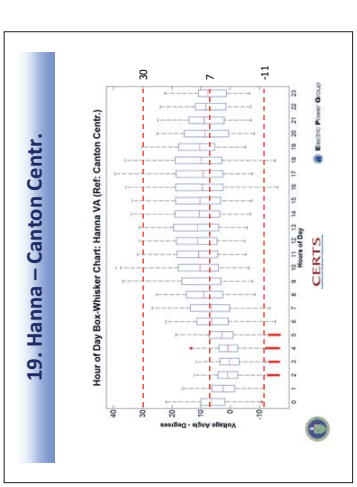

18. Hanna – Monroe
Daily Box-Whisker Chart: Hanna VA (Ref: Monroe)
Angle Difference - Degrees
Days
40
17
-1
CERTS
Electric Power Group

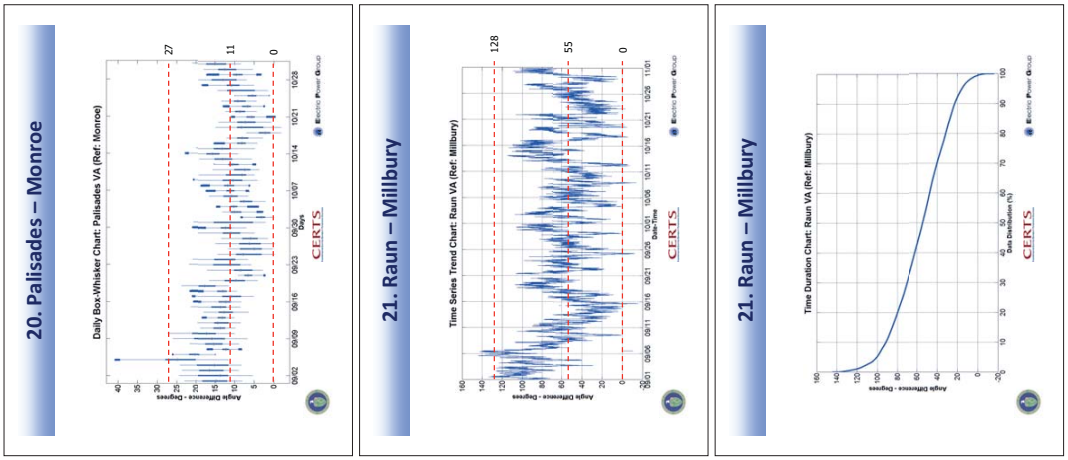

18. Hanna – Monroe
Hour of Day Box-Whisker Chart: Hanna VA (Ref: Monroe)
Angle Difference - Degrees
Hours of Day
40
17
-1
CERTS
Electric Power Group

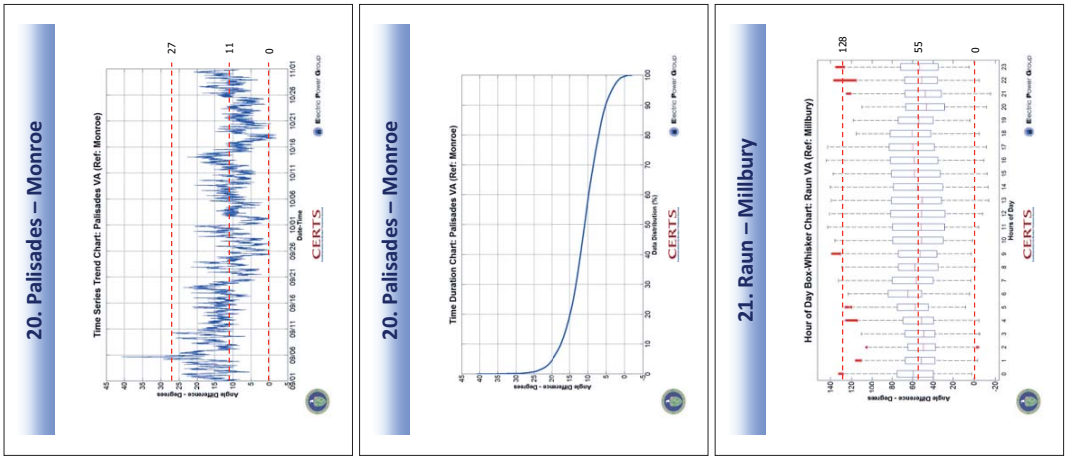

18. Hanna – Monroe
Time Duration Chart: Hanna VA (Ref: Monroe)
Angle Difference - Degrees
Data Duration (%)
CERTS
Electric Power Group

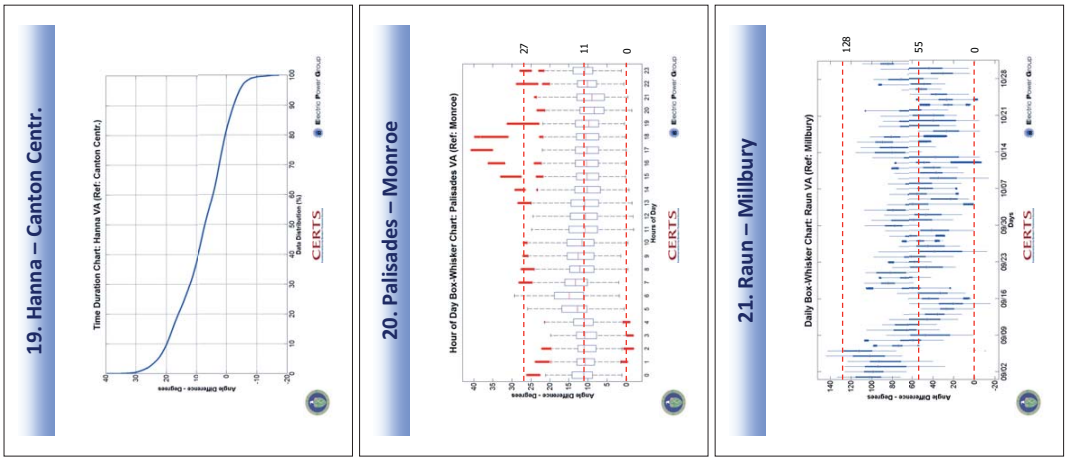

19. Hanna – Canton Centr.
Time Series Trend Chart: Hanna VA (Ref: Canton Centr.)
Angle Difference - Degrees
Date Time
30
7
-11
CERTS
Electric Power Group

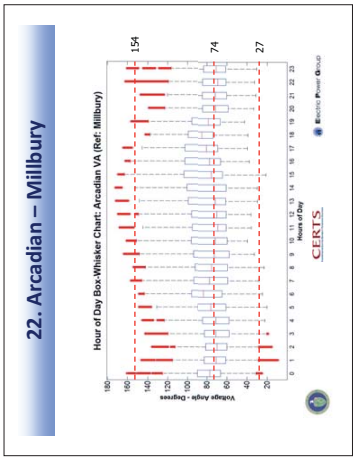

19. Hanna – Canton Centr.
Daily Box-Whisker Chart: Hanna VA (Ref: Canton Centr.)
Angle Difference - Degrees
Days
30
7
-11
CERTS
Electric Power Group

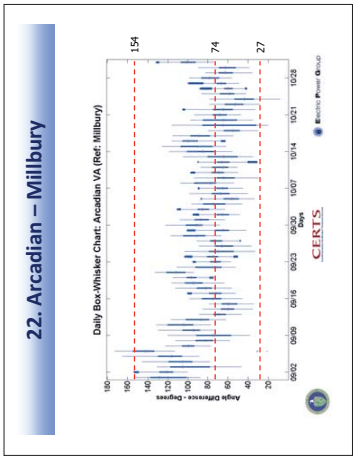

19. Hanna – Canton Centr.
Hour of Day Box-Whisker Chart: Hanna VA (Ref: Canton Centr.)
Voltage Angle - Degrees
Hours of Day
30
7
-11
CERTS
Electric Power Group

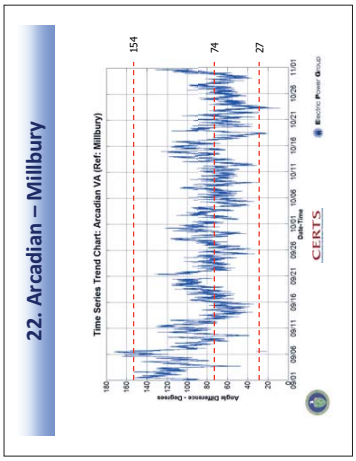

20. Palisades – Monroe
Daily Box-Whisker Chart: Palisades VA (Ref: Monroe)
Angle Difference - Degrees
Days
27
11
0
CERTS
21. Raun – Millbury
Time Series Trend Chart: Raun VA (Ref: Millbury)
Angle Difference - Degrees
Date-Time
128
55
0
CERTS
21. Raun – Millbury
Time Duration Chart: Raun VA (Ref: Millbury)
Angle Difference - Degrees
Data Distribution (%)
CERTS

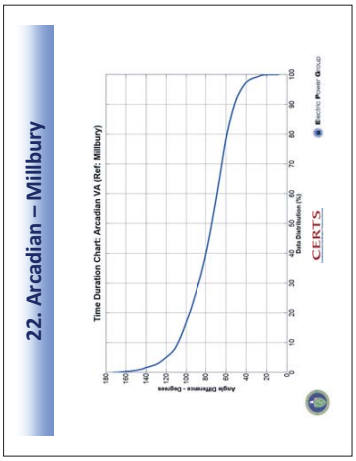

20. Palisades – Monroe
Time Series Trend Chart: Palisades VA (Ref: Monroe)
Angle Difference - Degrees
Date-Time
27
11
0
CERTS
20. Palisades – Monroe
Time Duration Chart: Palisades VA (Ref: Monroe)
Angle Difference - Degrees
Data Distribution (%)
CERTS
21. Raun – Millbury
Hour of Day Box-Whisker Chart: Raun VA (Ref: Millbury)
Angle Difference - Degrees
Hours of Day
128
55
0
CERTS


19. Hanna – Canton Centr.
Time Duration Chart: Hanna VA (Ref: Canton Centr.)
Angle Difference - Degrees
Data Distribution (%)
CERTS
20. Palisades – Monroe
Hour of Day Box-Whisker Chart: Palisades VA (Ref: Monroe)
Angle Difference - Degrees
Hours of Day
27
11
0
CERTS
21. Raun – Millbury
Daily Box-Whisker Chart: Raun VA (Ref: Millbury)
Angle Difference - Degrees
Days
128
55
0
CERTS

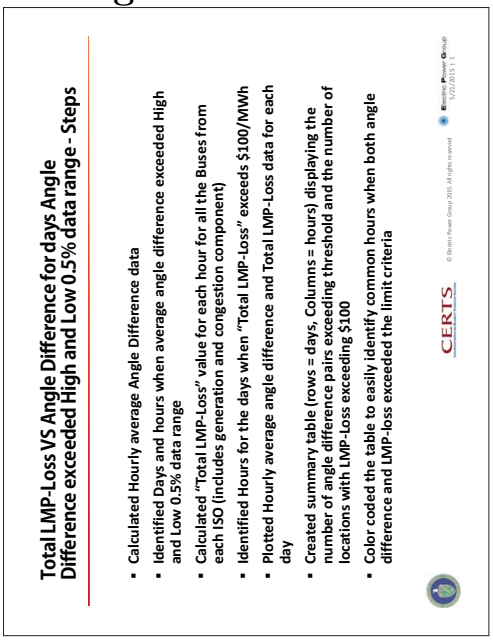

22. Arcadian – Millbury
Hour of Day Box-Whisker Chart: Arcadian VA (Ref: Millbury)
Voltage Angle - Degrees
Hours of Day
154
74
27
CERTS
Electric Power Group

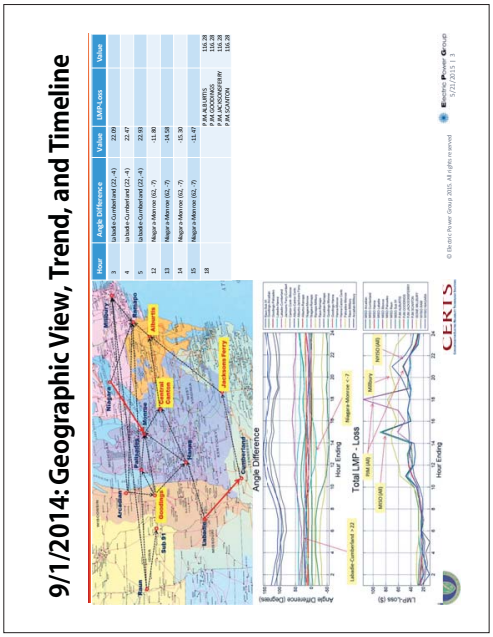

22. Arcadian – Millbury
Daily Box-Whisker Chart: Arcadian VA (Ref: Millbury)
Angle Difference - Degrees
Days
154
74
27
CERTS
Electric Power Group

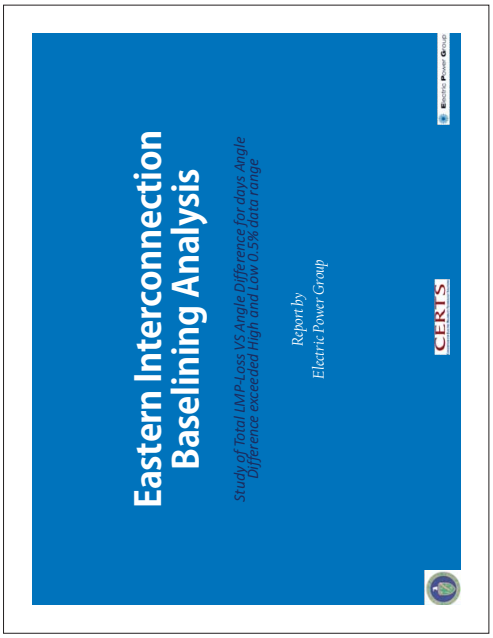

22. Arcadian – Millbury
Time Series Trend Chart: Arcadian VA (Ref: Millbury)
Angle Difference - Degrees
Date-Time
154
74
27
CERTS
Electric Power Group

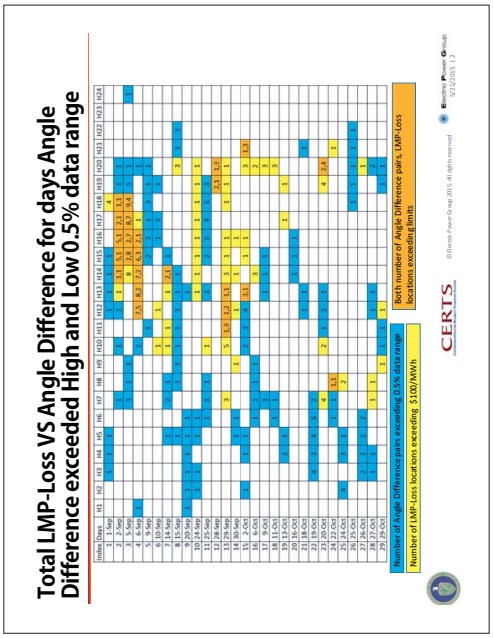

22. Arcadian – Millbury
Time Duration Chart: Arcadian VA (Ref: Millbury)
Angle Difference - Degrees
Data Distribution (%)
CERTS
Electric Power Group

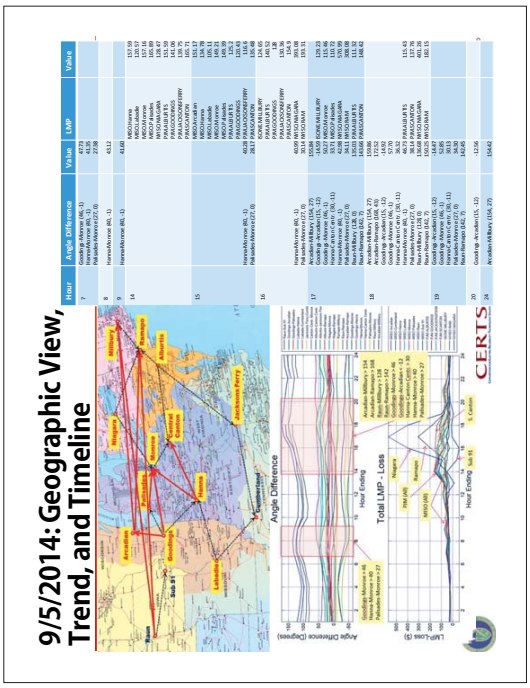
## 8.3 Study of Total LMP-Loss VS Angle Difference for Days Angle Difference Exceeded High and Low 0.5% Data Range




9/5/2014: Geographic View, Trend, and Timeline
Angle Difference
Total LMP - Loss
Hour Ending
CERTS
Electric Power Group
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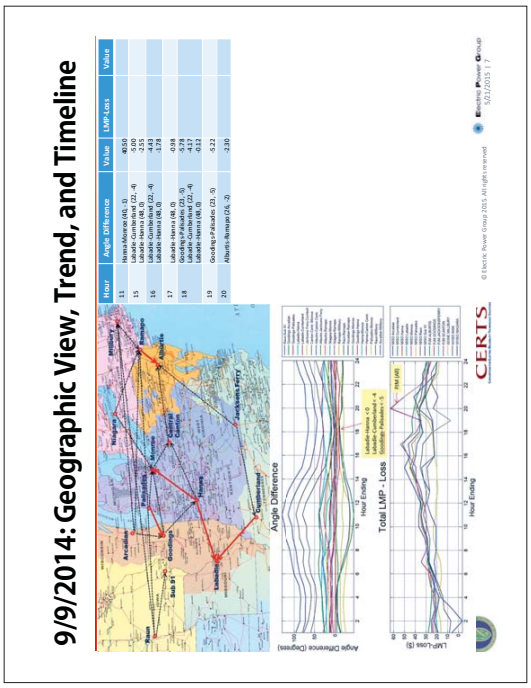
5/21/2015 | 7


9/9/2014: Geographic View, Trend, and Timeline
Angle Difference
Total LMP - Loss
Hour Ending
CERTS
Electric Power Group
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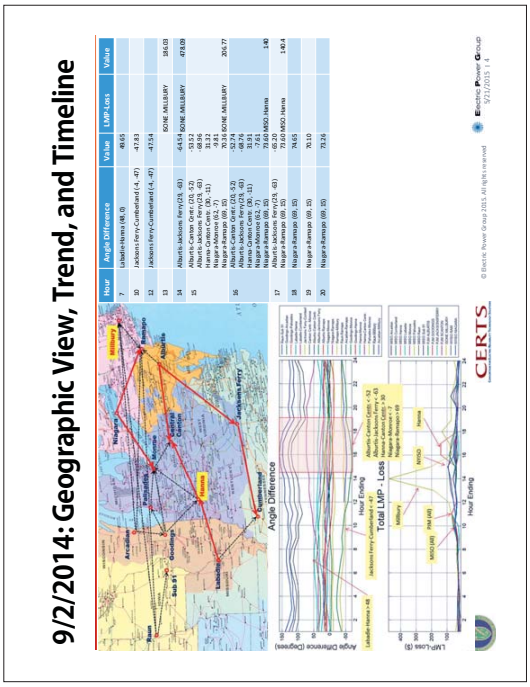
5/21/2015 | 7


9/2/2014: Geographic View, Trend, and Timeline
Angle Difference
Total LMP - Loss
Hour Ending
CERTS
Electric Power Group
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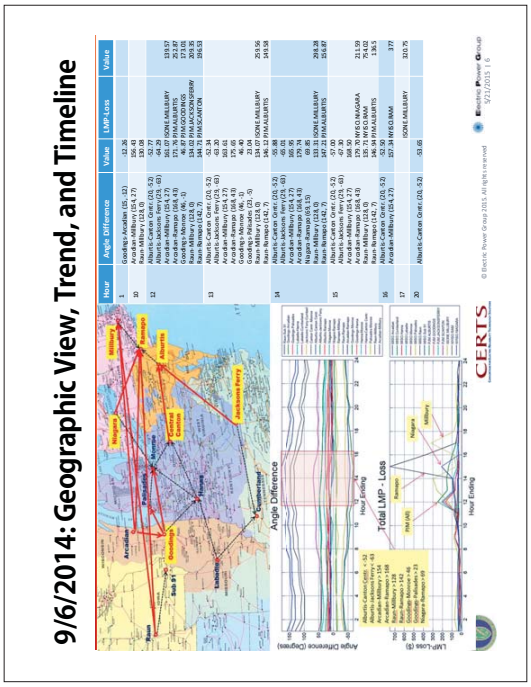
5/21/2015 | 4


9/6/2014: Geographic View, Trend, and Timeline
Angle Difference
Total LMP - Loss
Hour Ending
CERTS
Electric Power Group
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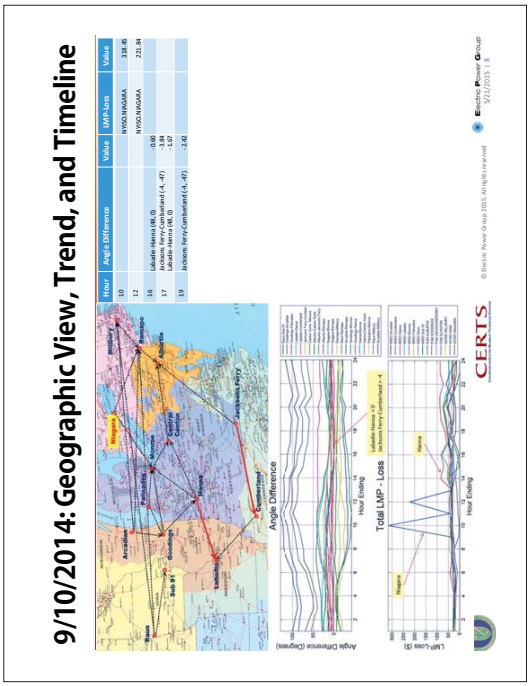
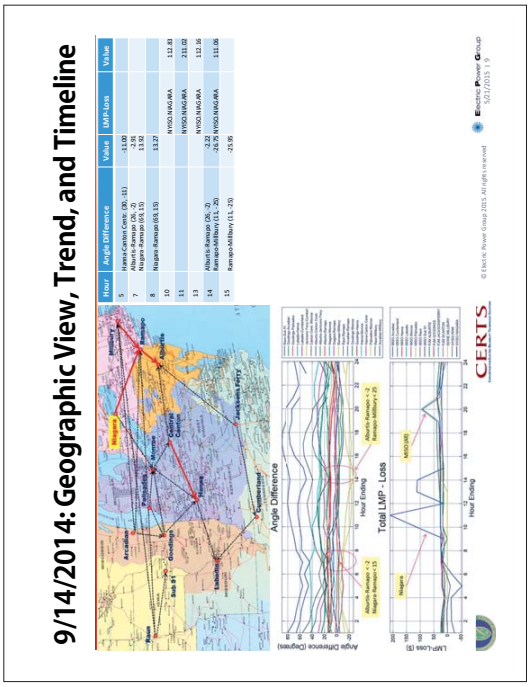
5/21/2015 | 6




| Hour | Angle Difference | Value | LMP-Loss | Value |
|---|---|---|---|---|
| 10 | | | NYISO.NIAGARA | 318.46 |
| 12 | | | NYISO.NIAGARA | 221.84 |
| 16 | Lakeide-Hanna (48, 0) | -0.60 | | |
| 17 | Jackson, Ferry-Cumberland (-4, -47) | -3.84 | | |
| | Lakeide-Hanna (-4, 0) | -3.60 | | |
| 19 | Jackson, Ferry-Cumberland (-4, -47) | -2.42 | | |



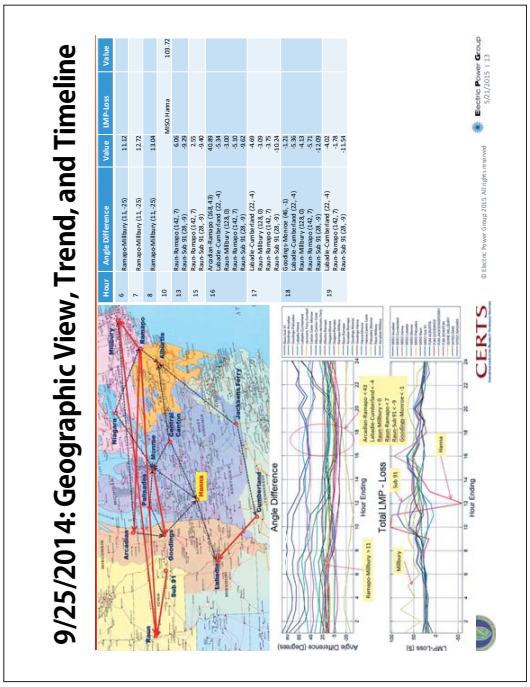

| Hour | Angle Difference | Value | LMP-Loss | Value |
|---|---|---|---|---|
| 5 | Hanna-Canton Centr. (20, -31) | -11.00 | | |
| 7 | Albaris-Ramapo (26, -2) | -1.95 | | |
| | Ramapo-Millbury (31, -25) | -1.58 | | |
| 8 | Niagara-Ramapo (69, 13) | 13.27 | | |
| 10 | | | NYISO.NIGARA | 112.83 |
| 11 | | | NYISO.NIGARA | 211.02 |
| 13 | | | NYISO.NIGARA | 112.16 |
| 14 | Albaris-Ramapo (26, -2) | -2.22 | | |
| | Ramapo-Millbury (31, -25) | -26.75 | NYISO.NIAGARA | 111.06 |
| 15 | Ramapo-Millbury (31, -23) | -21.95 | | |




| Hour | Angle Difference | Value | LMP-Loss | Value |
|---|---|---|---|---|
| 5 | Niagara-Ramapo (69, 13) | 14.71 | | |
| 8 | Canton Centr.-Monroe (27, -9) | 27.65 | | |
| 9 | Canton Centr.-Monroe (27, -9) | 29.22 | | |
| 10 | Canton Centr.-Monroe (27, -9) | 32.40 | | |
| 11 | Canton Centr.-Monroe (27, -9) | 31.80 | | |
| 12 | Canton Centr.-Monroe (27, -9) | 31.78 | | |
| 13 | Canton Centr.-Monroe (27, -9) | 29.63 | | |
| 14 | Canton Centr.-Monroe (27, -9) | 27.52 | | |
| 20 | | | PJM.ECONOMIC | 120.08 |
| | | | PJM.CONTINGENCY | 172.94 |
| | | | PJM.SCARCITY | 116.46 |
| 21 | Ruan-Millbury (-128, 0) | -0.28 | | |
| 22 | Ruan-Millbury (-128, 0) | -8.66 | | |
| | Ruan-Sub 91 (-128, -9) | -5.46 | | |
| | Ruan-Sub 91 (-128, -9) | -9.41 | | |




| Hour | Angle Difference | Value | LMP-Loss | Value |
|---|---|---|---|---|
| 1 | Goodrap.-Hanna (22, -16) | 23.42 | | |
| 2 | Goodrap.-Hanna (22, -16) | 23.62 | | |
| 3 | Goodrap.-Hanna (22, -16) | 23.80 | | |
| 4 | Goodrap.-Hanna (22, -16) | 23.16 | | |
| 5 | Goodrap.-Hanna (22, -16) | 23.40 | | |
| 6 | Goodrap.-Hanna (22, -16) | 22.78 | | |
| 13 | Ruan-Sub 91 (28, -9) | -9.34 | | |


9/25/2014: Geographic View, Trend, and Timeline
Hour Angle Difference Value LMP-Loss Value
6 Ramapo-Millbury (11, 25) 11.12
7 Ramapo-Millbury (11, 25) 12.72
8 Ramapo-Millbury (11, 25) 13.04 MISO:Hana 103.72
10
13 Raun-Rymgco (142, 7) -6.09
Raun-Sub 91 (28, 9) -2.29
Raun-Rymgco (142, 7) 2.55
Raun-Sub 91 (28, 9) 2.49
14 Arcadia-Sub 91 (164, 63) 49.80
15 Labadie-Cumberland (22, -4) -5.34
Raun-Rymgco (142, 7) -5.10
16 Raun-Rymgco (142, 7) -5.10
Raun-Sub 91 (28, 9) -4.63
17 Labadie-Cumberland (22, -4) -4.69
Raun-Millbury (124, 0) -3.09
Raun-Rymgco (142, 7) -2.75
Raun-Sub 91 (28, 9) -10.24
18 Goodings-Hanna (22, -16) -5.33
Labadie-Cumberland (22, -4) -5.56
Raun-Millbury (124, 0) -4.13
Raun-Rymgco (142, 7) -4.52
Raun-Sub 91 (28, 9) -12.02
19 Raun-Sub 91 (28, 9) -1.43
Labadie-Cumberland (22, -4) -1.76
Raun-Rymgco (142, 7) -11.54
Angle Difference
Total LMP - Loss
Hour Ending
CERTS
Electric Power Group
5/21/2015 | 13
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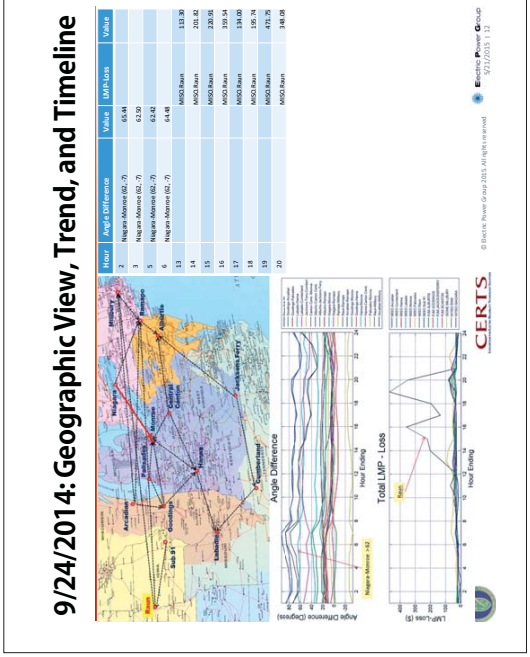
9/24/2014: Geographic View, Trend, and Timeline
Hour Angle Difference Value LMP-Loss Value
2 Niagara-Monroe (62, -7) 65.44
3 Niagara-Monroe (62, -7) 62.50
5 Niagara-Monroe (62, -7) 62.42
6 Niagara-Monroe (62, -7) 64.48
13 MISO:Raun 113.30
14 MISO:Raun 201.42
15 MISO:Raun 230.91
16 MISO:Raun 339.54
17 MISO:Raun 134.00
18 MISO:Raun 195.74
19 MISO:Raun 471.25
20 MISO:Raun 348.08
Angle Difference
Total LMP - Loss
Hour Ending
CERTS
Electric Power Group
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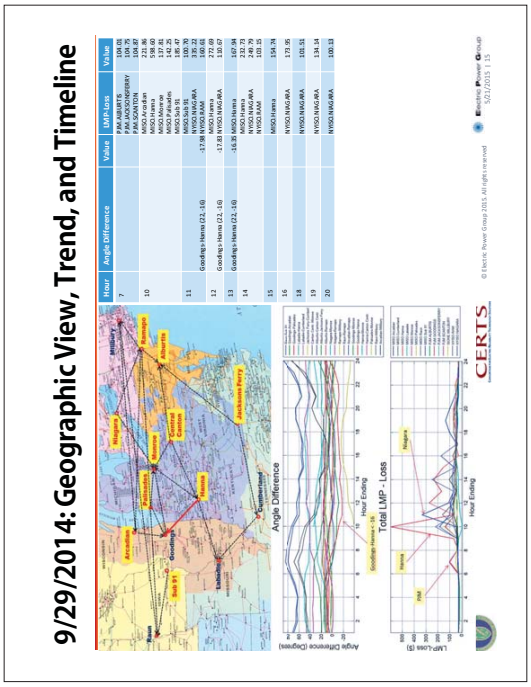
9/29/2014: Geographic View, Trend, and Timeline
Hour Angle Difference Value LMP-Loss Value
7 PJM:AUDUTE 109.03
PJM:AUDUTE 109.03
PJM:SOUTHERN 109.87
10 PJM:SOUTHERN 109.87
PJM:SOUTHERN 109.87
MISO:Hana 114.24
MISO:Monroe 59.60
MISO:Sub 91 137.35
MISO:Sub 91 137.35
MISO:Sub 91 145.22
MISO:Sub 91 185.47
MISO:Sub 91 185.47
11 NYISO:NIAGARA 139.78
NYISO:NIAGARA 139.22
Goodings-Hanna (22, -16) -17.98 NYISO:PJM 160.61
PJM:AUDUTE 172.69
12 Goodings-Hanna (22, -16) -17.83 NYISO:NIAGARA 110.67
13 Goodings-Hanna (22, -16) -16.35 MISO:Hana 167.34
14 MISO:Hana 227.73
MISO:Hana 249.79
NYISO:NIAGARA 109.15
NYISO:PJM
15 MISO:Hana 154.74
16 NYISO:NIAGARA 179.95
17 NYISO:NIAGARA 105.51
18 NYISO:NIAGARA 134.14
19 NYISO:NIAGARA 103.13
20 NYISO:NIAGARA
Angle Difference
Total LMP - Loss
Hour Ending
CERTS
Electric Power Group
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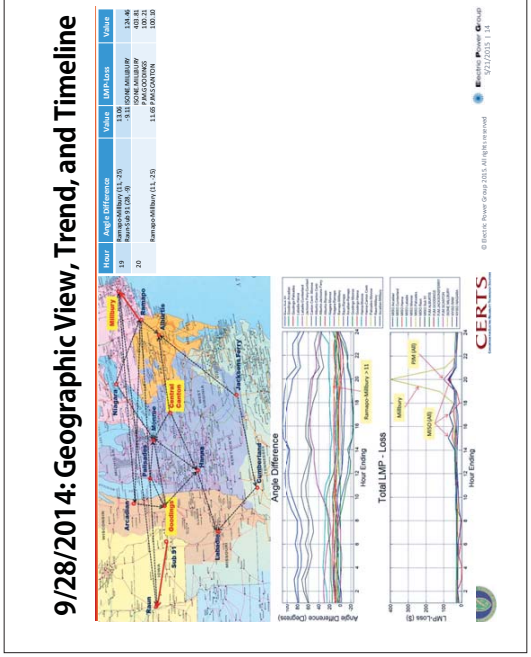
9/28/2014: Geographic View, Trend, and Timeline
Hour Angle Difference Value LMP-Loss Value
19 Ramapo-Millbury (11, -25) 13.06 ISO:NE:MILLBURY 124.46
Raun-Sub 91 (28, 9) 5.56 ISO:NE:MILLBURY 403.81
PJM:SOUTHERN 174.23
20 Ramapo-Millbury (11, -25) 11.65 PJM:SOUTHERN 100.10
Angle Difference
Total LMP - Loss
Hour Ending
CERTS
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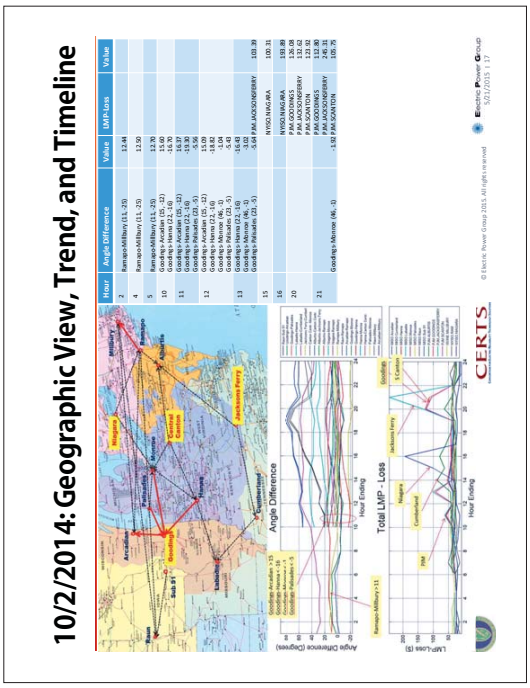
10/2/2014: Geographic View, Trend, and Timeline
Hour | Angle Difference | Value | LMP-Loss | Value
2 | Ramapo-Millbury (11, 25) | 12.44
4 | Ramapo-Millbury (11, 25) | 12.50
5 | Ramapo-Millbury (11, 25) | 12.70
10 | Goodings-Arcadian (35, -1) | 15.40
Goodings-Hanna (21, 14) | 15.70
11 | Goodings-Arcadian (35, -1) | 16.37
Goodings-Hanna (21, 14) | -15.39
Goodings-Palisades (23, -5) | -5.96
12 | Goodings-Arcadian (35, -1) | 11.09
Goodings-Hanna (21, 14) | -13.66
Goodings-Monroe (46, -1) | -1.04
Goodings-Monroe (46, -1) | -1.43
13 | Goodings-Hanna (21, 14) | 14.43
Goodings-Palisades (23, -5) | -3.02
-3.64 | P.M.-JACKSONFERRY | 103.39
15 | NYISO.NYC.ROA | 100.31
16 | NYISO.NYC.ROA | 193.89
20 | P.M.-GOODINGS | 126.08
P.M.-JACKSONFERRY | 127.52
P.M.-SCRANTON | 132.14
21 | P.M.-GOODINGS | 112.80
P.M.-JACKSONFERRY | 114.31
-1.92 | P.M.-SCRANTON | 105.75
Angle Difference
Total LMP - Loss
Hour Ending
CERTS
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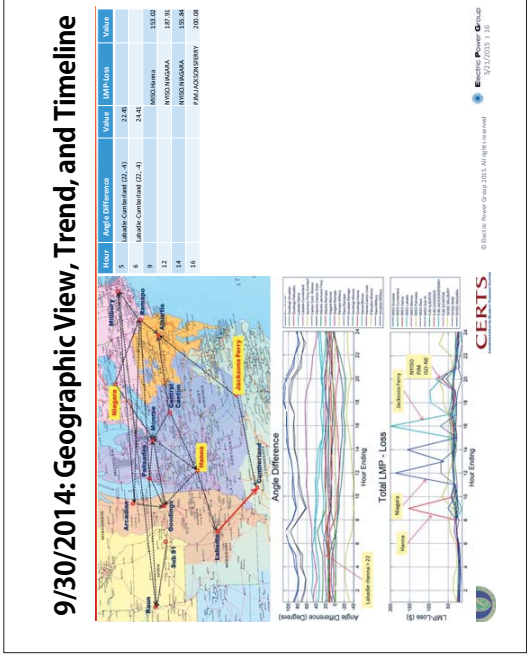
5/21/2015 | 17


9/30/2014: Geographic View, Trend, and Timeline
Hour | Angle Difference | Value | LMP-Loss | Value
5 | Lakeside-Cumberland (22, -1) | 22.46
6 | Lakeside-Cumberland (22, -1) | 24.41
9 | MISO.Hanna | 153.02
12 | NYISO.NIAGARA | 187.31
14 | NYISO.NIAGARA | 155.94
16 | P.M.JACKSONFERRY | 200.08
Angle Difference
Total LMP - Loss
Hour Ending
CERTS
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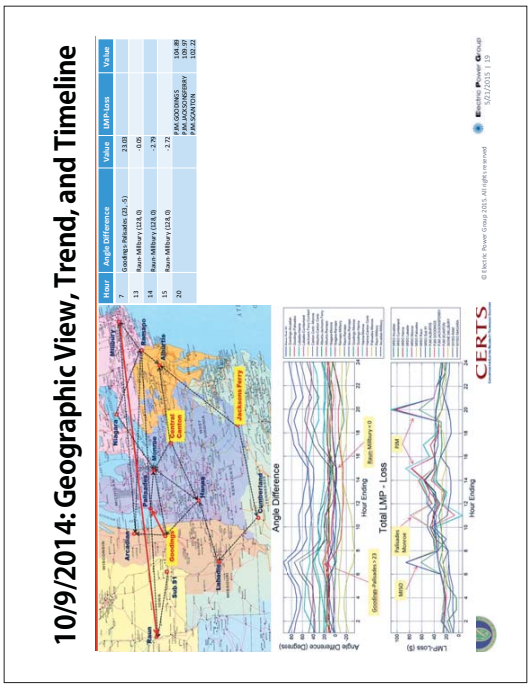
5/21/2015 | 16


10/9/2014: Geographic View, Trend, and Timeline
Hour | Angle Difference | Value | LMP-Loss | Value
7 | Goodings-Palisades (23, -5) | 23.03
13 | Ravn-Millbury (123, 0) | -0.05
14 | Ravn-Millbury (123, 0) | -2.79
15 | Ravn-Millbury (123, 0) | -2.72
20 | P.M.-GOODINGS | 108.89
P.M.-JACKSONFERRY | 109.87
P.M.-SCRANTON | 110.22
Angle Difference
Total LMP - Loss
Hour Ending
CERTS
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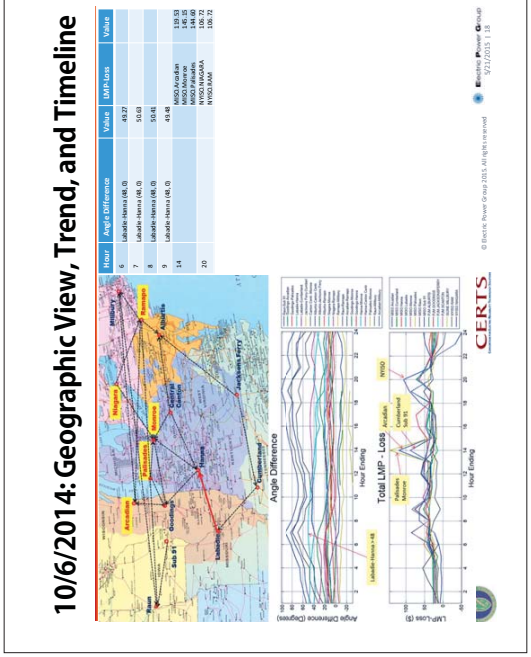
10/6/2014: Geographic View, Trend, and Timeline
Hour | Angle Difference | Value | LMP-Loss | Value
6 | Lakeside-Hanna (48, 0) | 49.27
7 | Lakeside-Hanna (48, 0) | 50.03
8 | Lakeside-Hanna (48, 0) | 50.41
9 | Lakeside-Hanna (48, 0) | 49.48
MISO.Arcadian | 129.53
MISO.Hanna | 145.55
14 | MISO.Palisades | 144.40
NYISO.NIAGARA | 106.72
20 | NYISO.ROA | 106.72
Angle Difference
Total LMP - Loss
Hour Ending
CERTS
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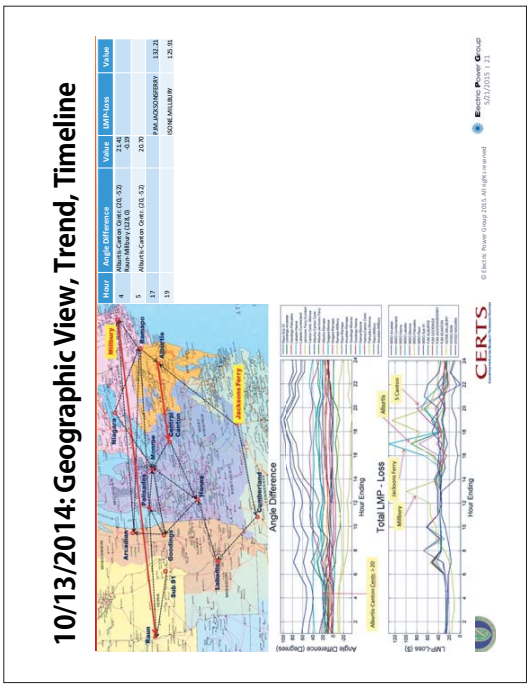
5/21/2015 | 18


10/13/2014: Geographic View, Trend, Timeline
Hour | Angle Difference | Value | LMP-Loss | Value
4 | Atlantic-Carlton Gate; (20, 52) | 21.48 | |
| Atlantic-Bamuyo (20, -2) | 21.53 | |
5 | Atlantic-Carlton Gate; (20, 52) | 20.70 | |
| | | PJM.JACSONFERRY | 132.21
| | | IOWE.MILBURN | 125.91
Angle Difference
Total LMP - Loss
Hour Ending
CERTS
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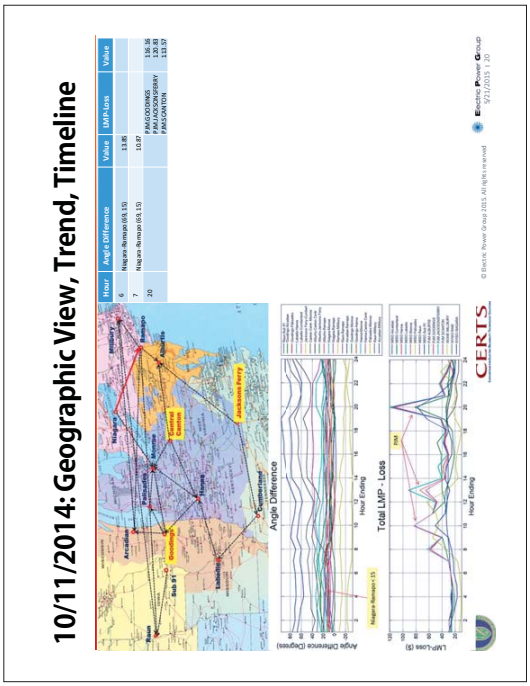
Electric Power Group
5/21/2015 | 21


10/18/2014: Geographic View, Trend, Timeline
Hour | Angle Difference | Value | LMP-Loss | Value
12 | Palisades-Monroe (27,0) | -0.65 | |
13 | Palisades-Monroe (27,0) | -0.74 | |
21 | Palisades-Monroe (27,0) | -0.20 | |
Angle Difference
Total LMP - Loss
Hour Ending
CERTS
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10/11/2014: Geographic View, Trend, Timeline
Hour | Angle Difference | Value | LMP-Loss | Value
6 | Niagara-Bunsuyo (69,15) | 13.86 | |
7 | Niagara-Bunsuyo (69,15) | 10.87 | |
| | | PJM.GOTONDS | 136.36
| | | PJM.JACSONFERRY | 135.83
20 | | | PJM.SANTON | 133.37
Angle Difference
Total LMP - Loss
Hour Ending
CERTS
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5/21/2015 | 20


10/16/2014: Geographic View, Trend, Timeline
Hour | Angle Difference | Value | LMP-Loss | Value
14 | Atlantic-Bamuyo (26, -2) | 26.75 | |
15 | Atlantic-Bamuyo (26, -2) | 27.49 | |
16 | Atlantic-Bamuyo (26, -2) | 26.58 | |
Angle Difference
Total LMP - Loss
Hour Ending
CERTS
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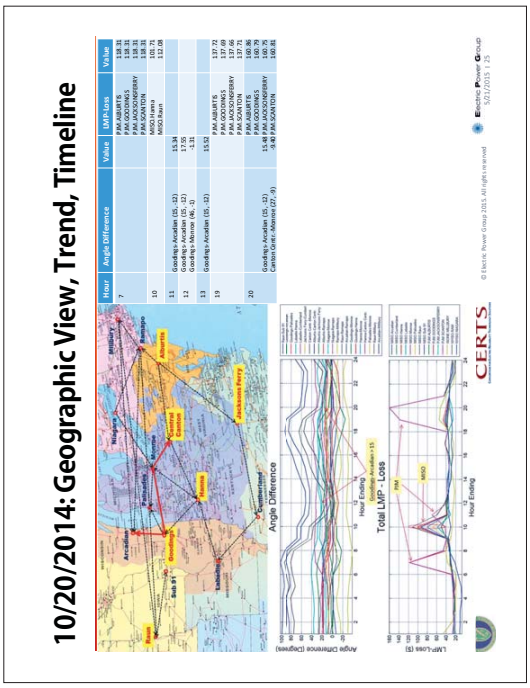
5/21/2015 | 22


10/20/2014: Geographic View, Trend, Timeline
Hour
Angle Difference
Value
LMP-Loss
Value
Angle Difference (Degrees)
Total LMP - Loss
LMP-Loss ($)
Hour Ending
CERTS
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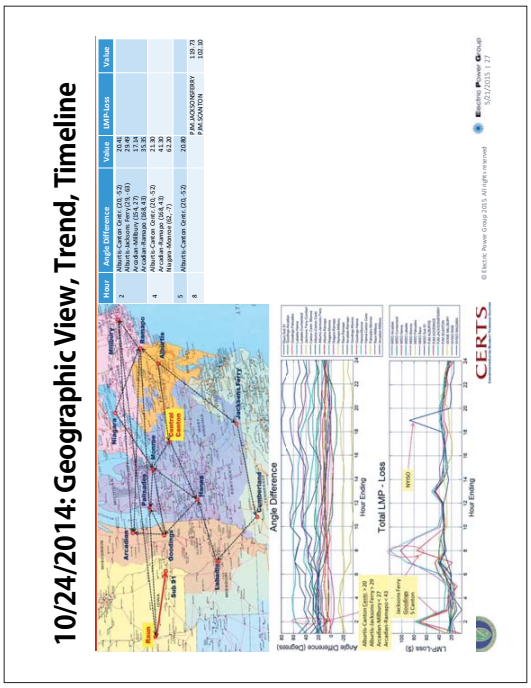
5/21/2015 | 25


10/24/2014: Geographic View, Trend, Timeline
Hour
Angle Difference
Value
LMP-Loss
Value
Angle Difference (Degrees)
Total LMP - Loss
LMP-Loss ($)
Hour Ending
CERTS
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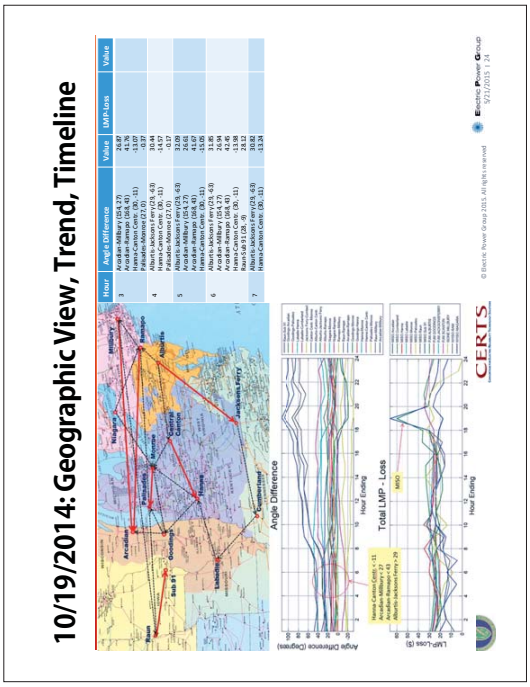
5/21/2015 | 27


10/19/2014: Geographic View, Trend, Timeline
Hour
Angle Difference
Value
LMP-Loss
Value
Angle Difference (Degrees)
Total LMP - Loss
LMP-Loss ($)
Hour Ending
CERTS
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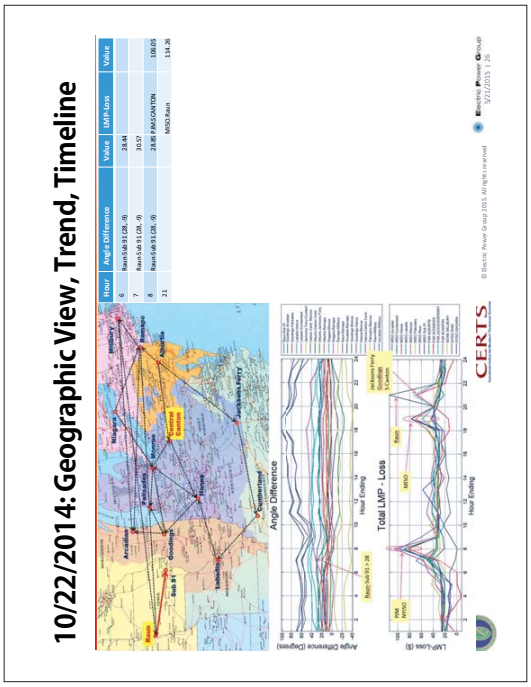
5/21/2015 | 24


10/22/2014: Geographic View, Trend, Timeline
Hour
Angle Difference
Value
LMP-Loss
Value
Angle Difference (Degrees)
Total LMP - Loss
LMP-Loss ($)
Hour Ending
CERTS
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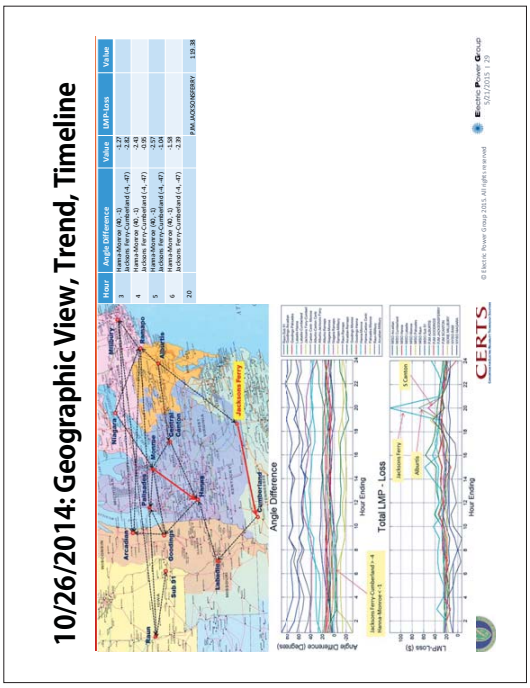
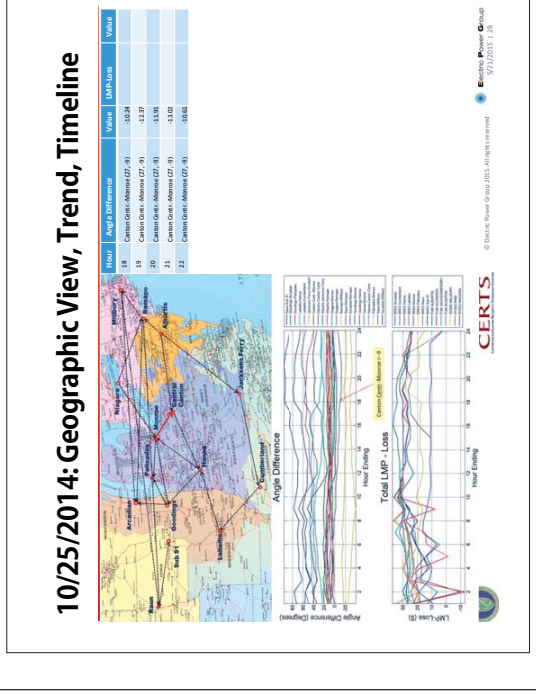
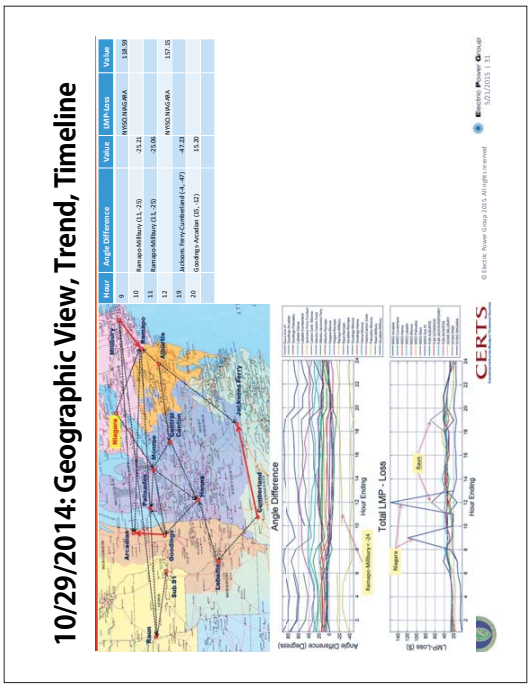
5/21/2015 | 26



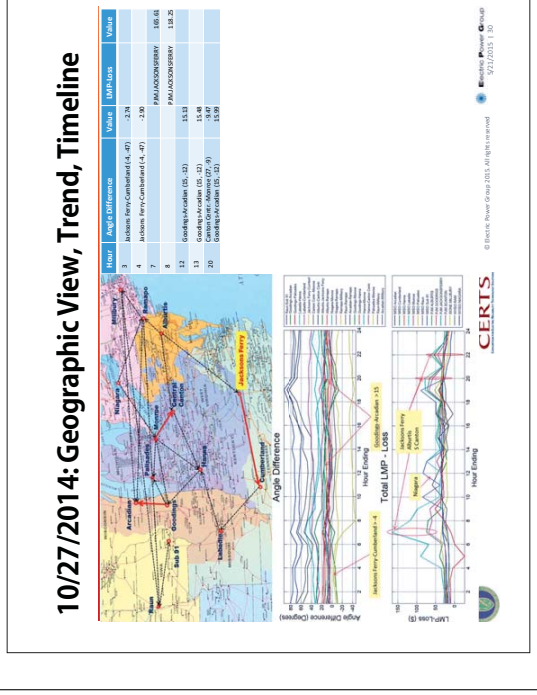

| Hour | Angle Difference | Value | LMP-Loss | Value |
|---|---|---|---|---|
| 3 | Hana-Moorse (45, -1) | -3.27 | | |
| | Jackson Ferry-Cumberland (-4, -47) | -3.24 | | |
| 4 | Hana-Moorse (45, -1) | -2.41 | | |
| | Jackson Ferry-Cumberland (-4, -47) | -2.09 | | |
| 5 | Hana-Moorse (45, -1) | -2.57 | | |
| | Jackson Ferry-Cumberland (-4, -47) | -1.04 | | |
| 6 | Hana-Moorse (45, -1) | -2.34 | | |
| | Jackson Ferry-Cumberland (-4, -47) | -2.39 | | |
| 20 | | | PJMJACKSONFERRY | 119.38 |




| Hour | Angle Difference | Value | LMP-Loss | Value |
|---|---|---|---|---|
| 18 | Canton Centr.-Monroe (27, -9) | -10.24 | | |
| 19 | Canton Centr.-Monroe (27, -9) | -12.37 | | |
| 20 | Canton Centr.-Monroe (27, -9) | -11.91 | | |
| 21 | Canton Centr.-Monroe (27, -9) | -13.02 | | |
| 22 | Canton Centr.-Monroe (27, -9) | -10.61 | | |

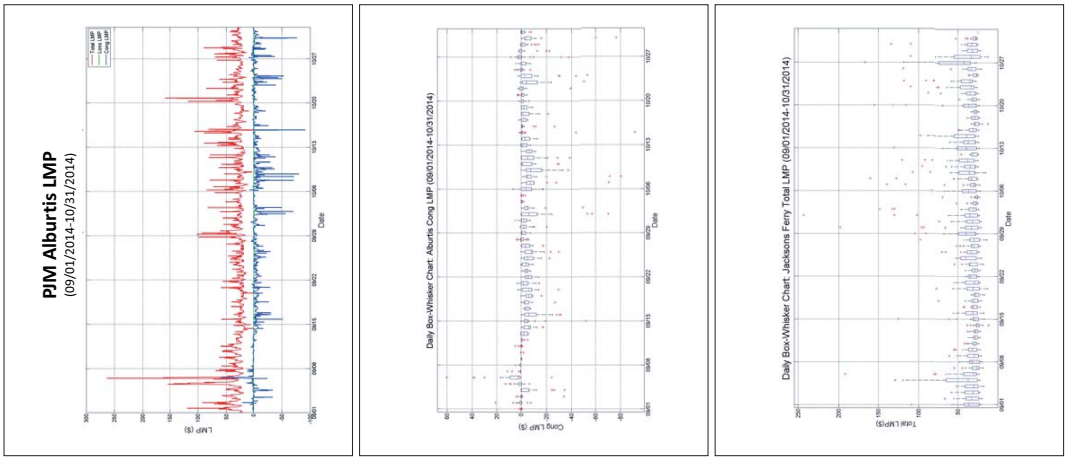


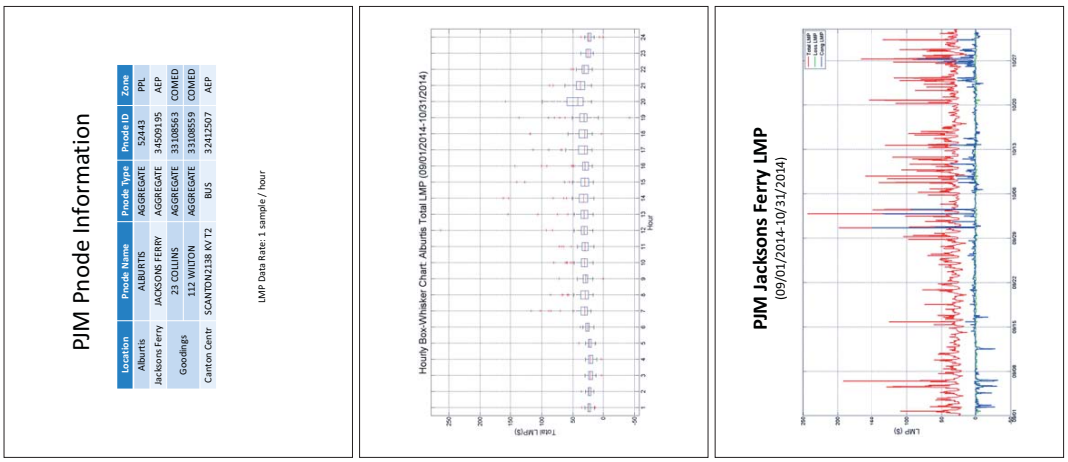

| Hour | Angle Difference | Value | LMP-Loss | Value |
|---|---|---|---|---|
| 9 | | | NYISO.NIG.RA | 118.59 |
| 10 | Ramapo-Mitbury (11, -23) | -23.21 | | |
| 11 | Ramapo-Mitbury (11, -23) | -23.06 | | |
| 12 | | | NYISO.NIG.RA | 157.35 |
| 19 | Jackson Ferry-Cumberland (-4, -47) | -47.23 | | |
| 20 | Goodings-Arcadian (35, -32) | 15.20 | | |




| Hour | Angle Difference | Value | LMP-Loss | Value |
|---|---|---|---|---|
| 3 | Jackson Ferry-Cumberland (-4, -47) | -2.74 | | |
| 4 | Jackson Ferry-Cumberland (-4, -47) | -2.90 | | |
| 7 | | | PJMJACKSONFERRY | 165.61 |
| 8 | | | PJMJACKSONFERRY | 118.25 |
| 12 | Goodings-Arcadian (35, -32) | 15.13 | | |
| 13 | Goodings-Arcadian (35, -32) | 15.48 | | |
| 20 | Canton Centr.-Monroe (27, -9) | -9.47 | | |
| | Goodings-Arcadian (35, -32) | 15.99 | | |

## 8.4 LMP Plots for Individual Buses



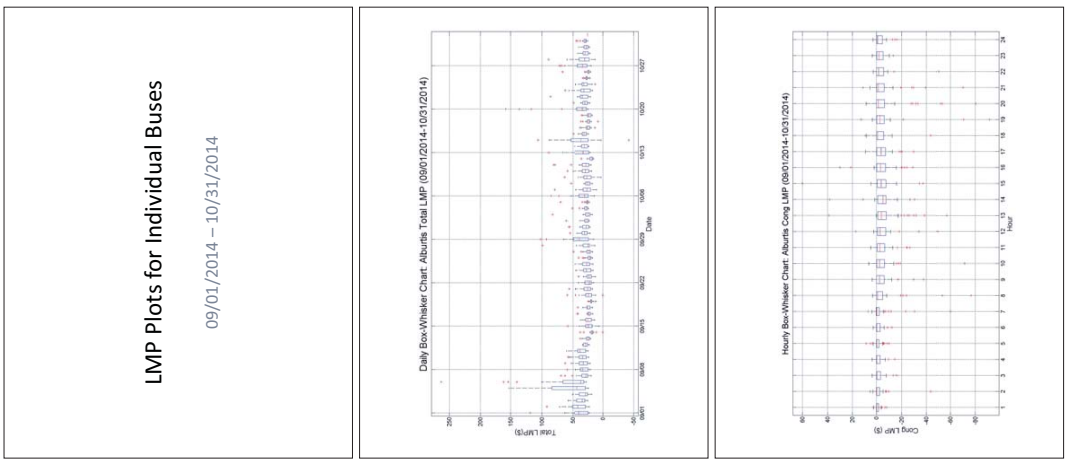



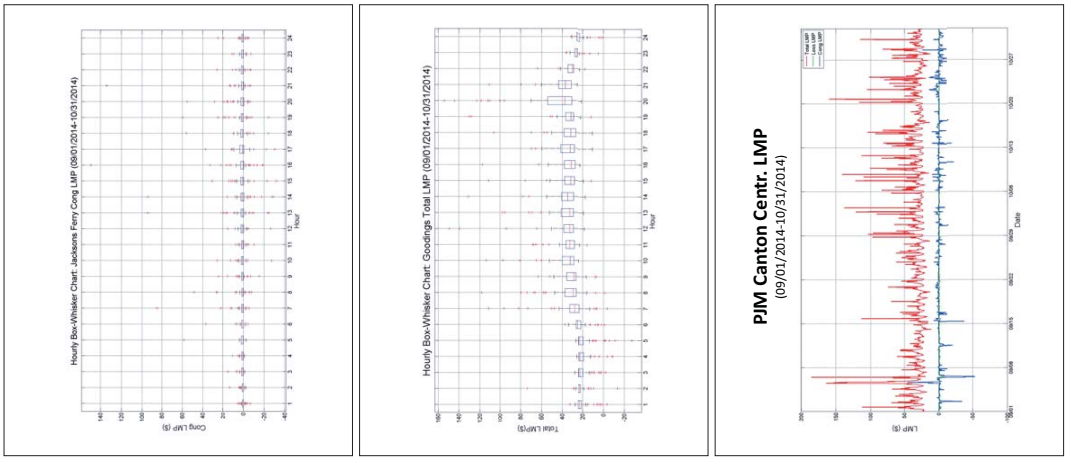
PJM Pnode Information

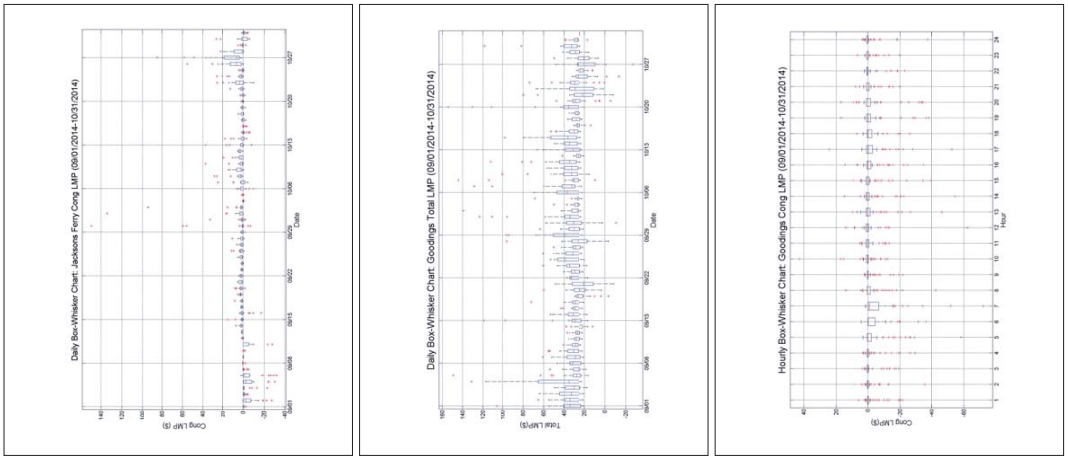
| Location | Pnode Name | Pnode Type | Pnode ID | Zone |
|---|---|---|---|---|
| Alburtis | ALBURTIS | AGGREGATE | 52443 | PPL |
| Jacksons Ferry | JACKSONS FERRY | AGGREGATE | 34509195 | AEP |
| Goodings | 23 COLLINS | AGGREGATE | 33108563 | COMED |
| | 112 WILTON | AGGREGATE | 33108559 | COMED |
| Canton Centr | SCANTON2138 KV T2 | BUS | 32412507 | AEP |

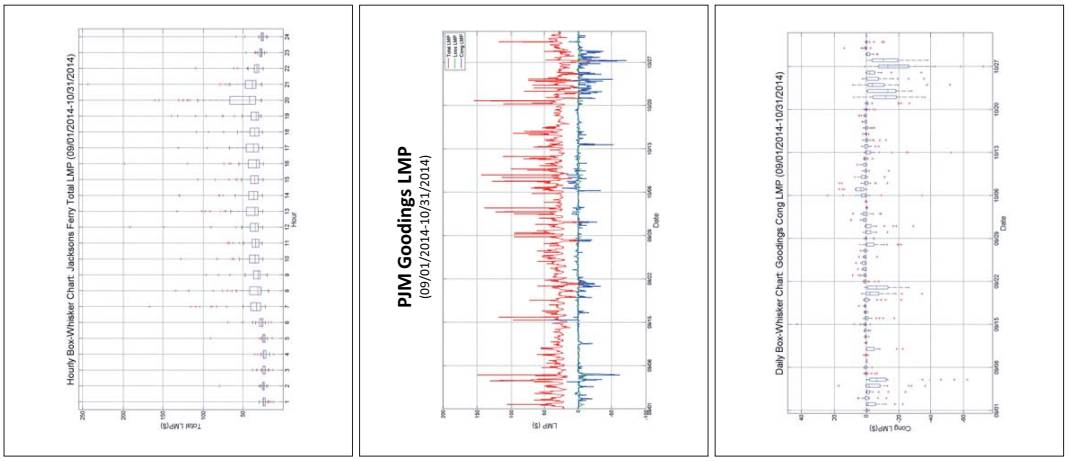
LMP Data Rate: 1 sample / hour

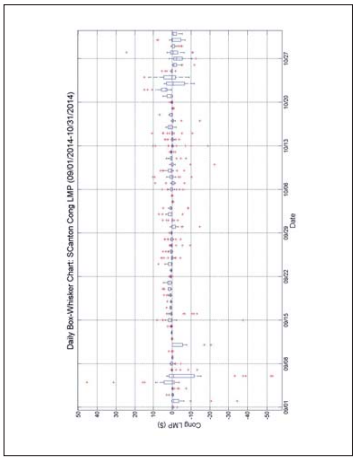


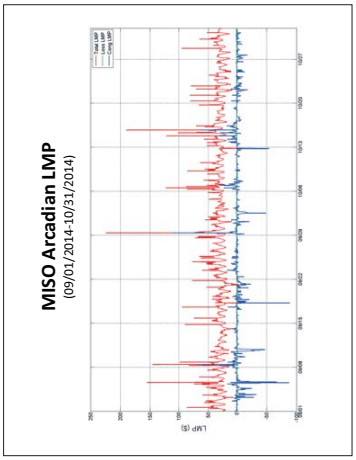


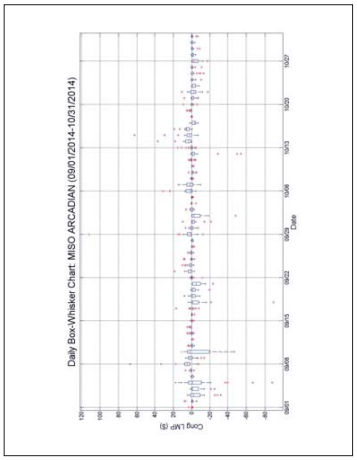

Hourly Box-Whisker Chart: Jacksons Ferry Cong LMP (09/01/2014-10/31/2014)
Cong LMP (S)
Hour
Hourly Box-Whisker Chart: Goodings Total LMP (09/01/2014-10/31/2014)
Total LMP(S)
Hour
PJM Canton Centr. LMP
(09/01/2014-10/31/2014)
LMP (S)
Date

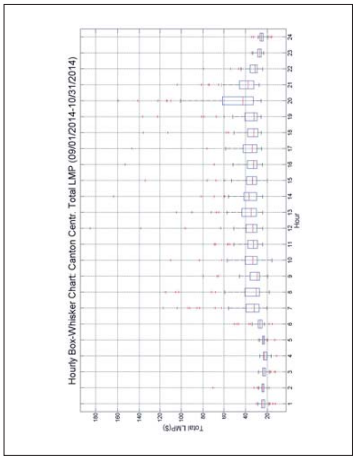

Daily Box-Whisker Chart: Jacksons Ferry Cong LMP (09/01/2014-10/31/2014)
Cong LMP (S)
Date
Daily Box-Whisker Chart: Goodings Total LMP (09/01/2014-10/31/2014)
Total LMP(S)
Date
Hourly Box-Whisker Chart: Goodings Cong LMP (09/01/2014-10/31/2014)
Cong LMP(S)
Hour


Hourly Box-Whisker Chart: Jacksons Ferry Total LMP (09/01/2014-10/31/2014)
Total LMP(S)
Hour
PJM Goodings LMP
(09/01/2014-10/31/2014)
LMP (S)
Date
Daily Box-Whisker Chart: Goodings Cong LMP (09/01/2014-10/31/2014)
Cong LMP(S)
Date



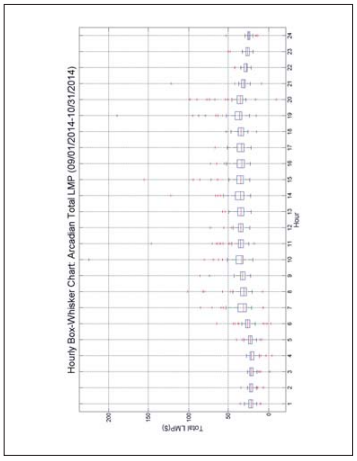



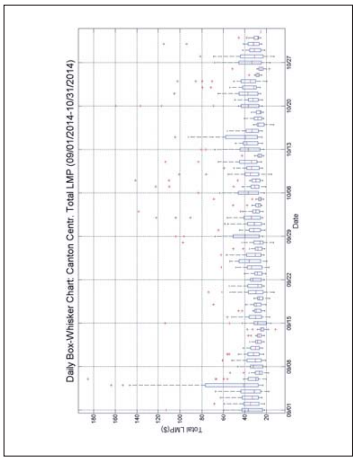



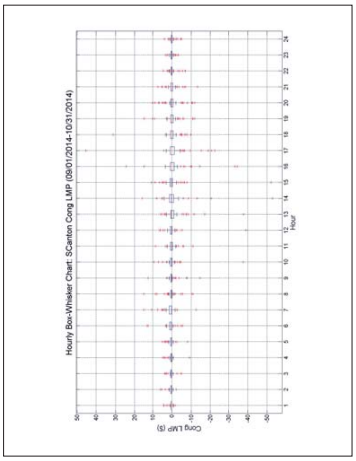

## MISO Pnode Information

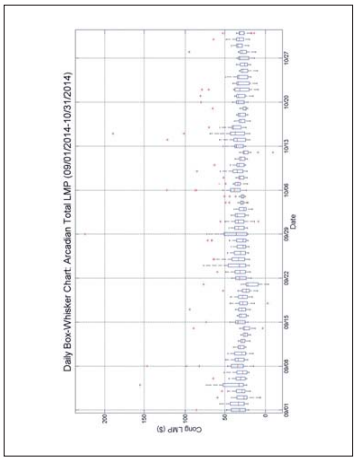
| Bus Name | Node Name |
|---|---|
| Arcadian | WC.FRG1<br>WC.FRG2 |
| Cumberland | EAI.PLUM1A_TFA<br>EAI.PLUM_1C<br>DAI.PLUM_2PEA |
| Hanna | AMMO.HANN_1A2 |
| Labadie | AMMO.LABGE1<br>AMMO.LABGE2<br>AMMO.LABGE3<br>AMMO.LABGE4 |
| Monroe | DECO.MONR2E1<br>DECO.MONR2E2<br>DECO.MONR2E3<br>DECO.MONR2E4 |
| Palisades | CONS.PALISADA1 |
| Raun | MEC.NEAUN_1<br>MEC.NEAUN_2<br>MEC.NEAUN_3<br>MEC.NEAUN_4 |
| Sub 91 | MEC.LOUSA_1 |

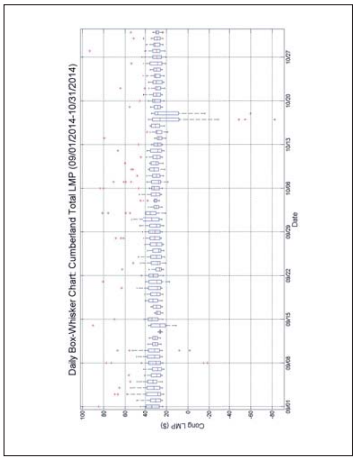
LMP Data Rate: 1 sample / hour

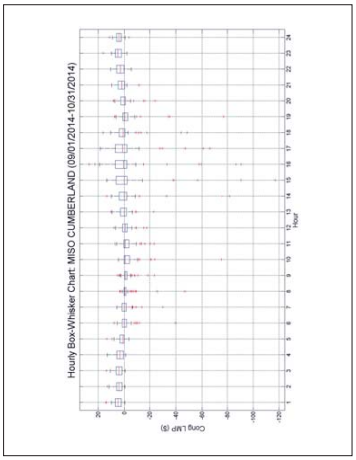


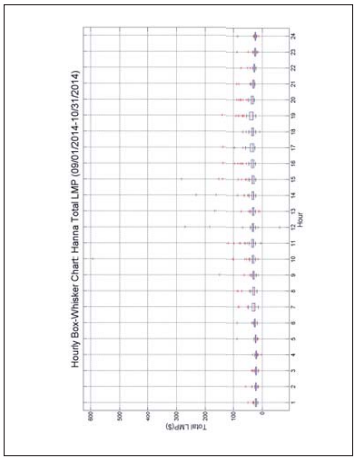



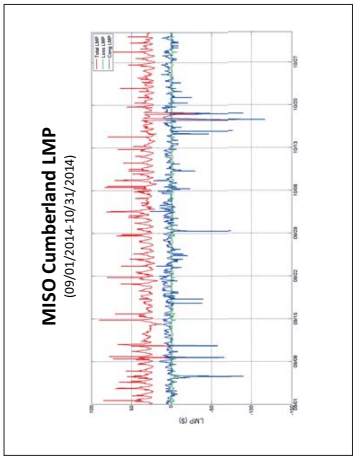



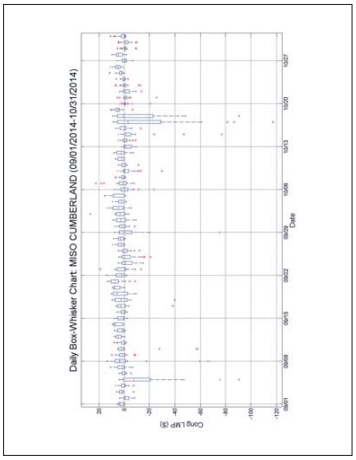



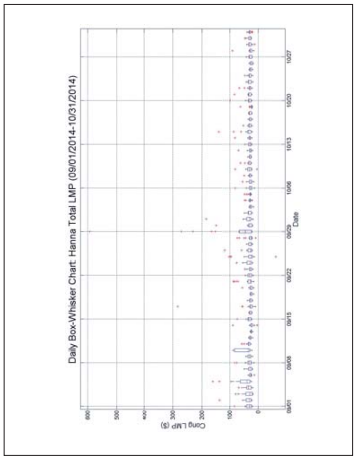

Daily Box-Whisker Chart: Cumberland Total LMP (09/01/2014-10/31/2014)
Congestion LMP ($)
Date

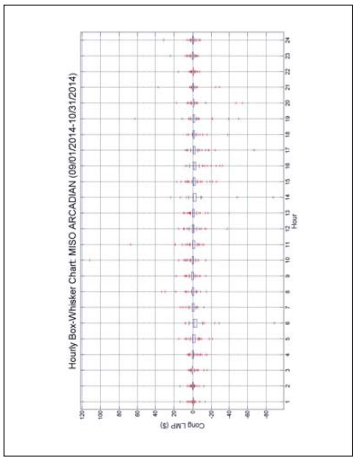

Hourly Box-Whisker Chart: MISO CUMBERLAND (09/01/2014-10/31/2014)
Congestion LMP ($)
Hour

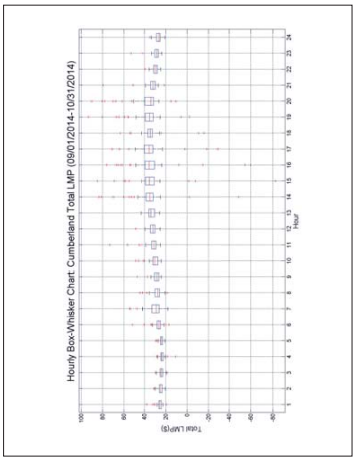

Hourly Box-Whisker Chart: Hanna Total LMP (09/01/2014-10/31/2014)
Total LMP($)
Hour

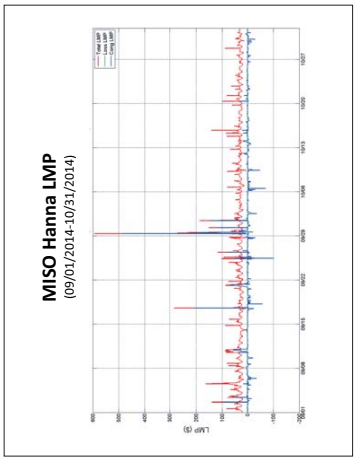

MISO Cumberland LMP
(09/01/2014-10/31/2014)
LMP ($)

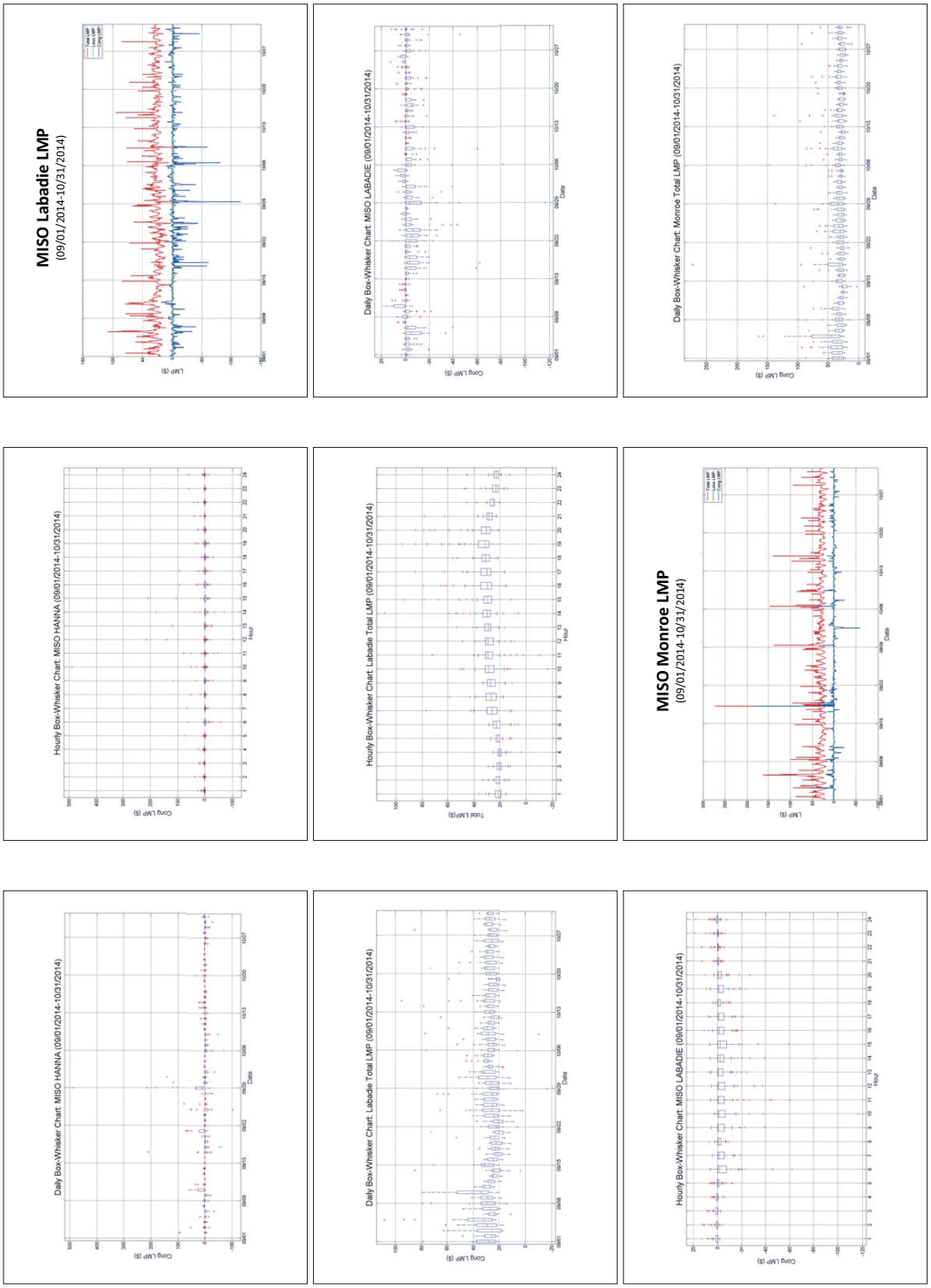

Daily Box-Whisker Chart: MISO CUMBERLAND (09/01/2014-10/31/2014)
Congestion LMP ($)
Date

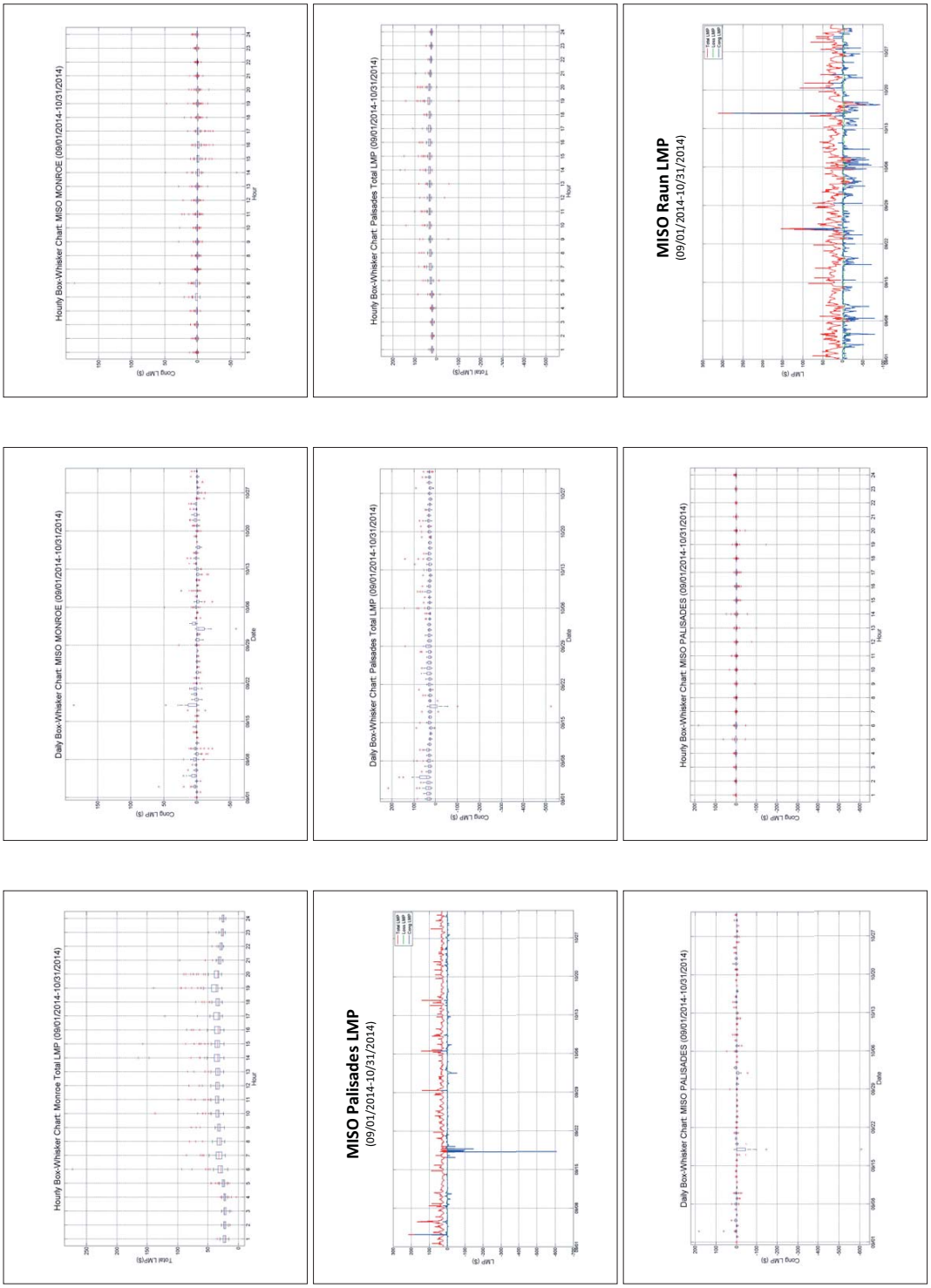

Daily Box-Whisker Chart: Hanna Total LMP (09/01/2014-10/31/2014)
Congestion LMP ($)
Date

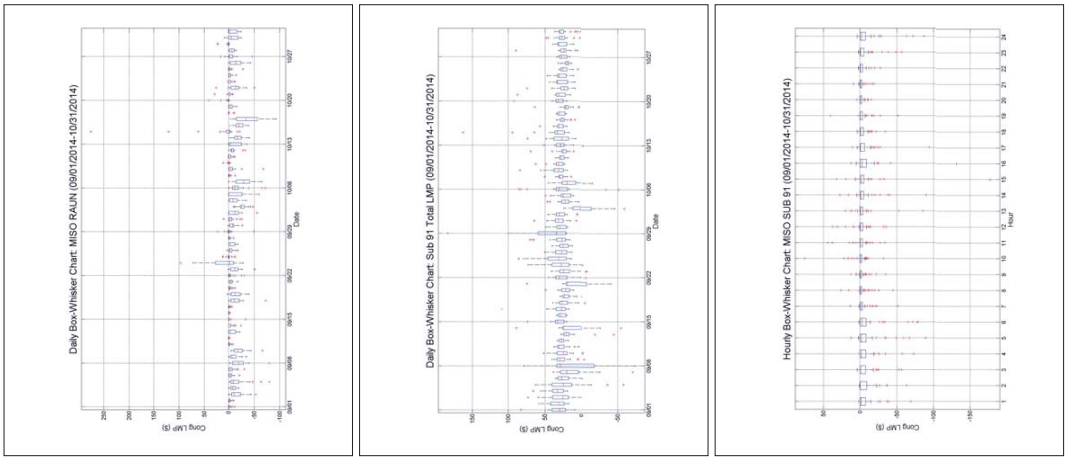

Hourly Box-Whisker Chart: MISO ARCADIAN (09/01/2014-10/31/2014)
Congestion LMP ($)
Hour

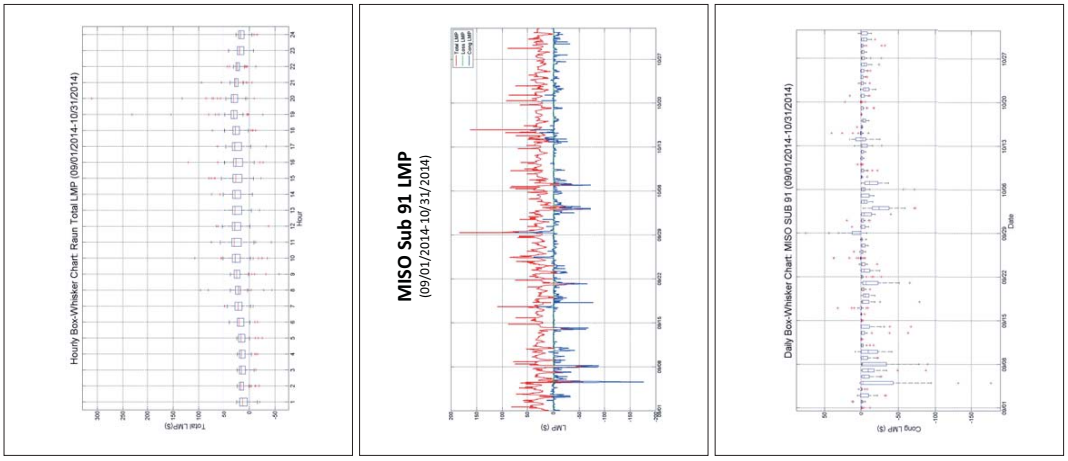

Hourly Box-Whisker Chart: Cumberland Total LMP (09/01/2014-10/31/2014)
Total LMP($)
Hour

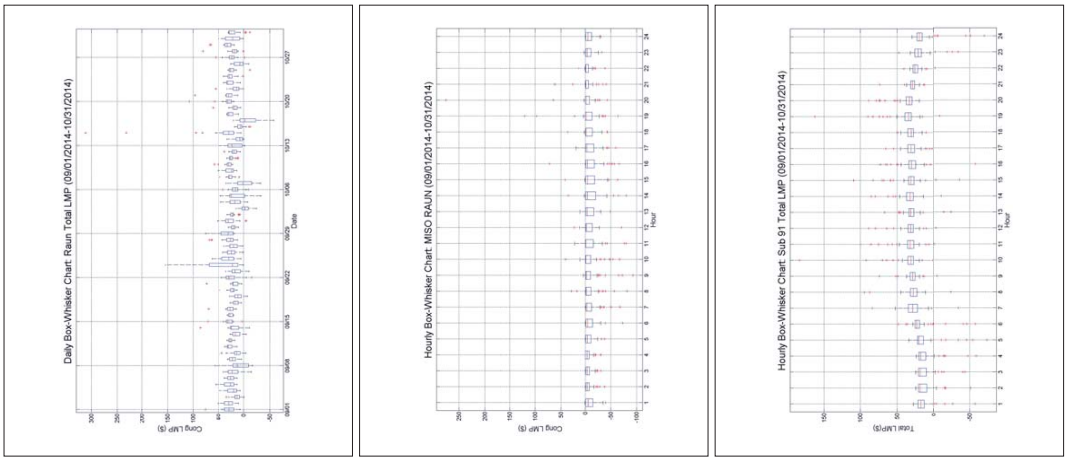

MISO Hanna LMP
(09/01/2014-10/31/2014)
LMP ($)

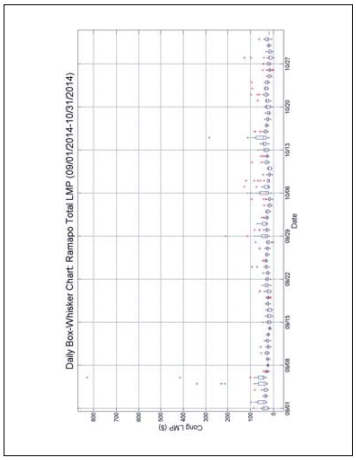

MISO Labadie LMP
(09/01/2014-10/31/2014)
Daily Box-Whisker Chart: MISO LABADIE (09/01/2014-10/31/2014)
Daily Box-Whisker Chart: Monroe Total LMP (09/01/2014-10/31/2014)
Hourly Box-Whisker Chart: MISO HANNA (09/01/2014-10/31/2014)
Hourly Box-Whisker Chart: Labadie Total LMP (09/01/2014-10/31/2014)
MISO Monroe LMP
(09/01/2014-10/31/2014)
Daily Box-Whisker Chart: MISO HANNA (09/01/2014-10/31/2014)
Daily Box-Whisker Chart: Labadie Total LMP (09/01/2014-10/31/2014)
Hourly Box-Whisker Chart: MISO LABADIE (09/01/2014-10/31/2014)

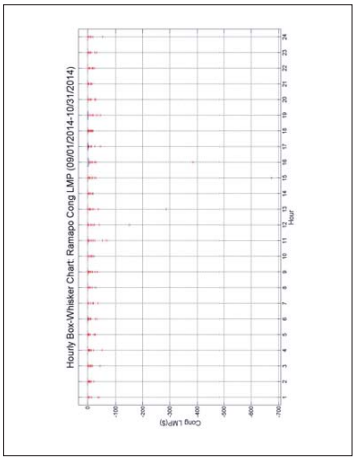

Hourly Box-Whisker Chart: MISO MONROE (09/01/2014-10/31/2014)
Hourly Box-Whisker Chart: Palisades Total LMP (09/01/2014-10/31/2014)
MISO Raun LMP
(09/01/2014-10/31/2014)
Daily Box-Whisker Chart: MISO MONROE (09/01/2014-10/31/2014)
Daily Box-Whisker Chart: Palisades Total LMP (09/01/2014-10/31/2014)
Hourly Box-Whisker Chart: MISO PALISADES (09/01/2014-10/31/2014)
Hourly Box-Whisker Chart: Monroe Total LMP (09/01/2014-10/31/2014)
MISO Palisades LMP
(09/01/2014-10/31/2014)
Daily Box-Whisker Chart: MISO PALISADES (09/01/2014-10/31/2014)

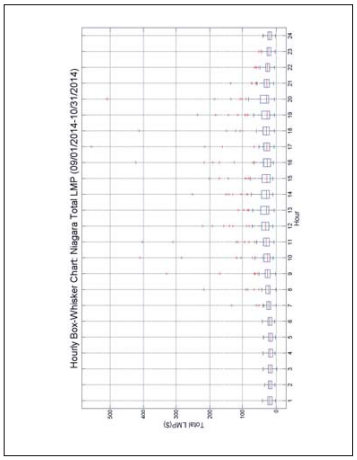

Daily Box-Whisker Chart: MISO RAUN (09/01/2014-10/31/2014)
Cong LMP ($)
Date
Daily Box-Whisker Chart: Sub 91 Total LMP (09/01/2014-10/31/2014)
Cong LMP ($)
Date
Hourly Box-Whisker Chart: MISO SUB 91 (09/01/2014-10/31/2014)
Cong LMP ($)
Hour

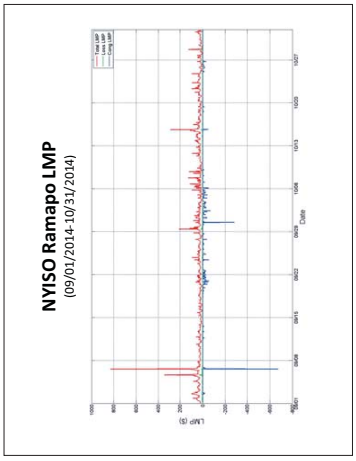

Hourly Box-Whisker Chart: Raun Total LMP (09/01/2014-10/31/2014)
Total LMP($)
Hour
MISO Sub 91 LMP
(09/01/2014-10/31/2014)
LMP ($)
Daily Box-Whisker Chart: MISO SUB 91 (09/01/2014-10/31/2014)
Cong LMP ($)
Date

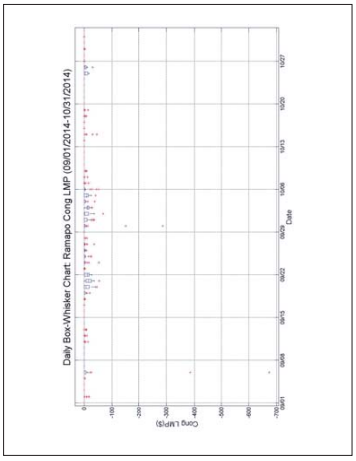

Daily Box-Whisker Chart: Raun Total LMP (09/01/2014-10/31/2014)
Cong LMP ($)
Date
Hourly Box-Whisker Chart: MISO RAUN (09/01/2014-10/31/2014)
Cong LMP ($)
Hour
Hourly Box-Whisker Chart: Sub 91 Total LMP (09/01/2014-10/31/2014)
Total LMP($)
Hour

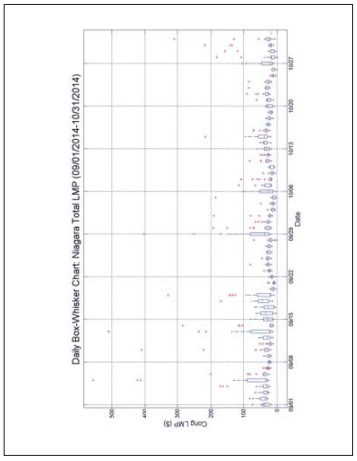


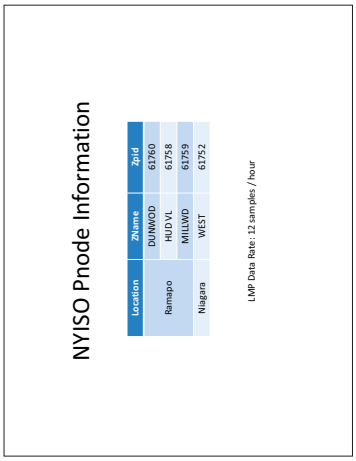



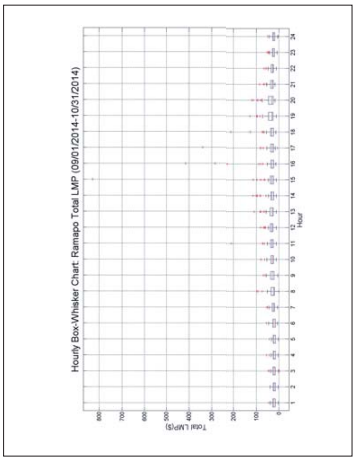



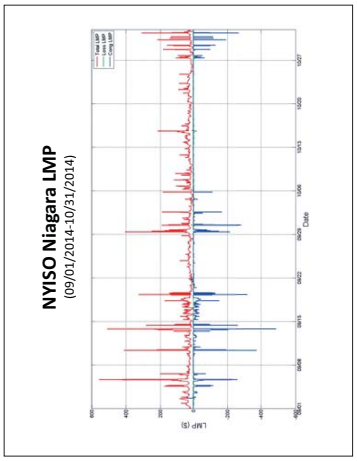



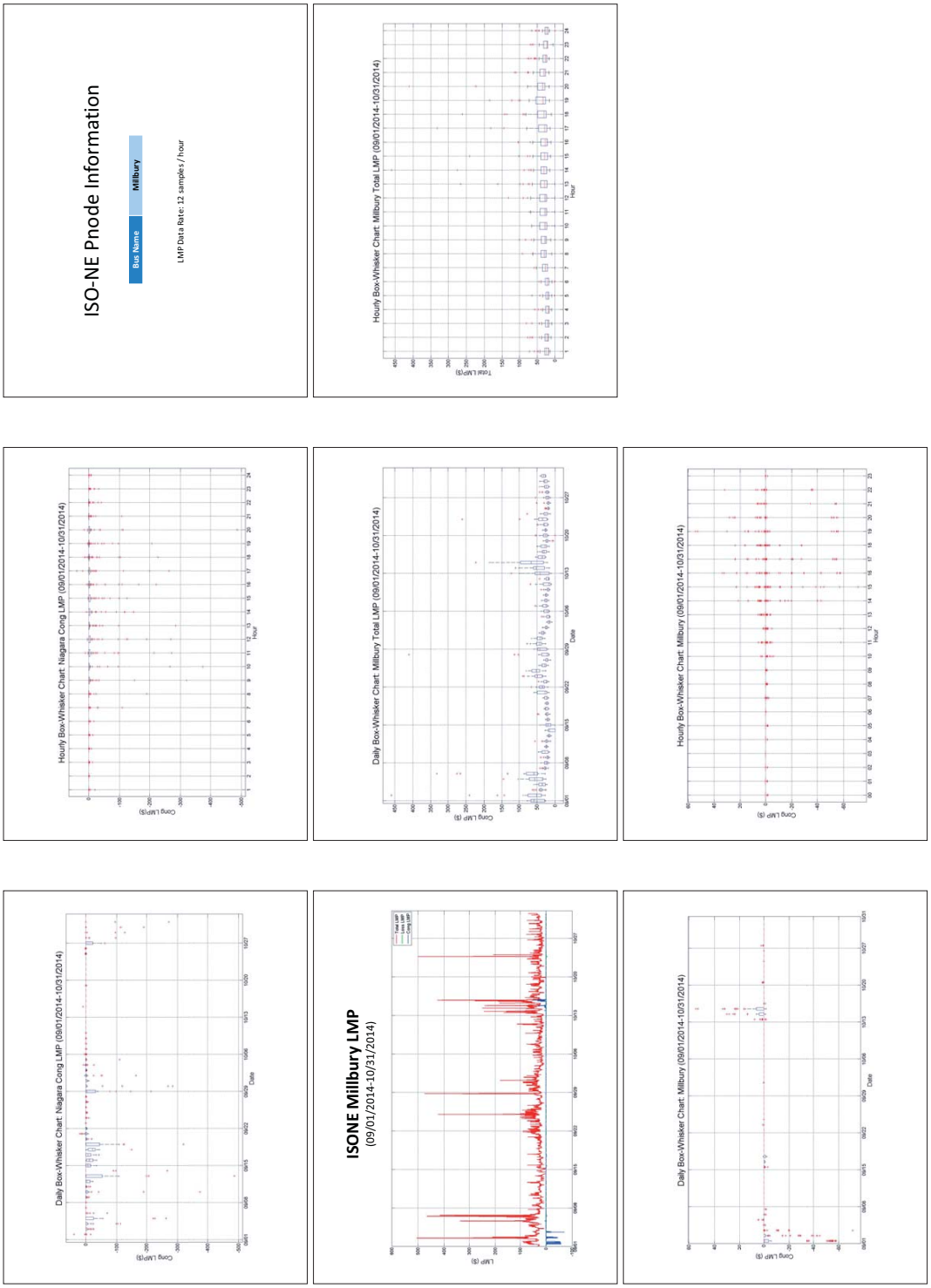
NYISO Pnode Information

| Location | ZName | Zpid |
|---|---|---|
| Ramapo | DUNWOD | 61760 |
| | HUDVL | 61758 |
| | MILLWD | 61759 |
| Niagara | WEST | 61752 |

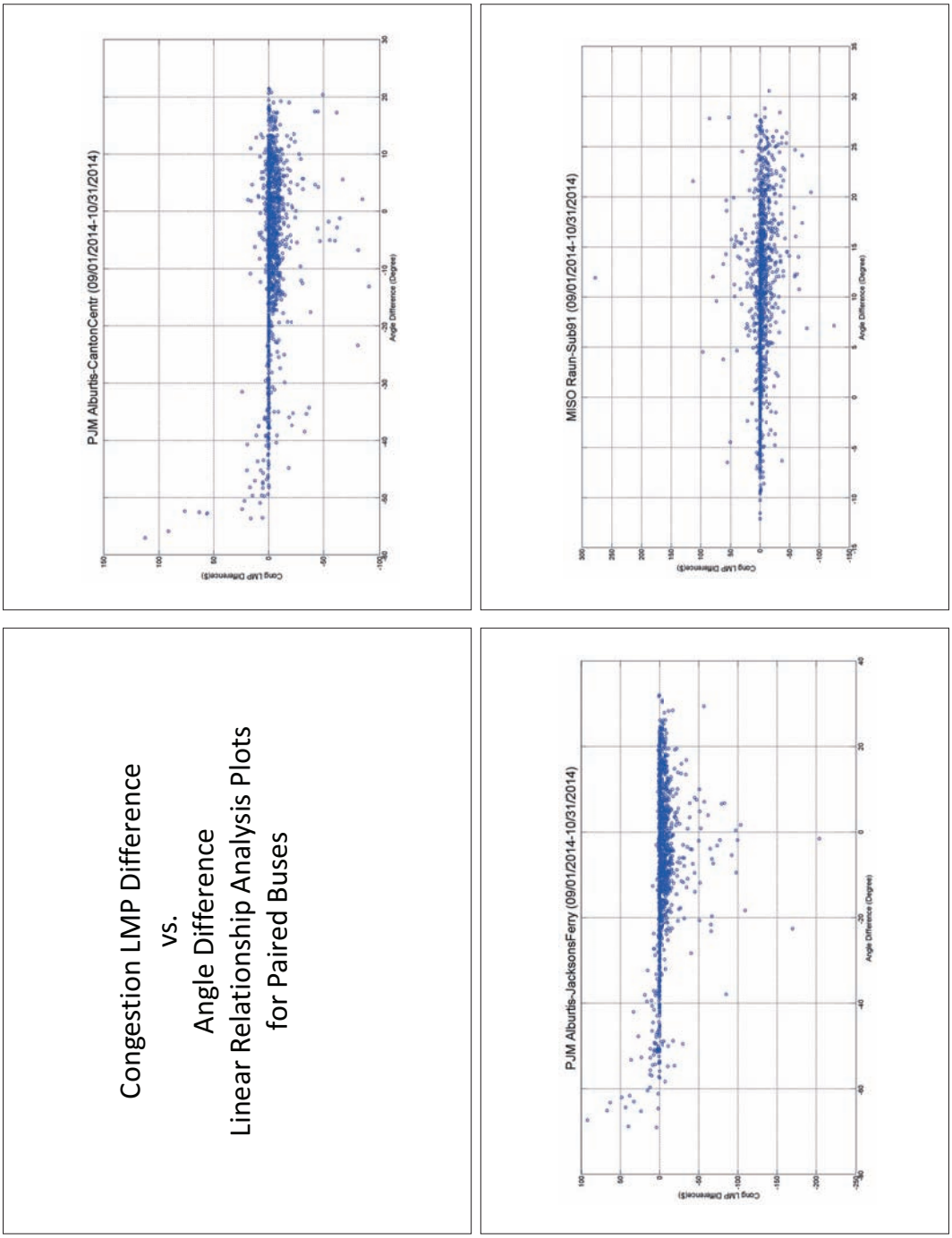
LMP Data Rate: 12 samples / hour

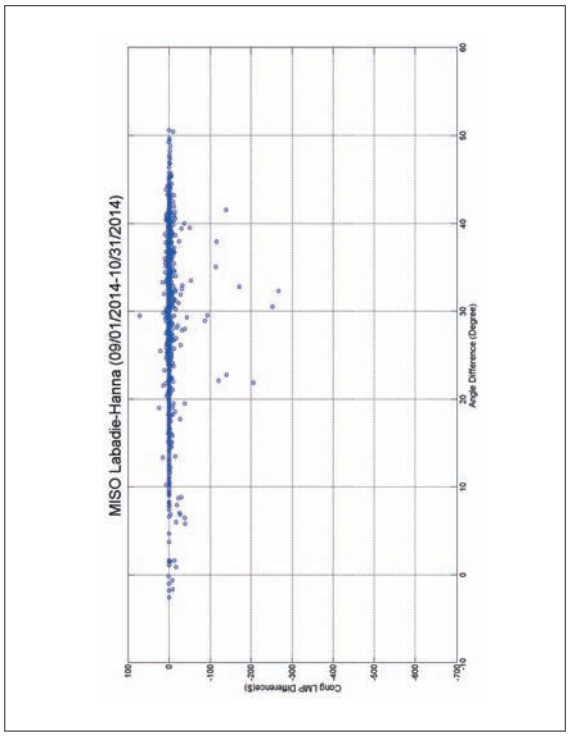


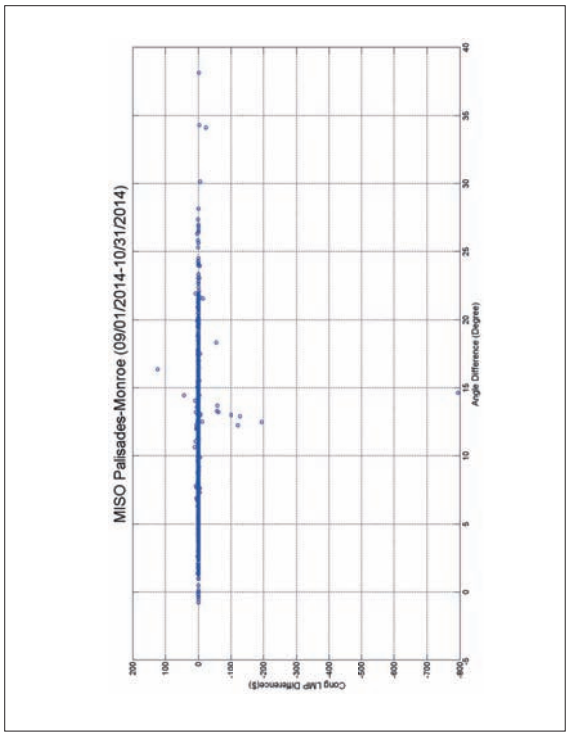



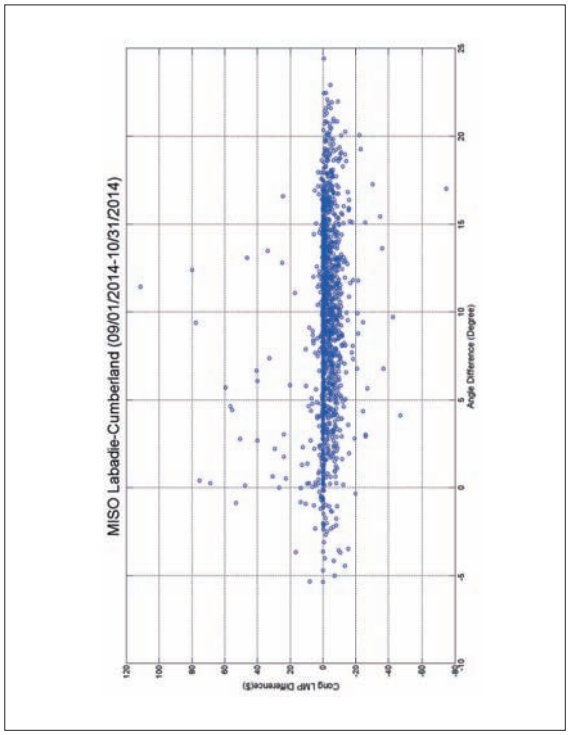

ISO-NE Pnode Information
Bus Name
Millbury
LMP Data Rate: 12 samples / hour
Hourly Box-Whisker Chart: Millbury Total LMP (09/01/2014-10/31/2014)
Total LMP ($)
Hour
Hourly Box-Whisker Chart: Nagara Cong LMP (09/01/2014-10/31/2014)
Cong LMP ($)
Hour
Daily Box-Whisker Chart: Millbury Total LMP (09/01/2014-10/31/2014)
Cong LMP ($)
Date
Hourly Box-Whisker Chart: Millbury (09/01/2014-10/31/2014)
Cong LMP ($)
Hour
Daily Box-Whisker Chart: Nagara Cong LMP (09/01/2014-10/31/2014)
Cong LMP ($)
Date
ISONE Millbury LMP
(09/01/2014-10/31/2014)
LMP ($)
Daily Box-Whisker Chart: Millbury (09/01/2014-10/31/2014)
Cong LMP ($)
Date

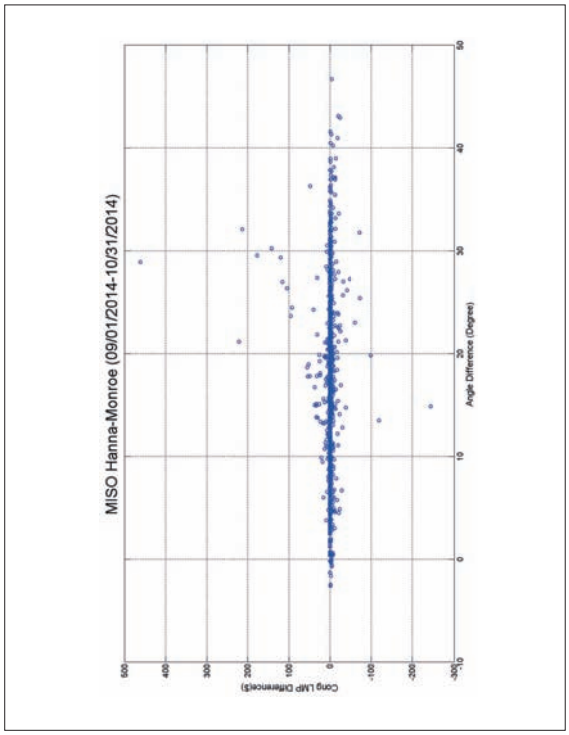
## 8.5 Scatter Plot for CongLMPDiff Vs AngleDiff

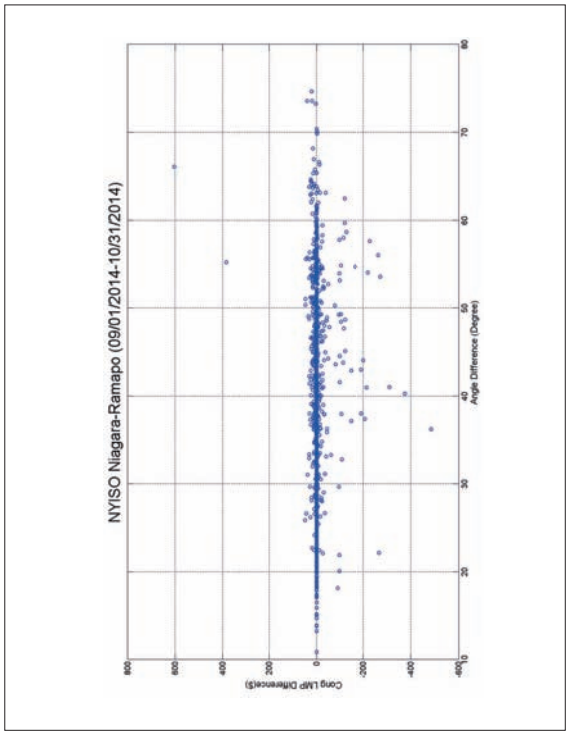



MISO Labadie-Hanna (09/01/2014-10/31/2014)
Cong LMP Difference($)
Angle Difference (Degree)

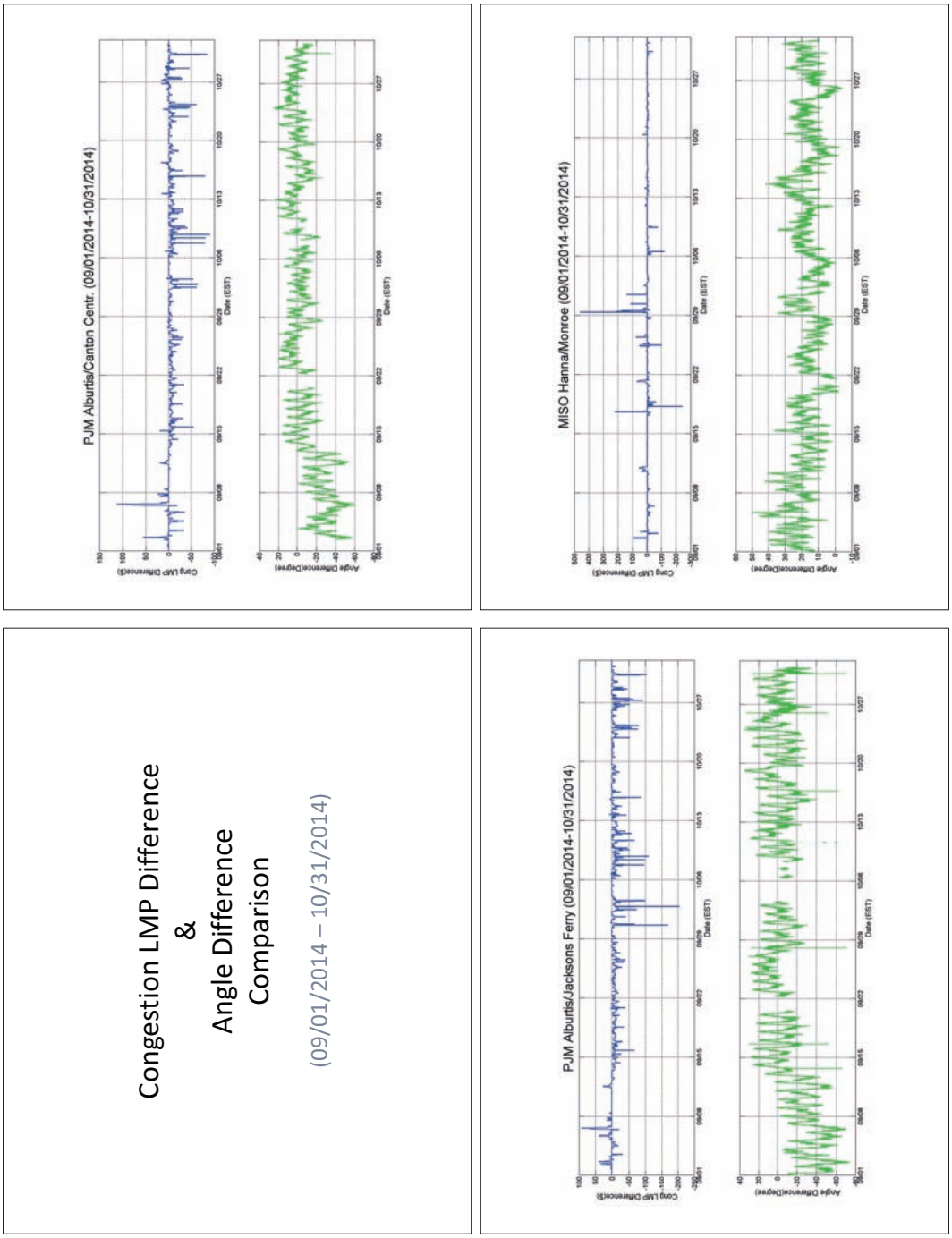

MISO Palisades-Monroe (09/01/2014-10/31/2014)
Cong LMP Difference($)
Angle Difference (Degree)

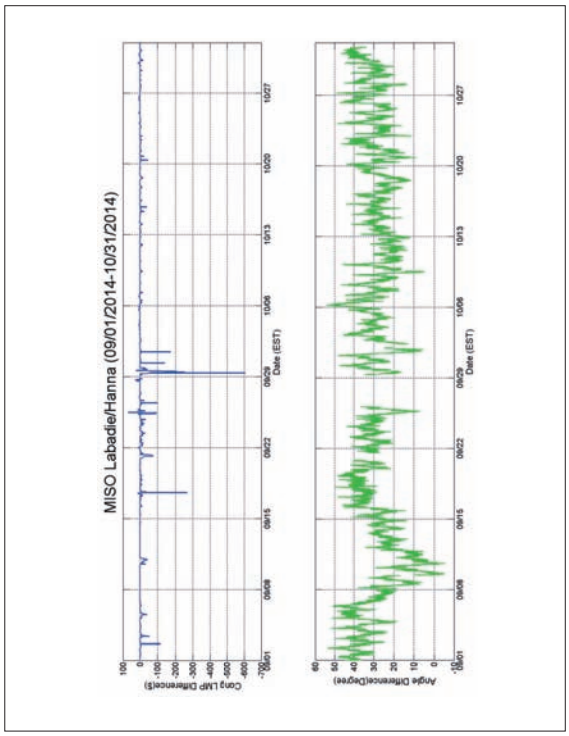

MISO Labadie-Cumberland (09/01/2014-10/31/2014)
Cong LMP Difference($)
Angle Difference (Degree)

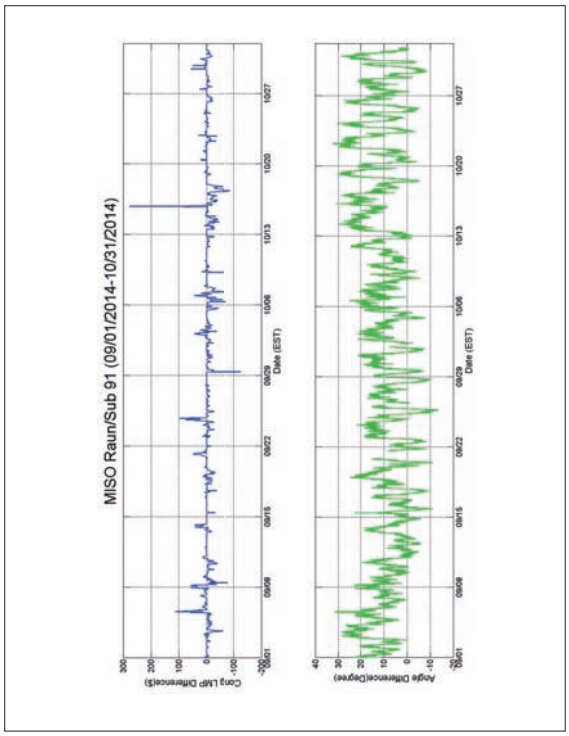

MISO Hanna-Monroe (09/01/2014-10/31/2014)
Cong LMP Difference($)
Angle Difference (Degree)

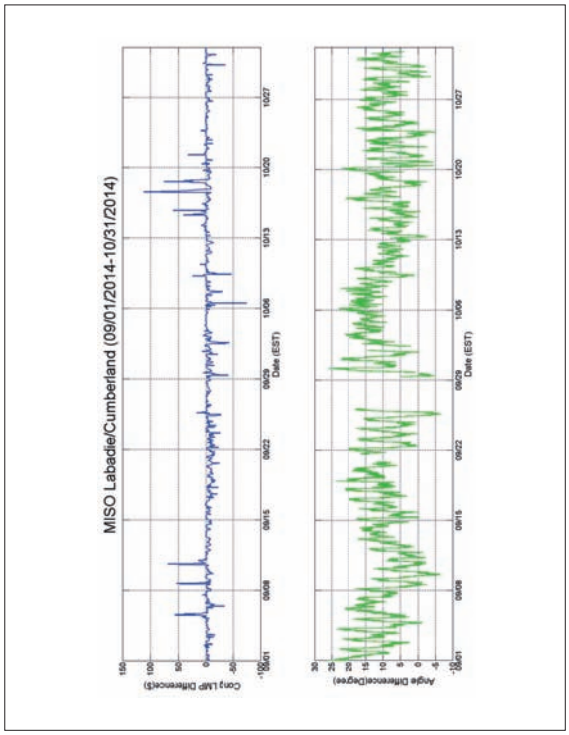

NYISO Niagara-Ramapo (09/01/2014-10/31/2014)
Cong LMP Difference($)
800
600
400
200
0
-200
-400
-600
10
20
30
40
50
60
70
80
Angle Difference (Degree)

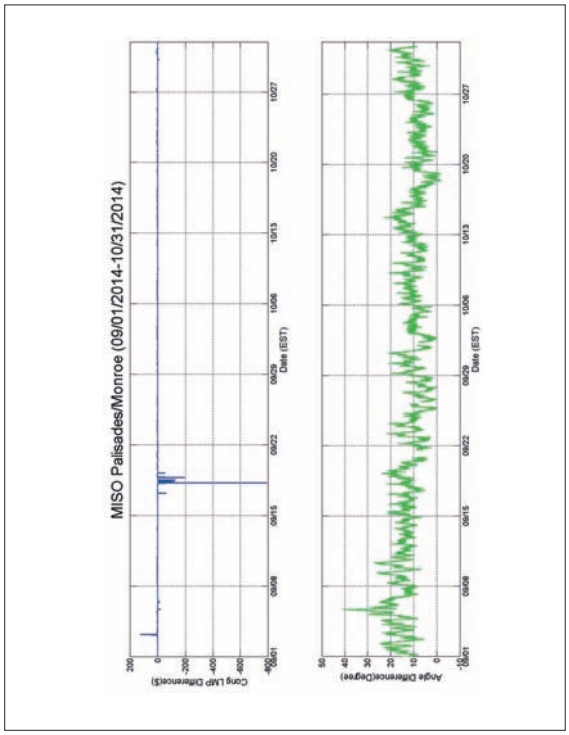
## 8.6 Comparison CongLMPDiff Vs. AngleDiff

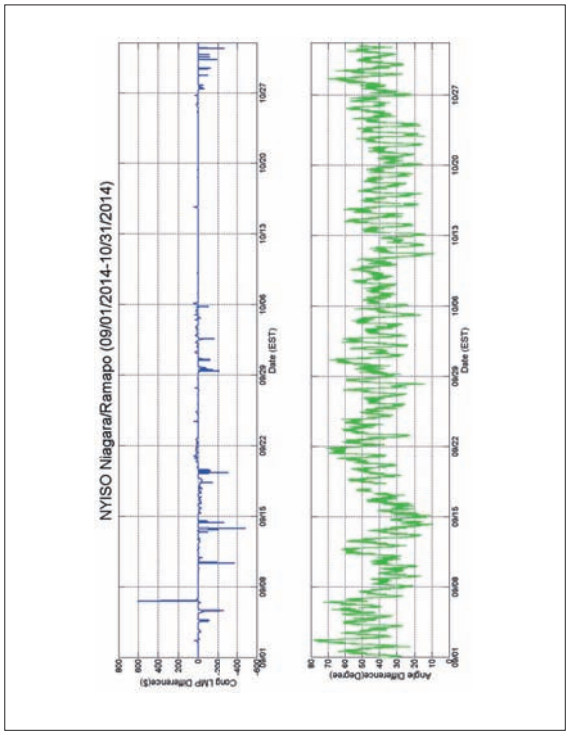



MISO Labadie/Hanna (09/01/2014-10/31/2014)
Cong LMP Difference(s)
Angle Difference(Degree)
Date (EST)

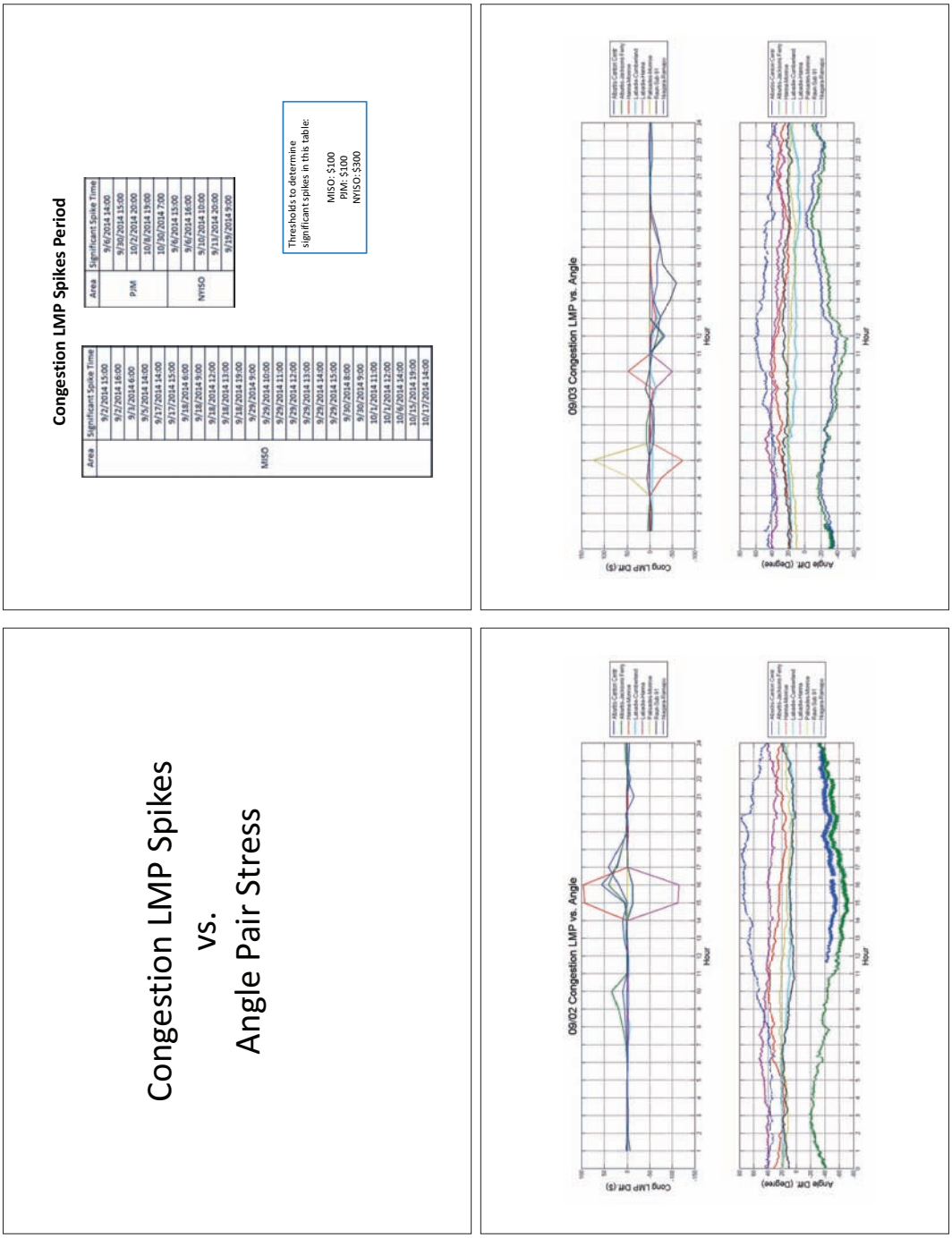

MISO Raun/Sub 91 (09/01/2014-10/31/2014)
Cong LMP Difference(s)
Angle Difference(Degree)
Date (EST)

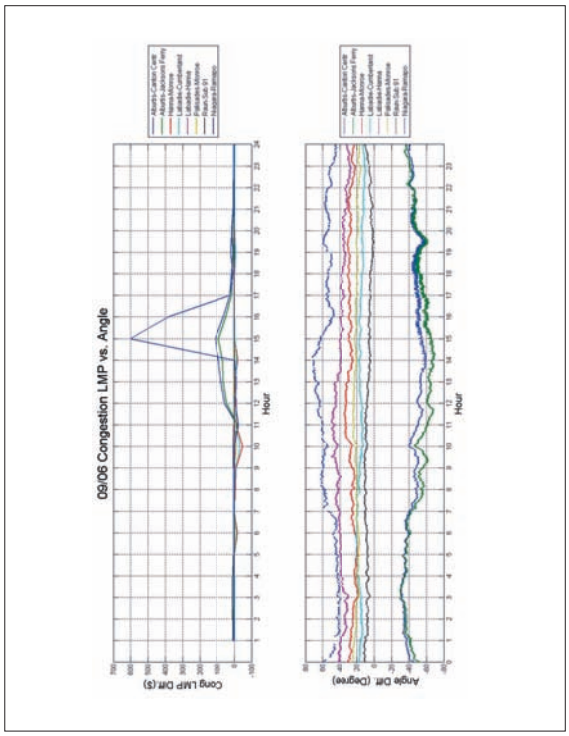

MISO Labadie/Cumberland (09/01/2014-10/31/2014)
Cong LMP Difference(s)
Angle Difference(Degree)
Date (EST)

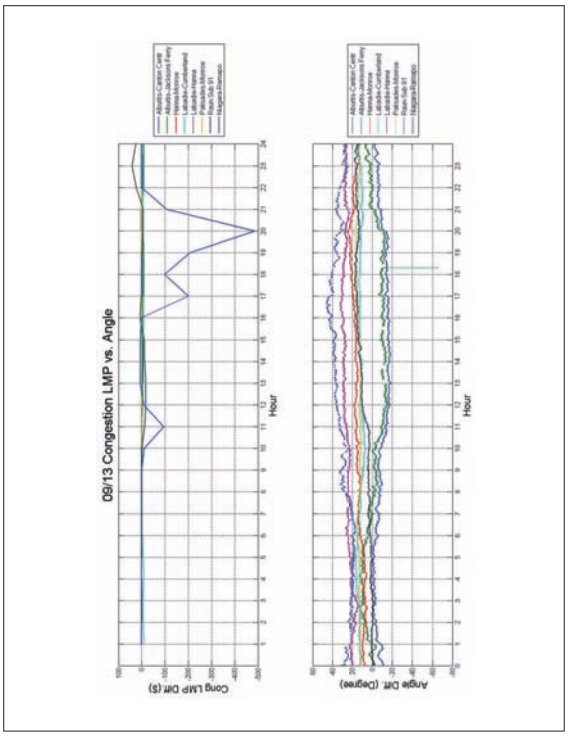

MISO Palisades/Monroe (09/01/2014-10/31/2014)
Cong LMP Difference(s)
Angle Difference(Degree)
Date (EST)

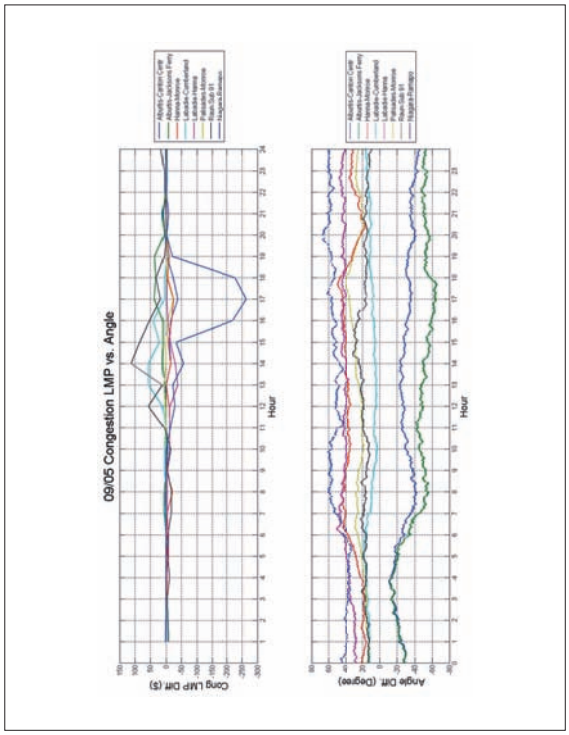

NYISO Niagara/Ramapo (09/01/2014-10/31/2014)
Cong LMP Difference($)
Date (EST)
Angle Difference(Degree)
Date (EST)

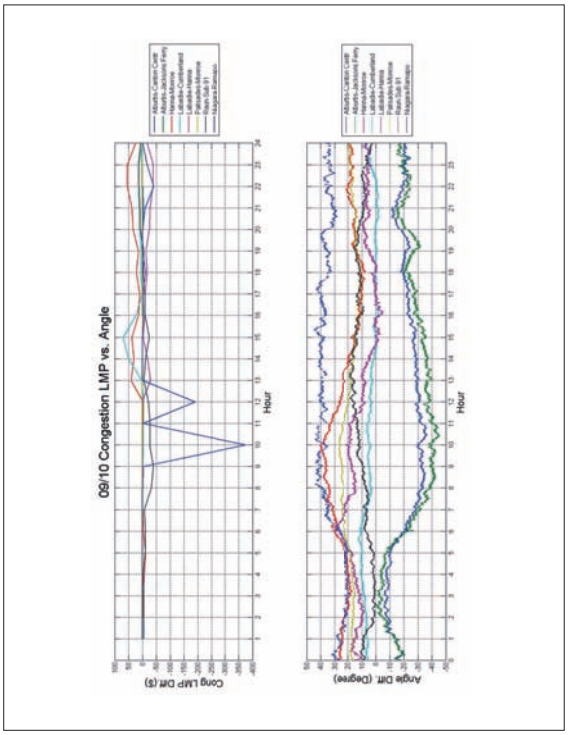
## 8.7 CongLMP Spikes

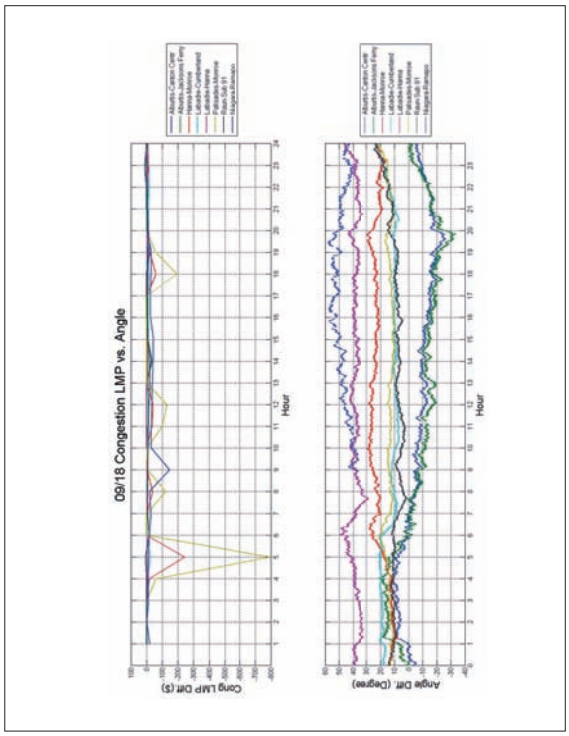


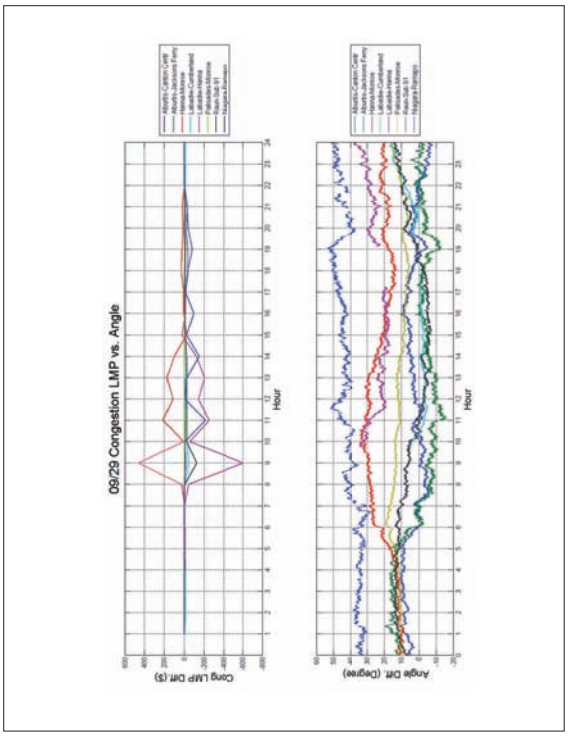

09/06 Congestion LMP vs. Angle
Cong LMP Diff ($)
Angle Diff (Degree)
Hour

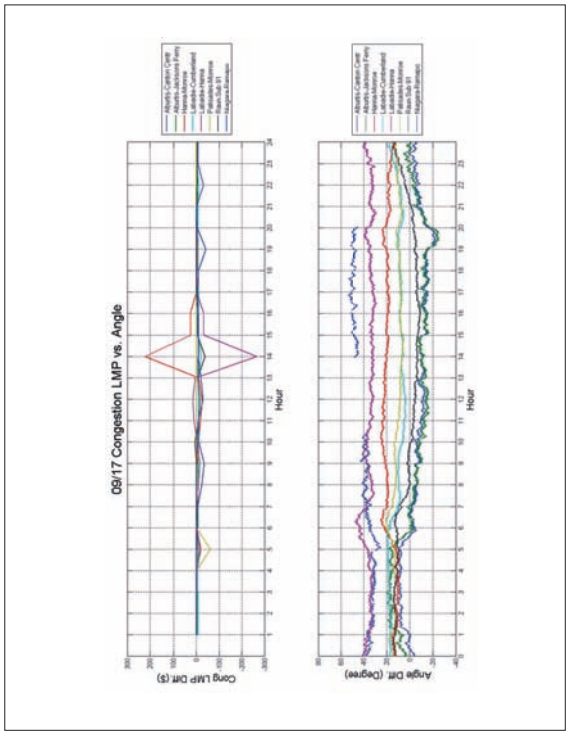

09/13 Congestion LMP vs. Angle
Cong LMP Diff ($)
Angle Diff (Degree)
Hour

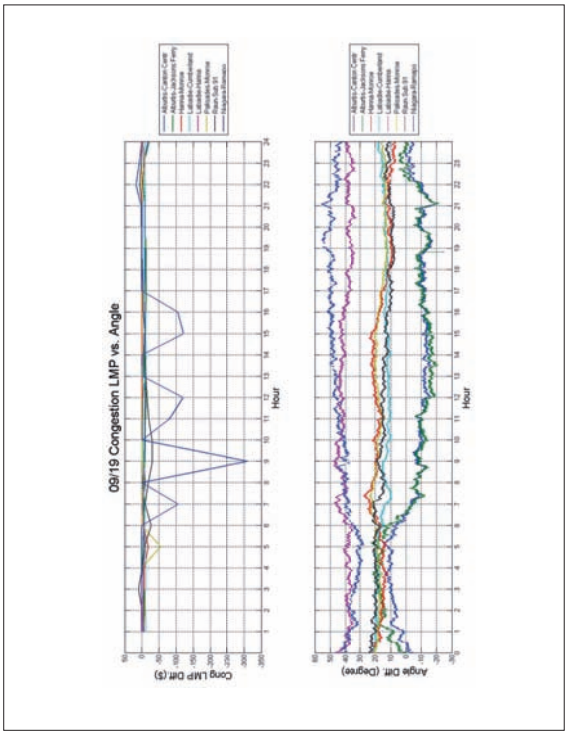

09/05 Congestion LMP vs. Angle
Cong LMP Diff ($)
Angle Diff (Degree)
Hour

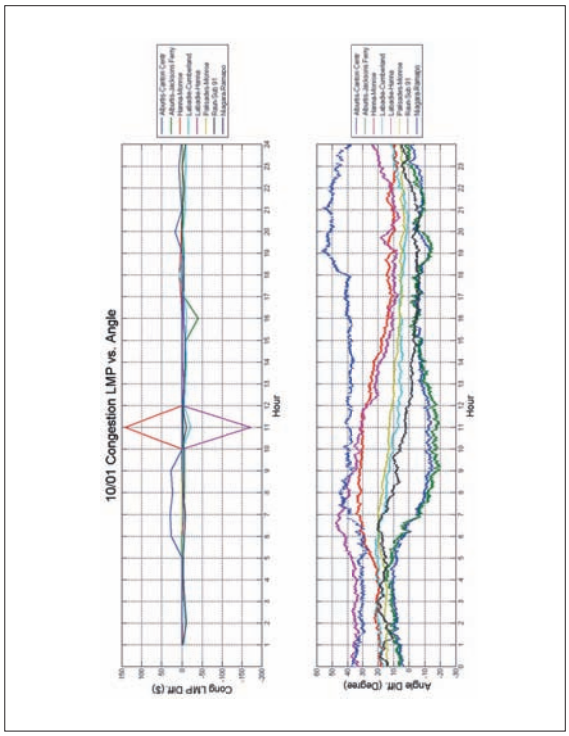

09/10 Congestion LMP vs. Angle
Cong LMP Diff ($)
Angle Diff (Degree)
Hour

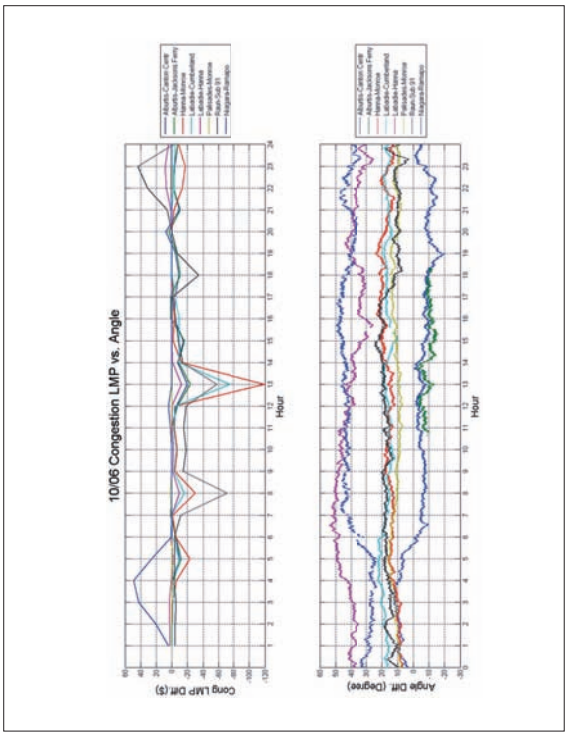

09/18 Congestion LMP vs. Angle
Cong LMP Diff ($)
Angle Diff. (Degree)
Hour

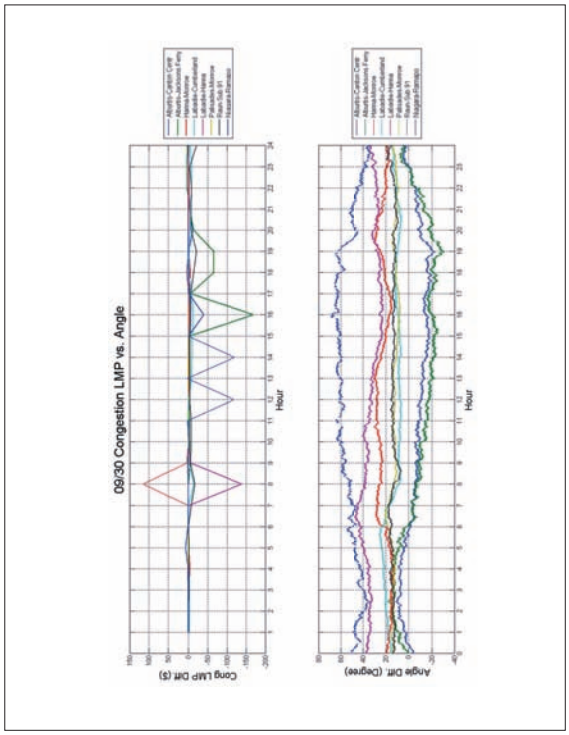

09/29 Congestion LMP vs. Angle
Cong LMP Diff ($)
Angle Diff. (Degree)
Hour

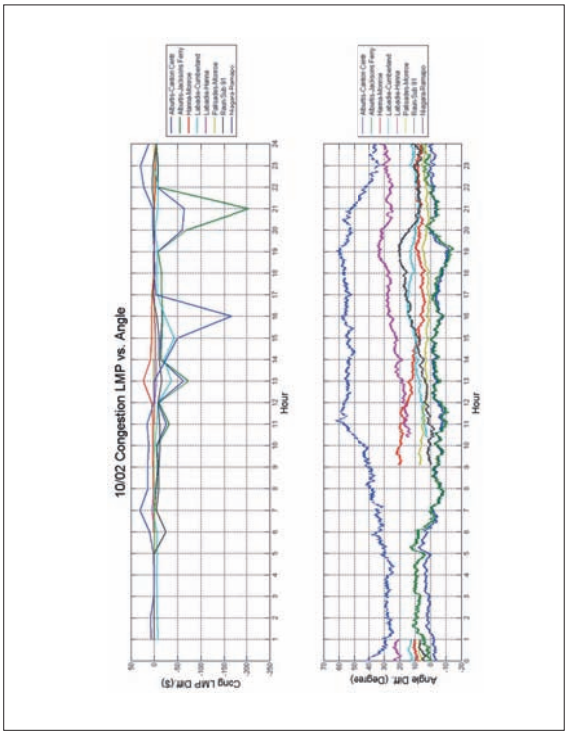

09/17 Congestion LMP vs. Angle
Cong LMP Diff ($)
Angle Diff. (Degree)
Hour

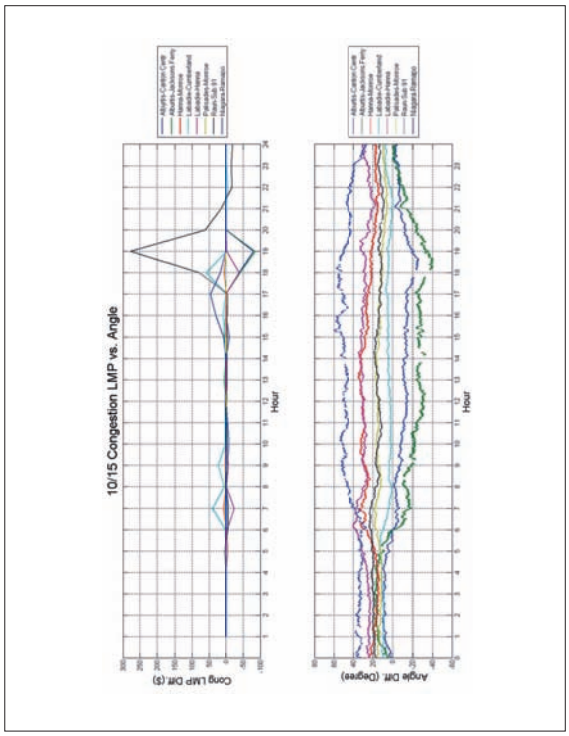

09/19 Congestion LMP vs. Angle
Cong LMP Diff ($)
Angle Diff. (Degree)
Hour

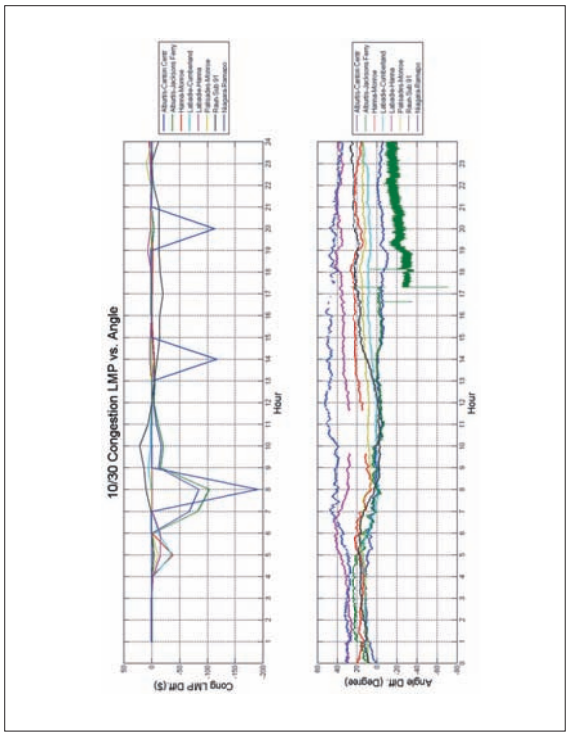

10/01 Congestion LMP vs. Angle
Cong LMP Diff ($)
Angle Diff (Degree)
Hour

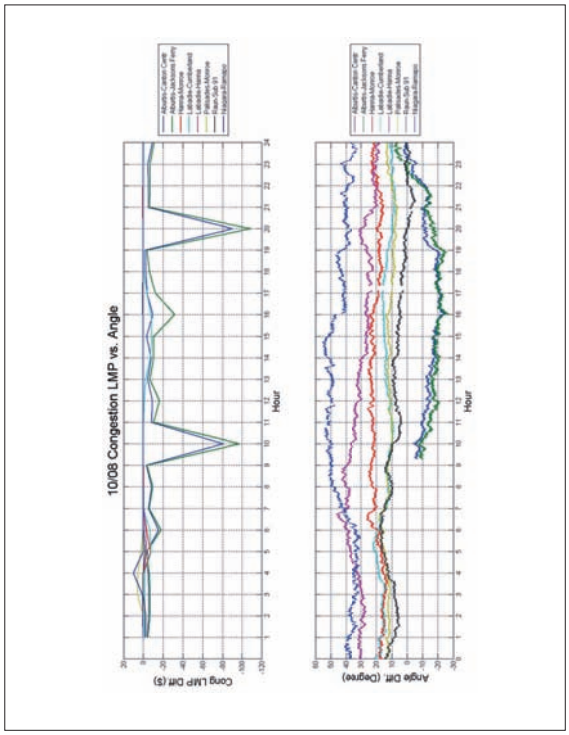

10/06 Congestion LMP vs. Angle
Cong LMP Diff ($)
Angle Diff (Degree)
Hour

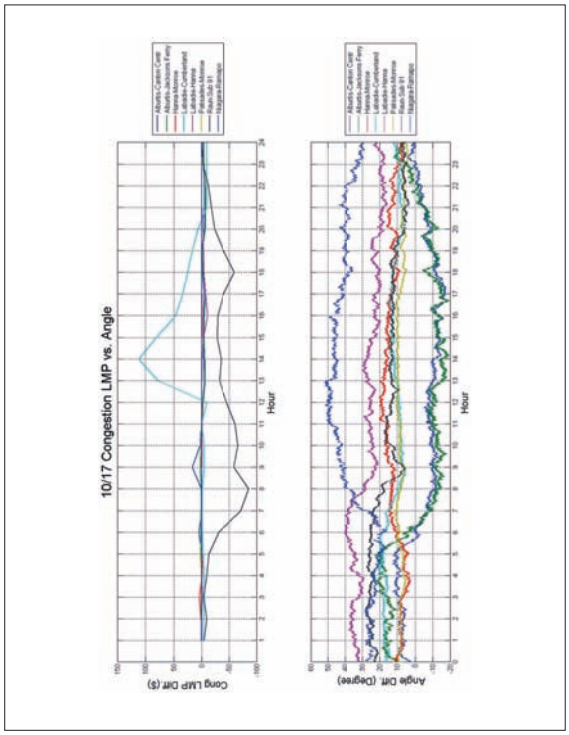

09/30 Congestion LMP vs. Angle
Cong LMP Diff ($)
Angle Diff (Degree)
Hour


10/02 Congestion LMP vs. Angle
Cong LMP Diff ($)
Angle Diff (Degree)
Hour

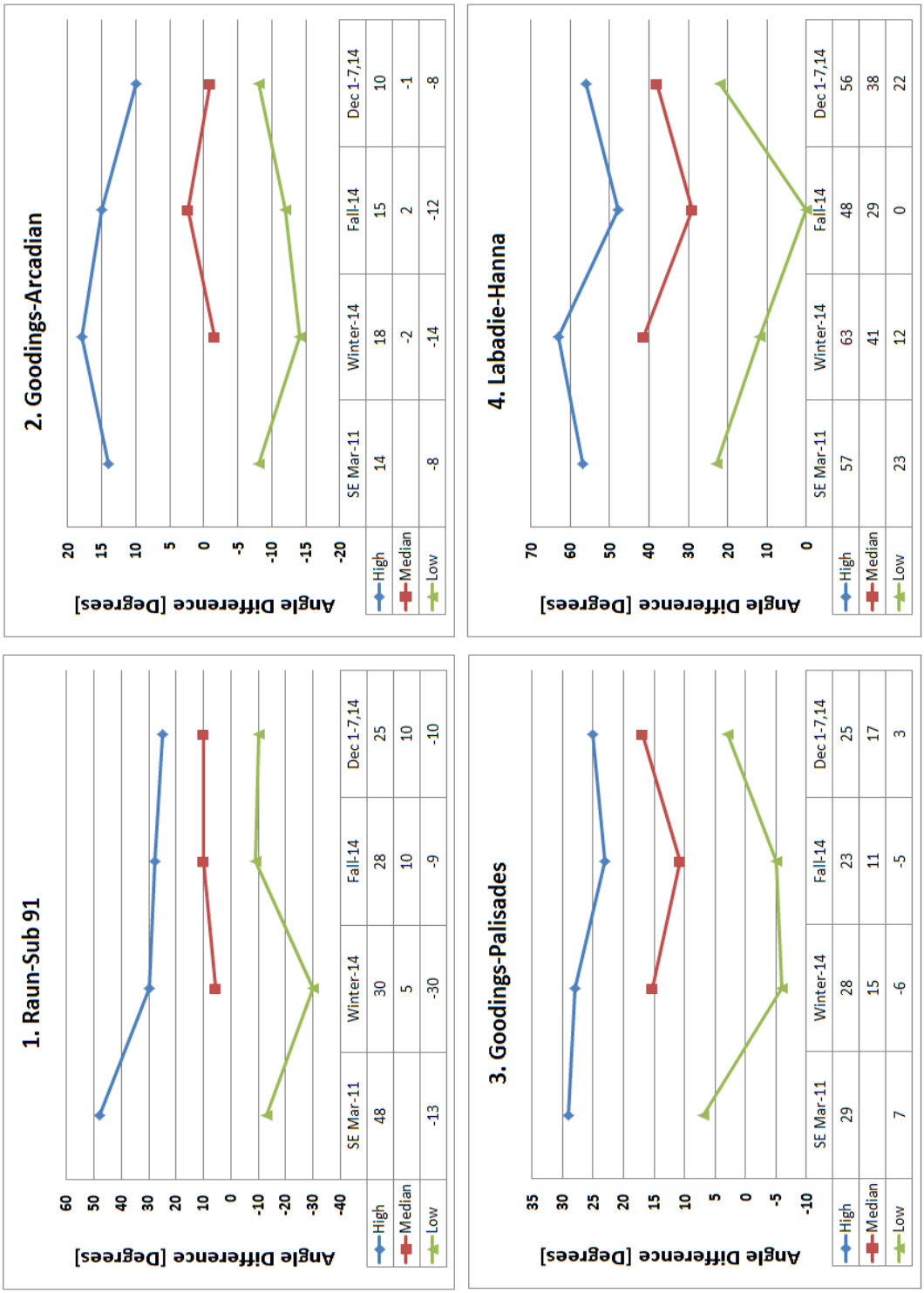

10/15 Congestion LMP vs. Angle
Cong LMP Diff ($)
Hour
Angle Diff. (Degree)
Hour

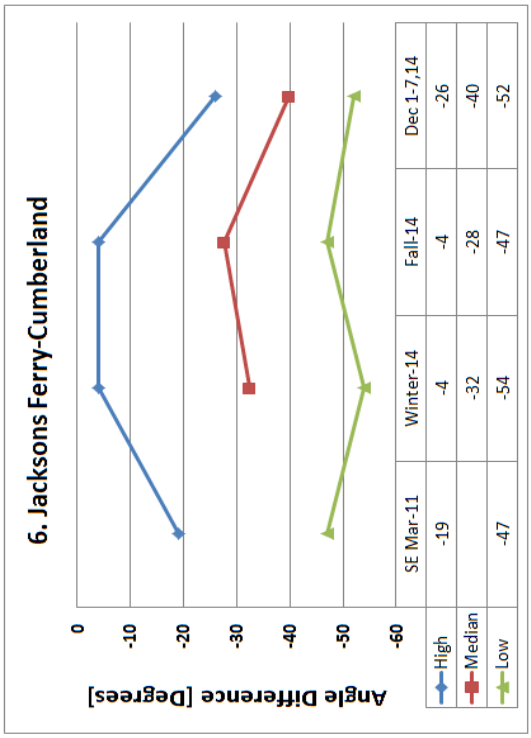

10/30 Congestion LMP vs. Angle
Cong LMP Diff ($)
Hour
Angle Diff. (Degree)
Hour

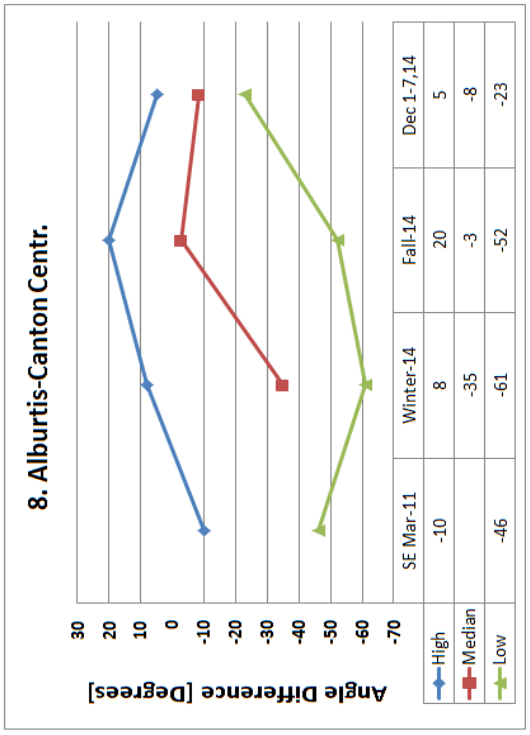

10/08 Congestion LMP vs. Angle
Cong LMP Diff ($)
Hour
Angle Diff. (Degree)
Hour

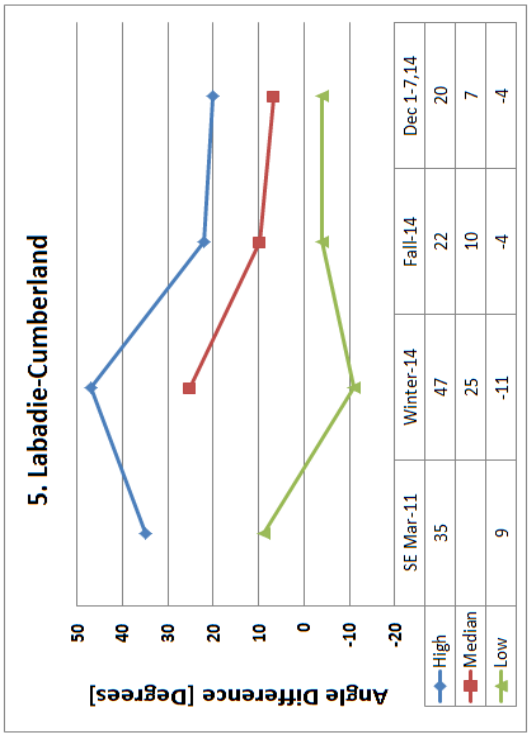

10/17 Congestion LMP vs. Angle
Cong LMP Diff ($)
Hour
Angle Diff. (Degree)
Hour

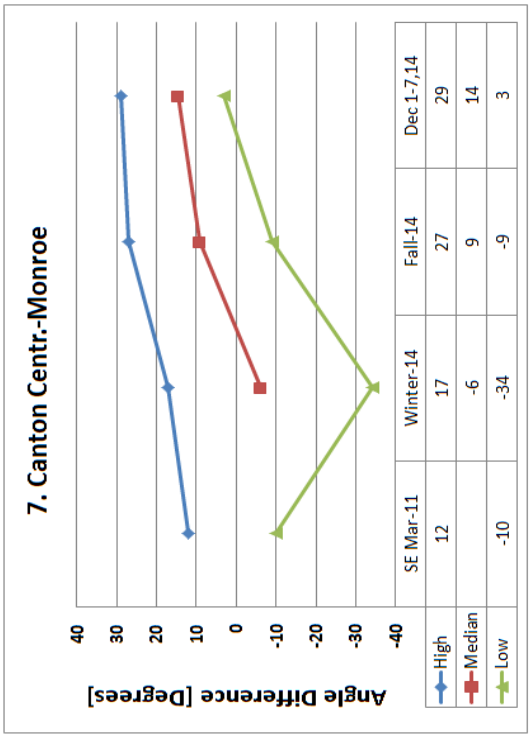
## 8.8 Comparison of High, Median and Low Values for Angle Difference Pairs

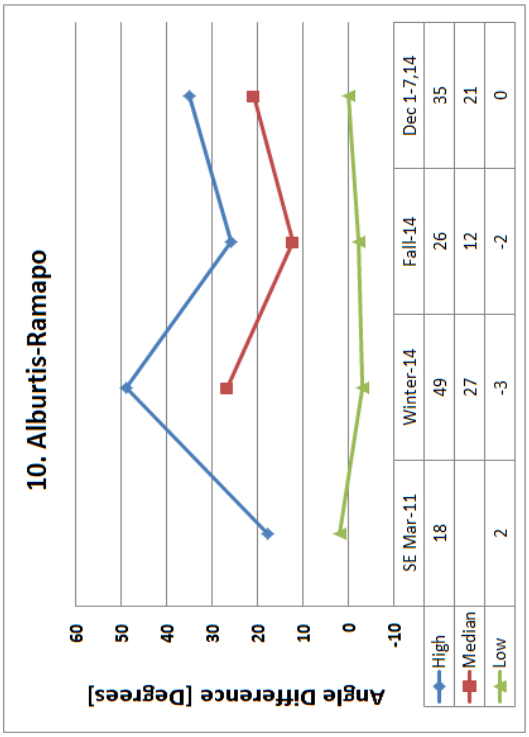


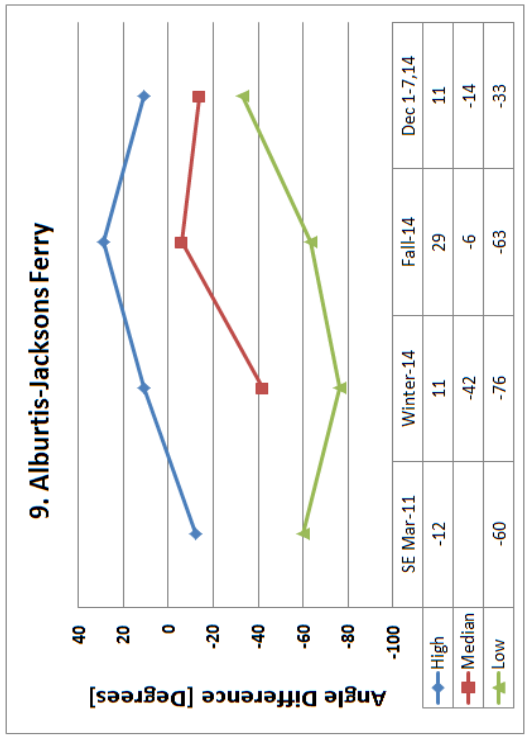

6. Jacksons Ferry-Cumberland
Angle Difference [Degrees]
0
-10
-20
-30
-40
-50
-60
SE Mar-11 Winter-14 Fall-14 Dec 1-7,14
High -19 -4 -4 -26
Median -32 -28 -40
Low -47 -54 -47 -52

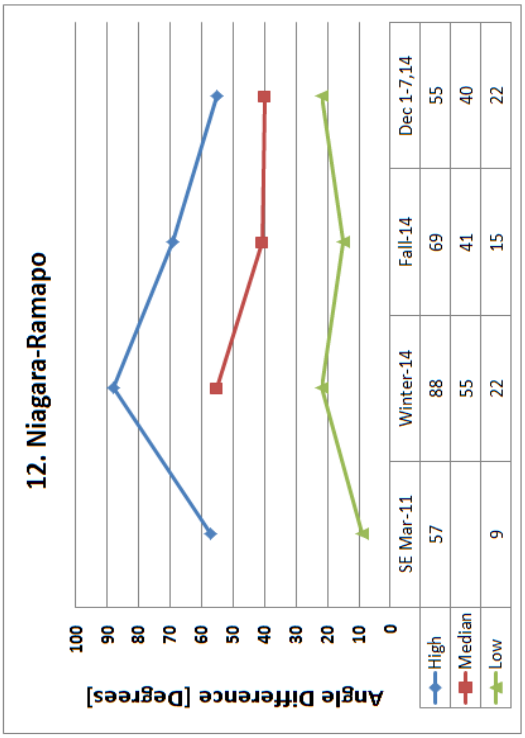

8. Alburtis-Canton Centr.
Angle Difference [Degrees]
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
SE Mar-11 Winter-14 Fall-14 Dec 1-7,14
High -10 8 20 5
Median -35 -3 -8
Low -46 -61 -52 -23

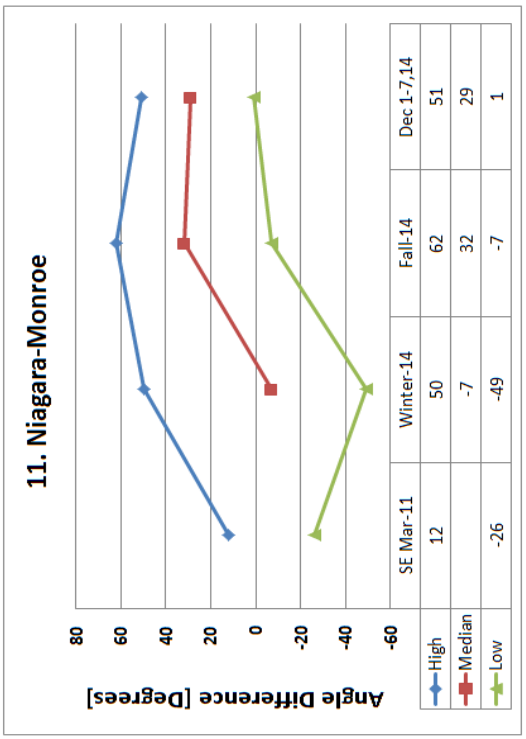

5. Labadie-Cumberland
Angle Difference [Degrees]
50
40
30
20
10
0
-10
-20
SE Mar-11 Winter-14 Fall-14 Dec 1-7,14
High 35 47 22 20
Median 25 10 7
Low 9 -11 -4 -4

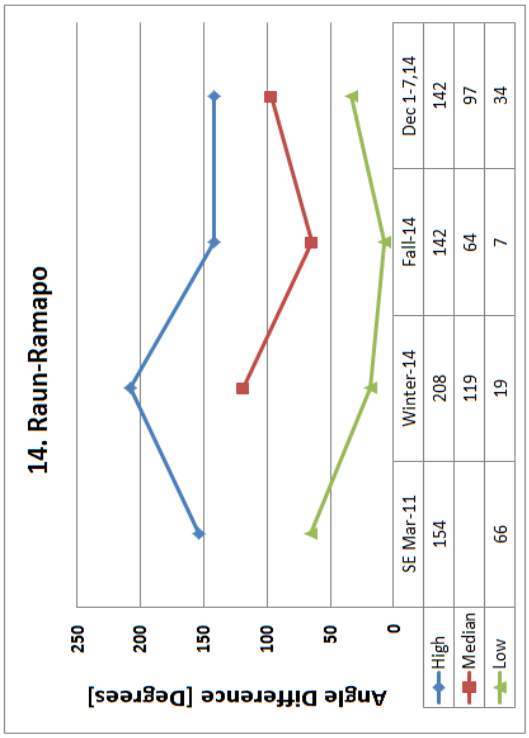

7. Canton Centr.-Monroe
Angle Difference [Degrees]
40
30
20
10
0
-10
-20
-30
-40
SE Mar-11 Winter-14 Fall-14 Dec 1-7,14
High 12 17 27 29
Median -6 9 14
Low -10 -34 -9 3

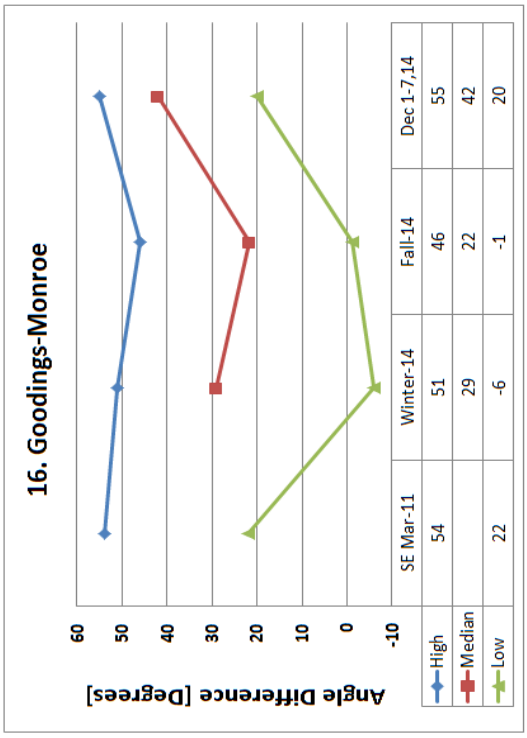

10. Alburtis-Ramapo
Angle Difference [Degrees]
60
50
40
30
20
10
0
-10
SE Mar-11 Winter-14 Fall-14 Dec 1-7,14
High 18 49 26 35
Median 27 12 21
Low 2 -3 -2 0

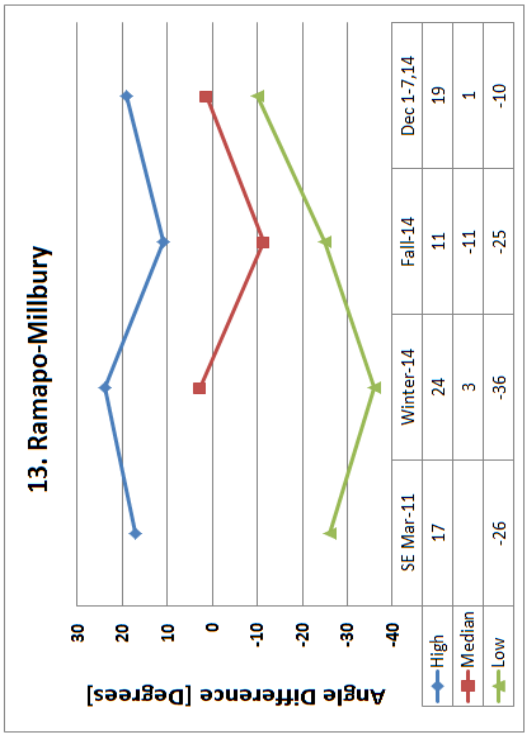

9. Alburtis-Jacksons Ferry
Angle Difference [Degrees]
40
20
0
-20
-40
-60
-80
-100
SE Mar-11 Winter-14 Fall-14 Dec 1-7,14
High -12 11 29 11
Median -42 -6 -14
Low -60 -76 -63 -33

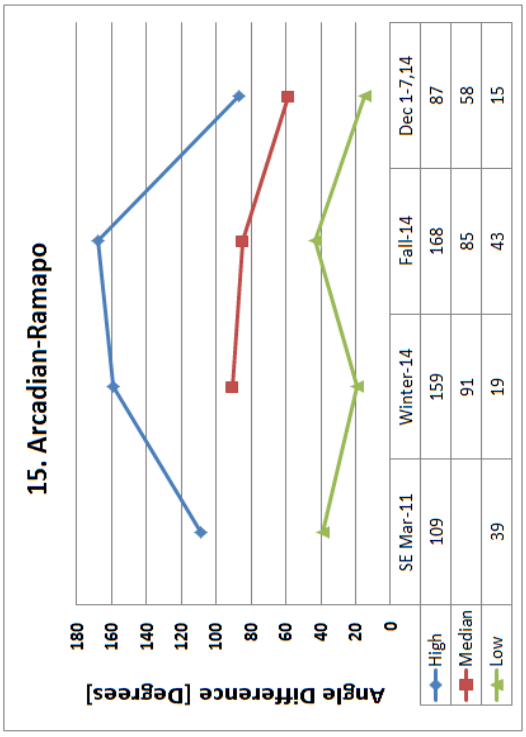

12. Niagara-Ramapo
Angle Difference [Degrees]
100
90
80
70
60
50
40
30
20
10
0
SE Mar-11 Winter-14 Fall-14 Dec 1-7,14
High 57 88 69 55
Median 55 41 40
Low 9 22 15 22

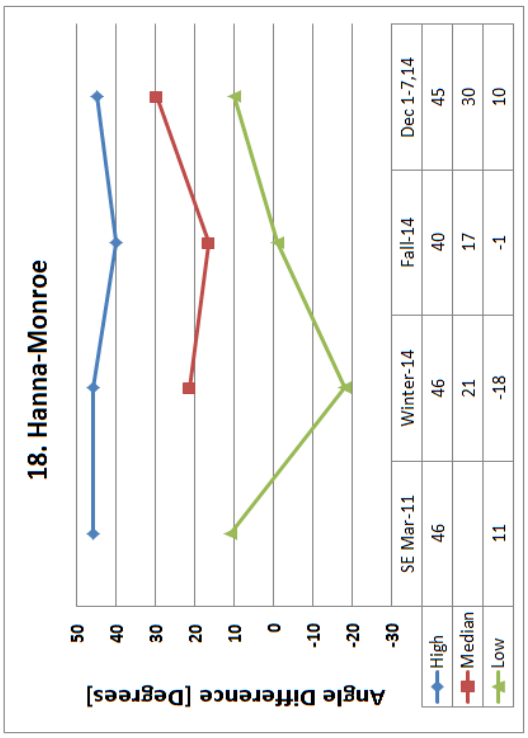

11. Niagara-Monroe
Angle Difference [Degrees]
80
60
40
20
0
-20
-40
-60
SE Mar-11 Winter-14 Fall-14 Dec 1-7,14
High 12 50 62 51
Median -7 32 29
Low -26 -49 -7 1

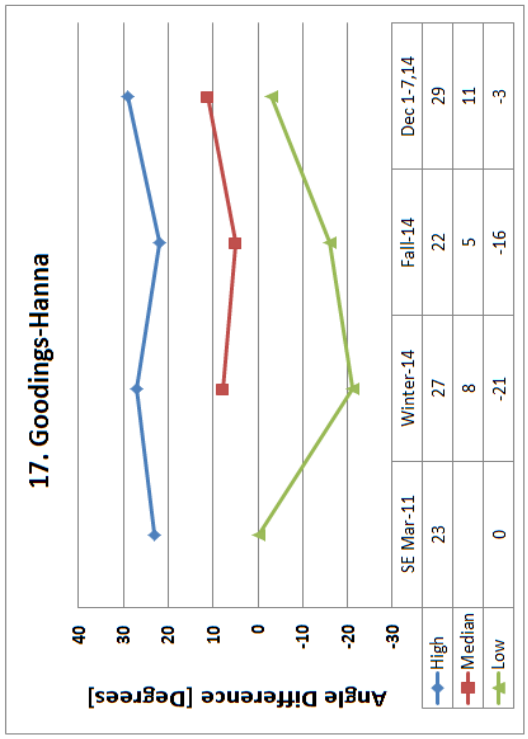

14. Raun-Ramapo
Angle Difference [Degrees]
250
200
150
100
50
0
SE Mar-11 Winter-14 Fall-14 Dec 1-7,14
High 154 208 142 142
Median 119 64 97
Low 66 19 7 34

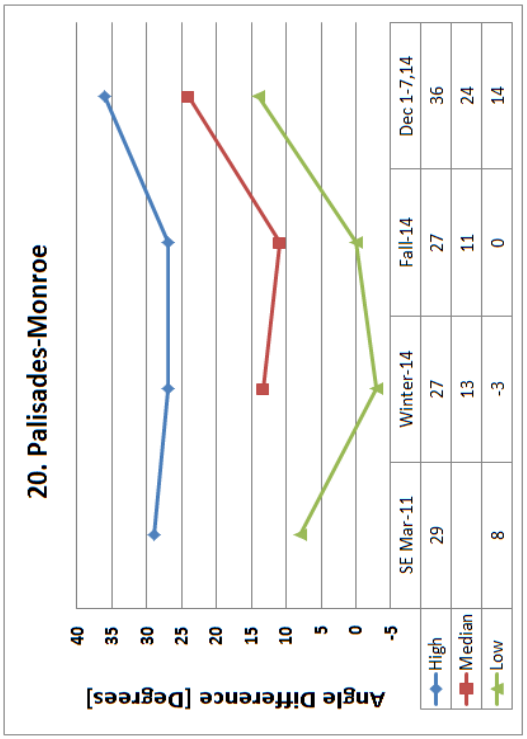

16. Goodings-Monroe
Angle Difference [Degrees]
60
50
40
30
20
10
0
-10
SE Mar-11 Winter-14 Fall-14 Dec 1-7,14
High 54 51 46 55
Median 29 22 42
Low 22 -6 -1 20

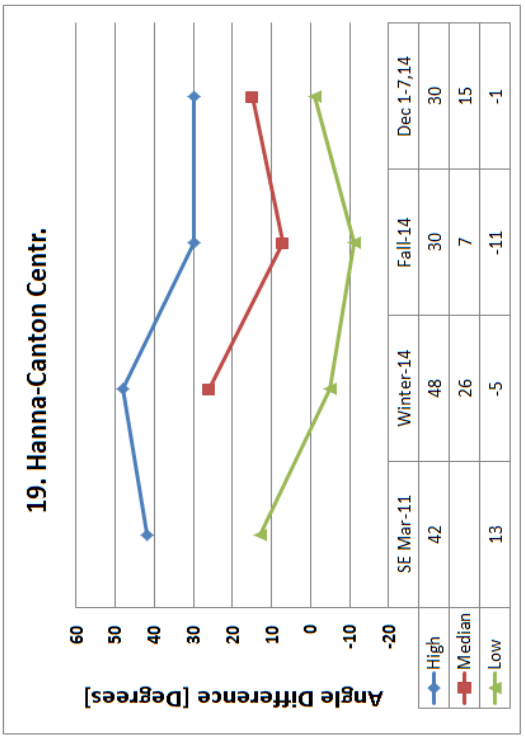

13. Ramapo-Millbury
Angle Difference [Degrees]
30
20
10
0
-10
-20
-30
-40
SE Mar-11 Winter-14 Fall-14 Dec 1-7,14
High 17 24 11 19
Median 3 -11 1
Low -26 -36 -25 -10

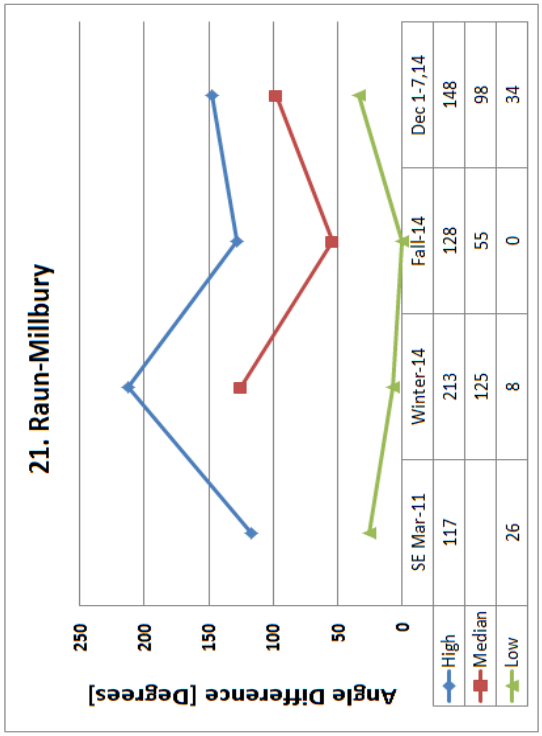

15. Arcadian-Ramapo
Angle Difference [Degrees]
180
160
140
120
100
80
60
40
20
0
SE Mar-11 Winter-14 Fall-14 Dec 1-7,14
High 109 159 168 87
Median 91 85 58
Low 39 19 43 15

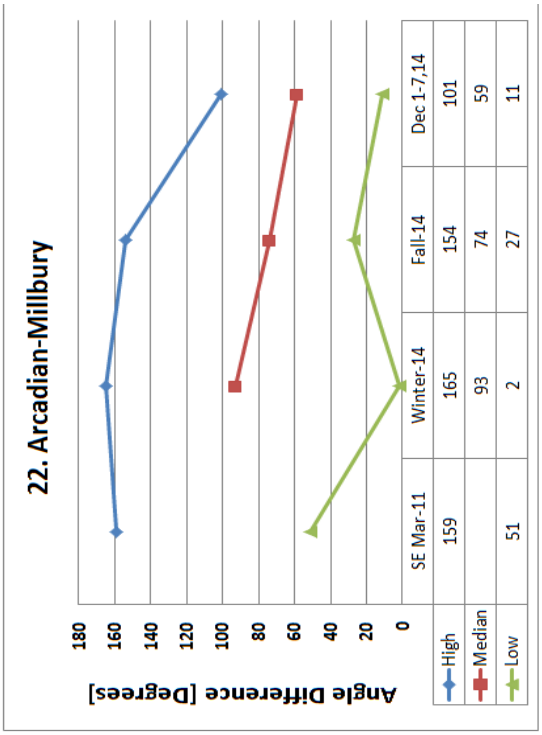

18. Hanna-Monroe
Angle Difference [Degrees]
50
40
30
20
10
0
-10
-20
-30
SE Mar-11 Winter-14 Fall-14 Dec 1-7,14
High 46 46 40 45
Median 21 17 30
Low 11 -18 -1 10


17. Goodings-Hanna
Angle Difference [Degrees]
40
30
20
10
0
-10
-20
-30
SE Mar-11 Winter-14 Fall-14 Dec 1-7,14
High 23 27 22 29
Median 8 5 11
Low 0 -21 -16 -3


20. Palisades-Monroe
Angle Difference [Degrees]
40
35
30
25
20
15
10
5
0
-5
SE Mar-11 Winter-14 Fall-14 Dec 1-7,14
High 29 27 27 36
Median 13 11 24
Low 8 -3 0 14


19. Hanna-Canton Centr.
Angle Difference [Degrees]
60
50
40
30
20
10
0
-10
-20
SE Mar-11 Winter-14 Fall-14 Dec 1-7,14
High 42 48 30 30
Median 26 7 15
Low 13 -5 -11 -1

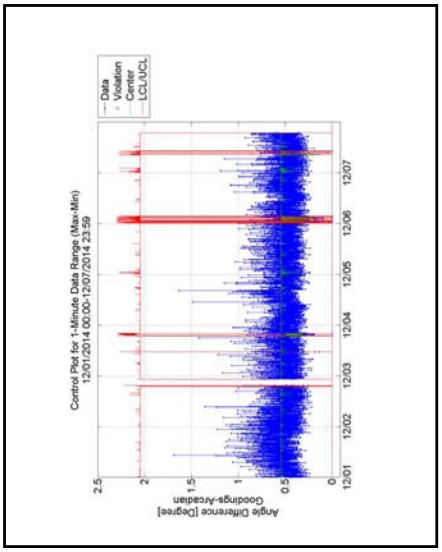

21. Raun-Millbury
Angle Difference [Degrees]
250
200
150
100
50
0
SE Mar-11
Winter-14
Fall-14
Dec 1-7,14
High 117 213 128 148
Median 125 55 98
Low 26 8 0 34

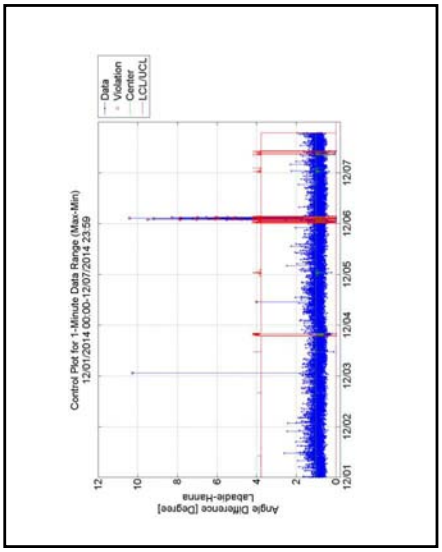

22. Arcadian-Millbury
Angle Difference [Degrees]
180
160
140
120
100
80
60
40
20
0
SE Mar-11
Winter-14
Fall-14
Dec 1-7,14
High 159 165 154 101
Median 93 74 59
Low 51 2 27 11

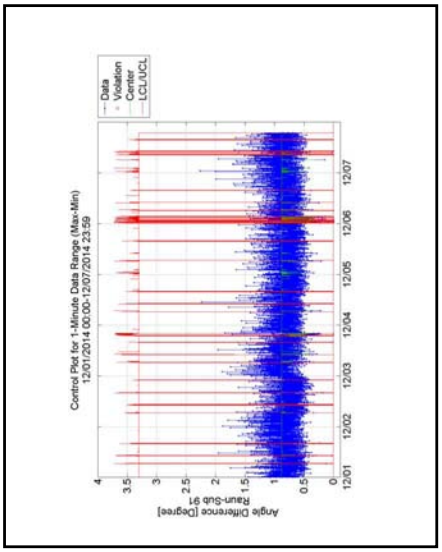
## 8.9 Control Plot for Angle Pair Difference for Dec 1 to Dec 7, 2014 With $nSigma = 20$

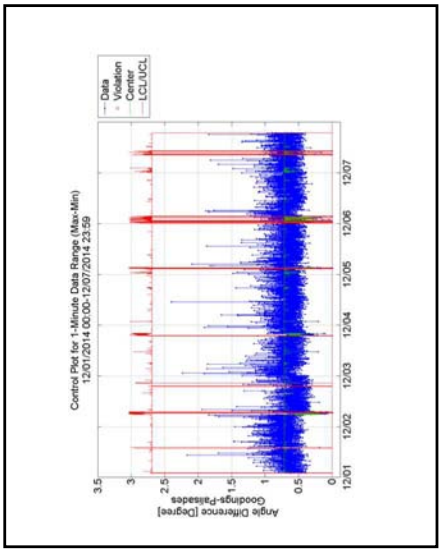
6/19/2015

1



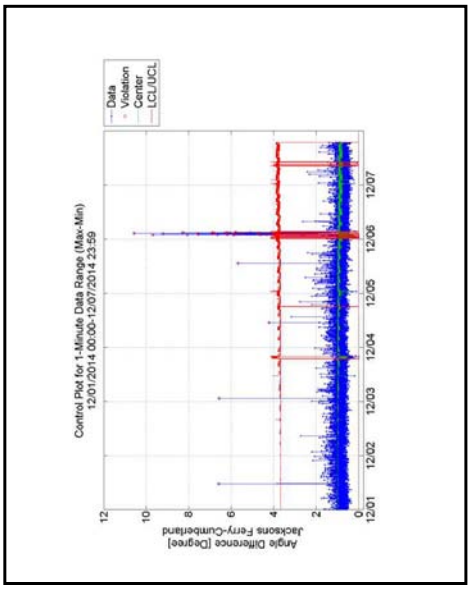



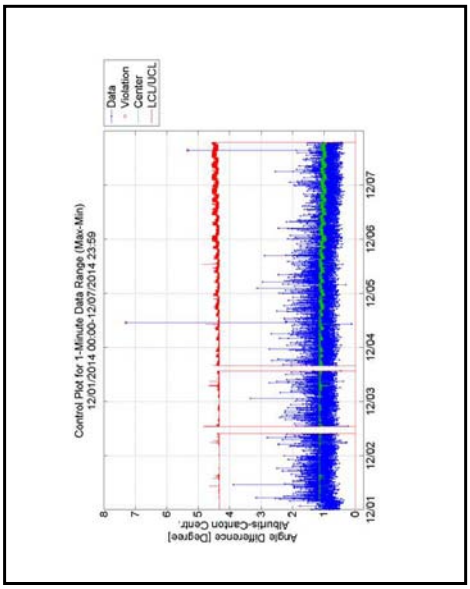



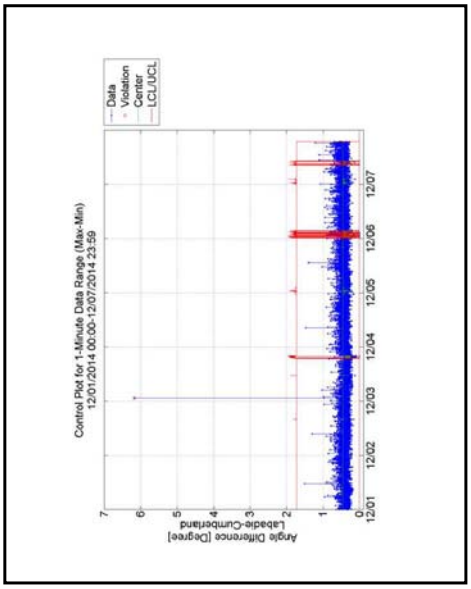



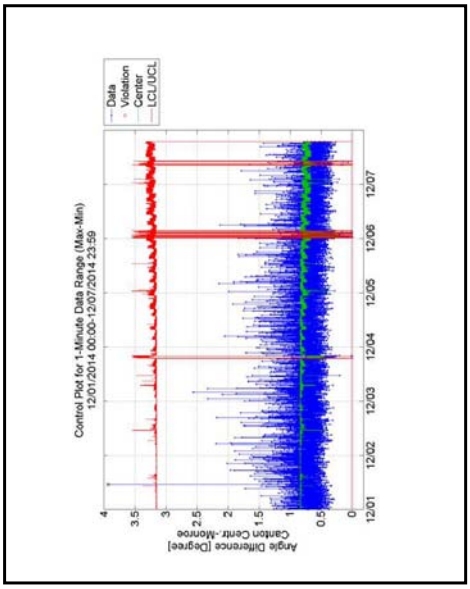
6/19/2015

2


Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Angle Difference [Degree]
Jacksons Ferry-Cumberland
Data
Violation
Center
LCL/UCL
12/01
12/02
12/03
12/04
12/05
12/06
12/07

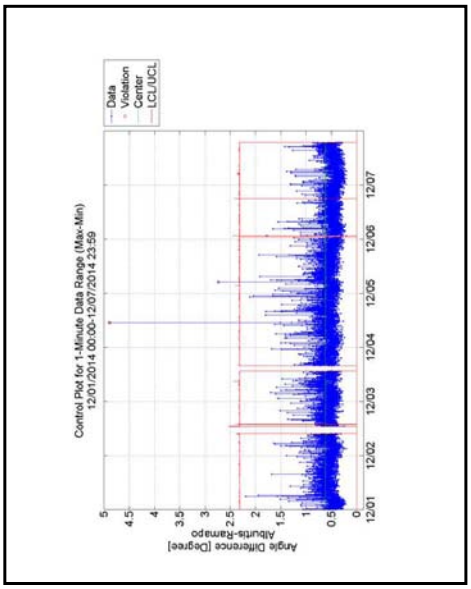

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Angle Difference [Degree]
Albunis-Canton Centr.
Data
Violation
Center
LCL/UCL
12/01
12/02
12/03
12/04
12/05
12/06
12/07

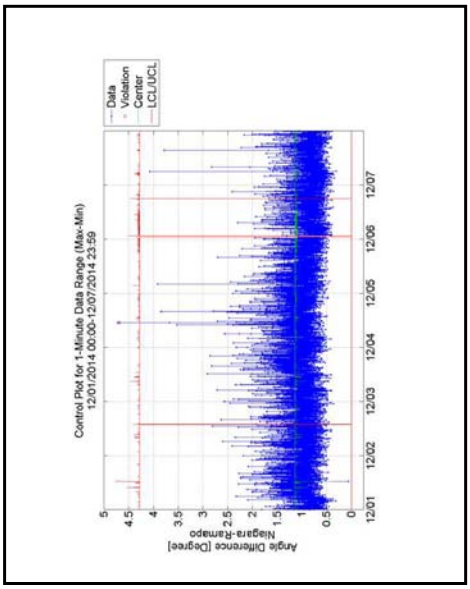

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Angle Difference [Degree]
Labadie-Cumberland
Data
Violation
Center
LCL/UCL
12/01
12/02
12/03
12/04
12/05
12/06
12/07

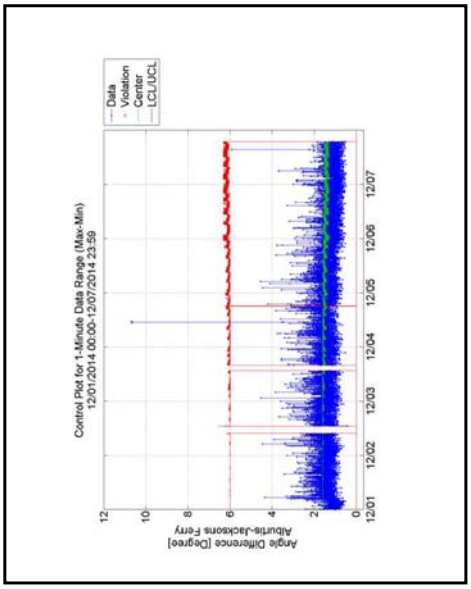

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Angle Difference [Degree]
Canton Centr.-Meramec
Data
Violation
Center
LCL/UCL
12/01
12/02
12/03
12/04
12/05
12/06
12/07

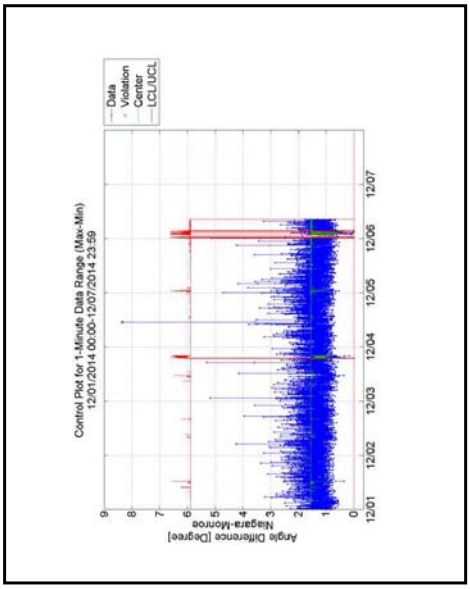
6/19/2015

3


Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Angle Difference [Degree]
Alburtis-Rammapo
Data
Violation
Center
LCL/UCL
12/01
12/02
12/03
12/04
12/05
12/06
12/07

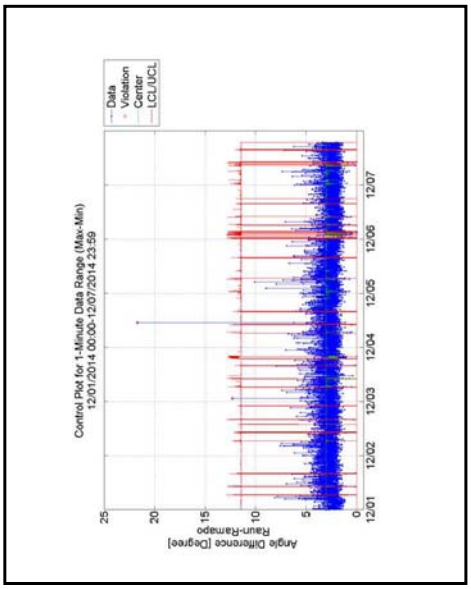

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Angle Difference [Degree]
Niagara-Rammapo
Data
Violation
Center
LCL/UCL
12/01
12/02
12/03
12/04
12/05
12/06
12/07

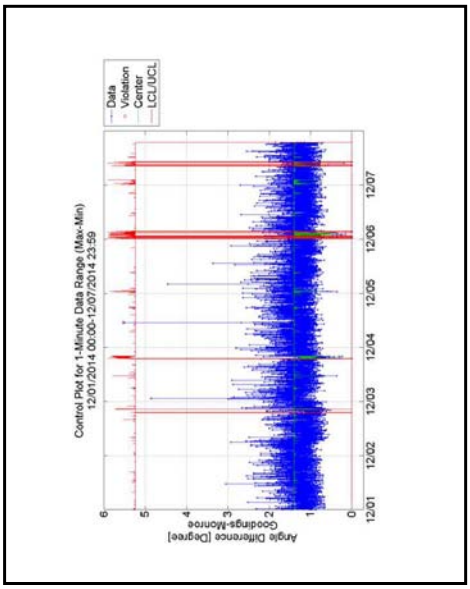

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Angle Difference [Degree]
Alburtis-Jacksons Ferry
Data
Violation
Center
LCL/UCL
12/01
12/02
12/03
12/04
12/05
12/06
12/07

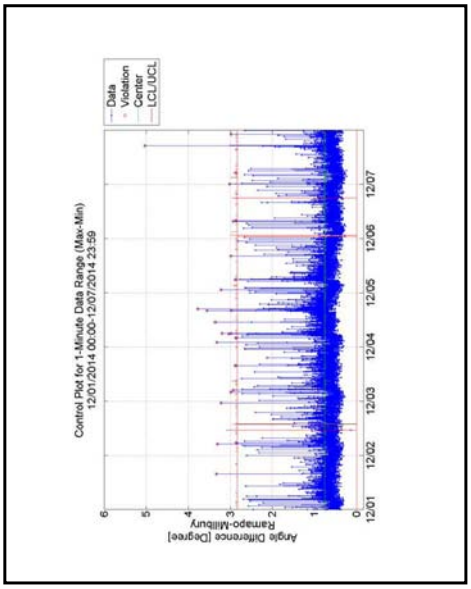

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Angle Difference [Degree]
Niagara-Ikonroe
Data
Violation
Center
LCL/UCL
12/01
12/02
12/03
12/04
12/05
12/06
12/07

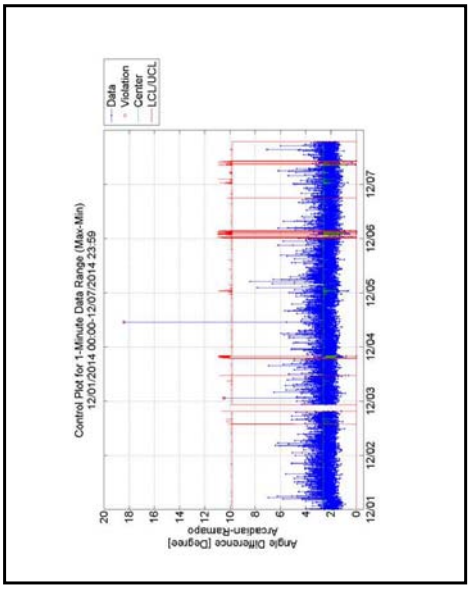
6/19/2015

4


Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Data
Violation
Center
LCL/UCL
Angle Difference [Degree]
Raun-Ramapo
25
20
15
10
5
0
12/01
12/02
12/03
12/04
12/05
12/06
12/07

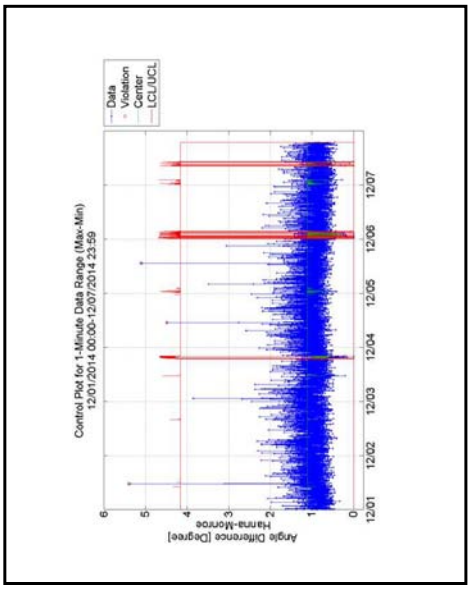

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Data
Violation
Center
LCL/UCL
Angle Difference [Degree]
Goodings-Monroe
6
5
4
3
2
1
0
12/01
12/02
12/03
12/04
12/05
12/06
12/07

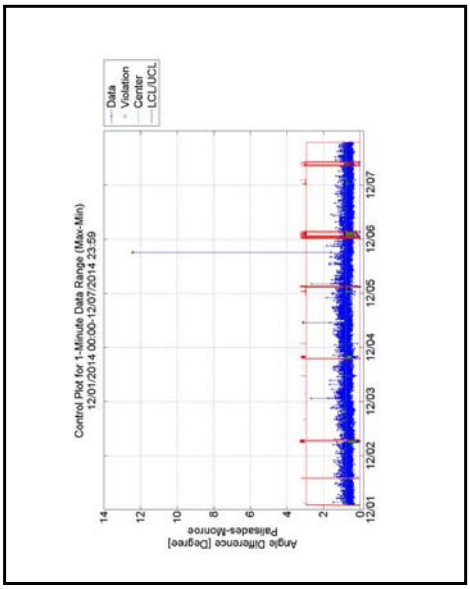

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Data
Violation
Center
LCL/UCL
Angle Difference [Degree]
Ramapo-Millbury
6
5
4
3
2
1
0
12/01
12/02
12/03
12/04
12/05
12/06
12/07

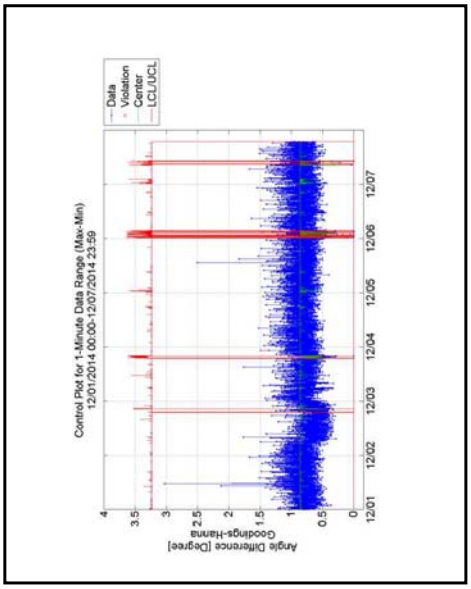

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Data
Violation
Center
LCL/UCL
Angle Difference [Degree]
Arcadian-Ramapo
20
18
16
14
12
10
8
6
4
2
0
12/01
12/02
12/03
12/04
12/05
12/06
12/07

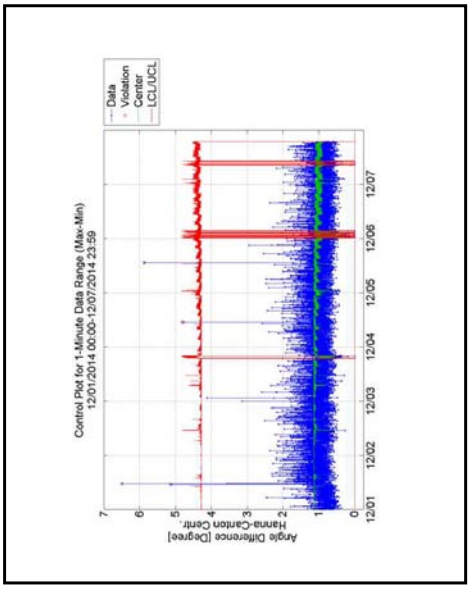
6/19/2015

5


Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Data
Violation
Center
LCL/UCL
Angle Difference [Degree]
Hanna-Monroe
12/01
12/02
12/03
12/04
12/05
12/06
12/07

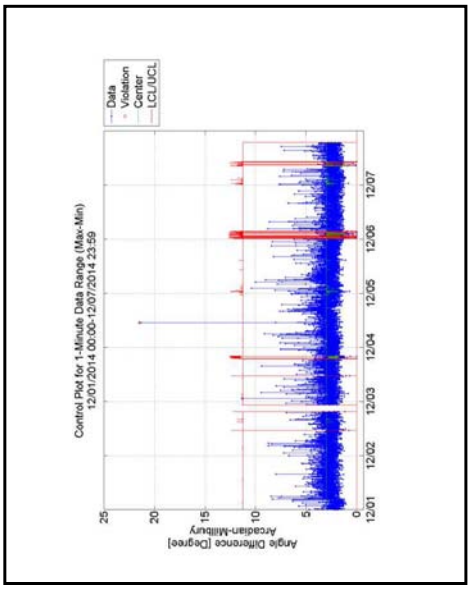

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Data
Violation
Center
LCL/UCL
Angle Difference [Degree]
Palisades-Monroe
12/01
12/02
12/03
12/04
12/05
12/06
12/07

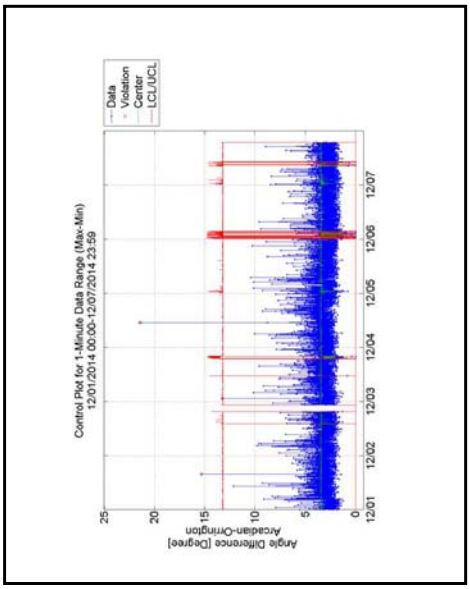

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Data
Violation
Center
LCL/UCL
Angle Difference [Degree]
Goodings-Hanna
12/01
12/02
12/03
12/04
12/05
12/06
12/07

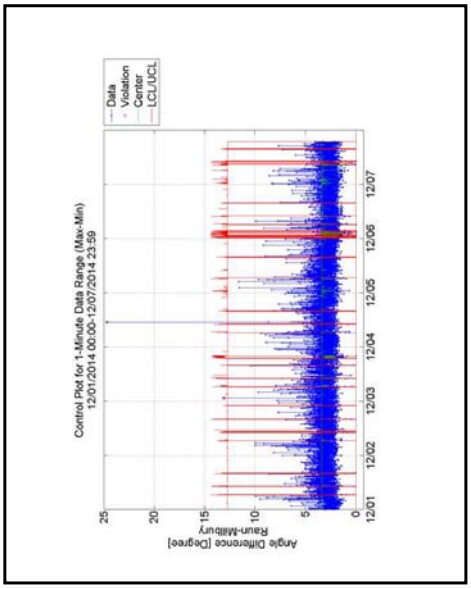

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Data
Violation
Center
LCL/UCL
Angle Difference [Degree]
Hanna-Garton Centr.
12/01
12/02
12/03
12/04
12/05
12/06
12/07

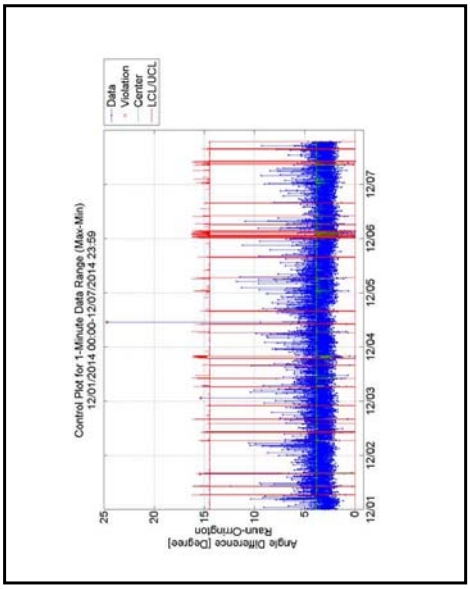
6/19/2015

9


Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Data
Violation
Center
LCL/UCL
Angle Difference [Degree]
Arcadian-Millbury
25
20
15
10
5
0
12/01
12/02
12/03
12/04
12/05
12/06
12/07

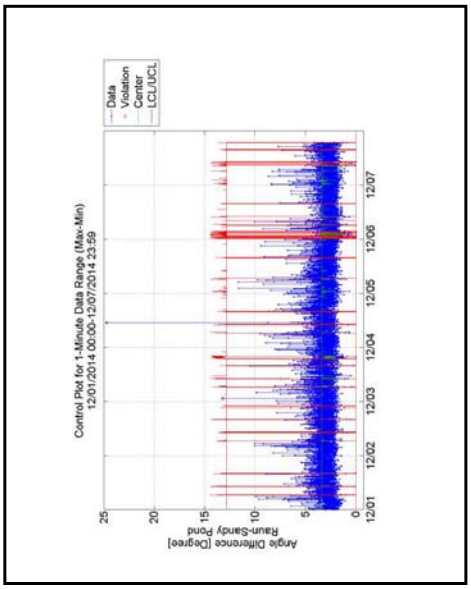

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Data
Violation
Center
LCL/UCL
Angle Difference [Degree]
Arcadian-Orrington
25
20
15
10
5
0
12/01
12/02
12/03
12/04
12/05
12/06
12/07

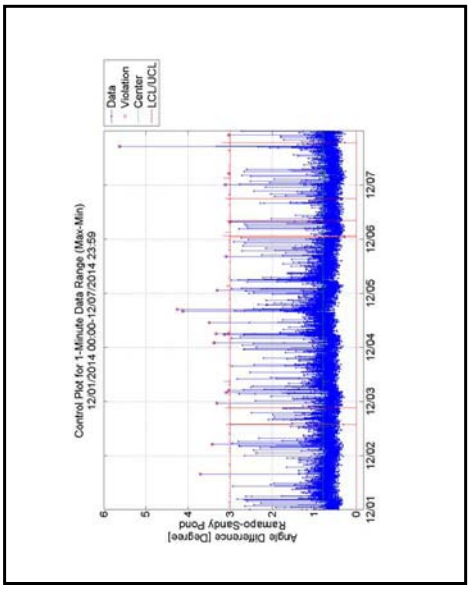

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Data
Violation
Center
LCL/UCL
Angle Difference [Degree]
Raun-Millbury
25
20
15
10
5
0
12/01
12/02
12/03
12/04
12/05
12/06
12/07

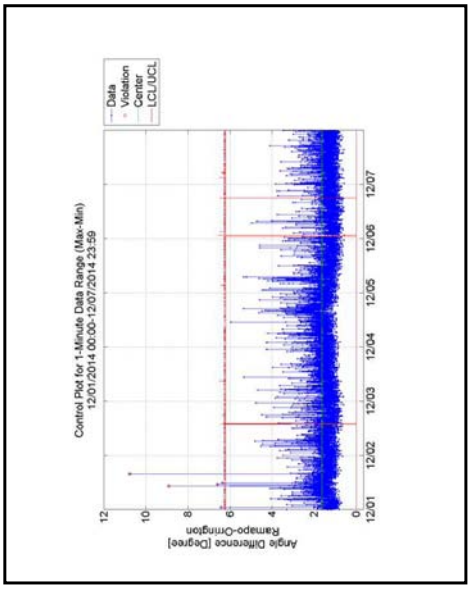

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Data
Violation
Center
LCL/UCL
Angle Difference [Degree]
Raun-Orrington
25
20
15
10
5
0
12/01
12/02
12/03
12/04
12/05
12/06
12/07

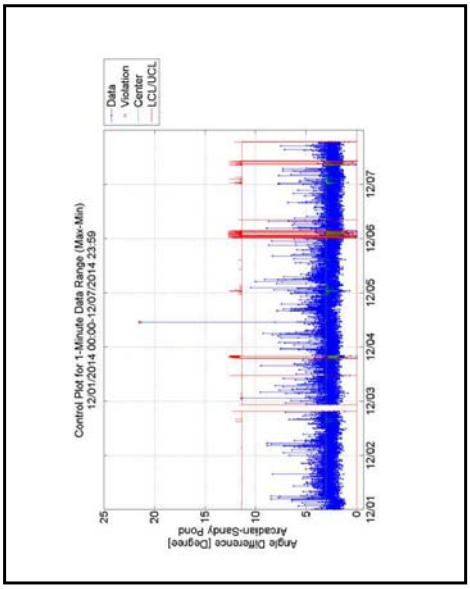
6/19/2015

7

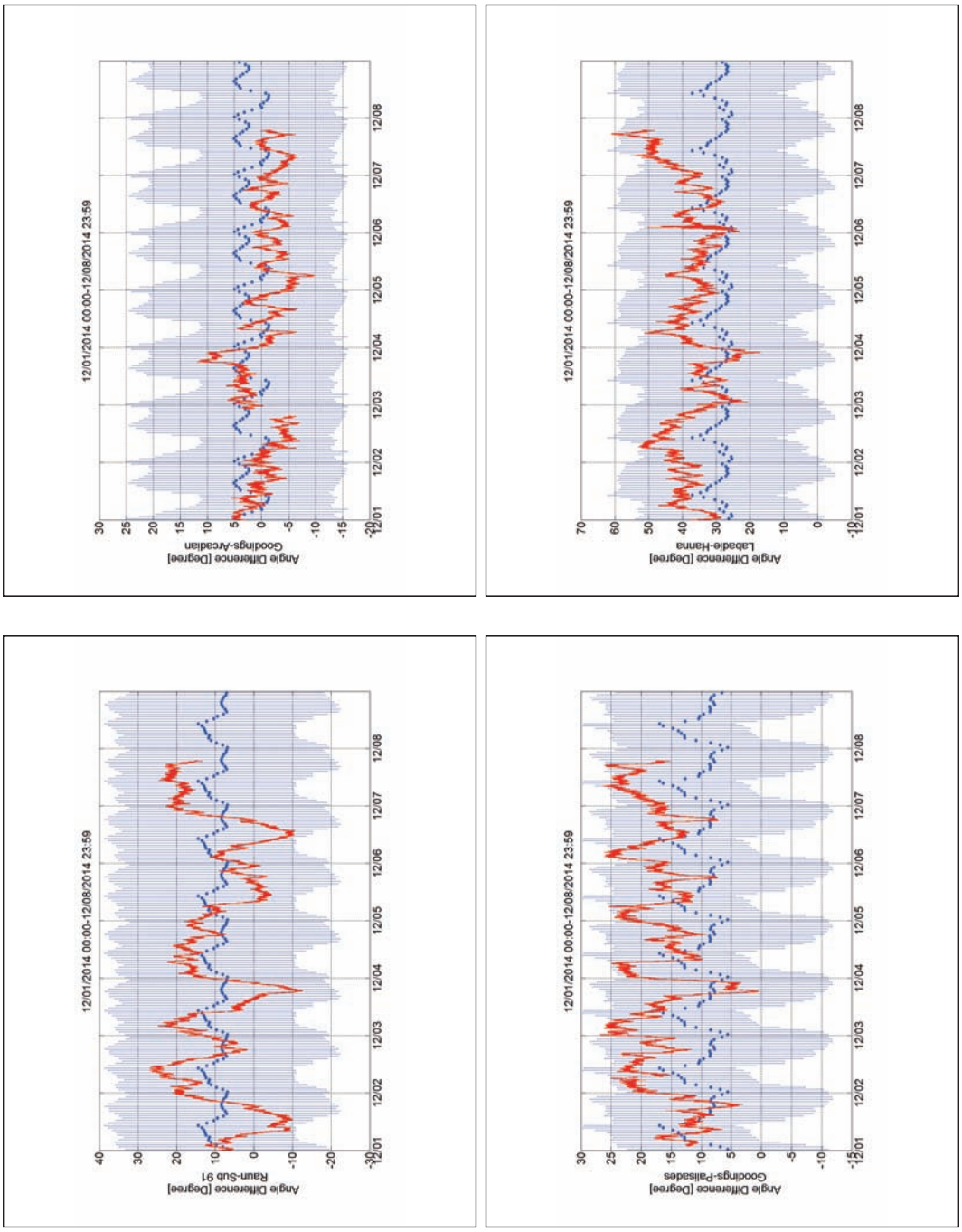

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Angle Difference [Degree]
Raun-Sandy Pond
Data
Violation
Center
LCL/UCL
25
20
15
10
5
0
12/01
12/02
12/03
12/04
12/05
12/06
12/07

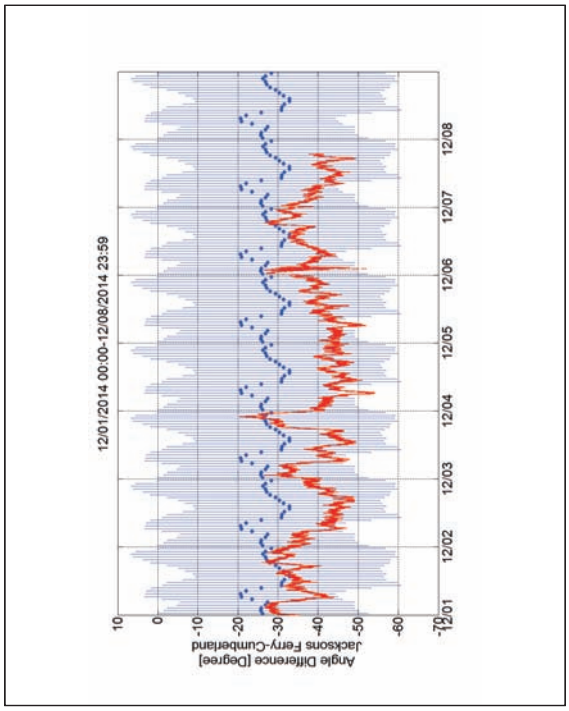

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Angle Difference [Degree]
Ramapo-Sandy Pond
Data
Violation
Center
LCL/UCL
6
5
4
3
2
1
0
12/01
12/02
12/03
12/04
12/05
12/06
12/07

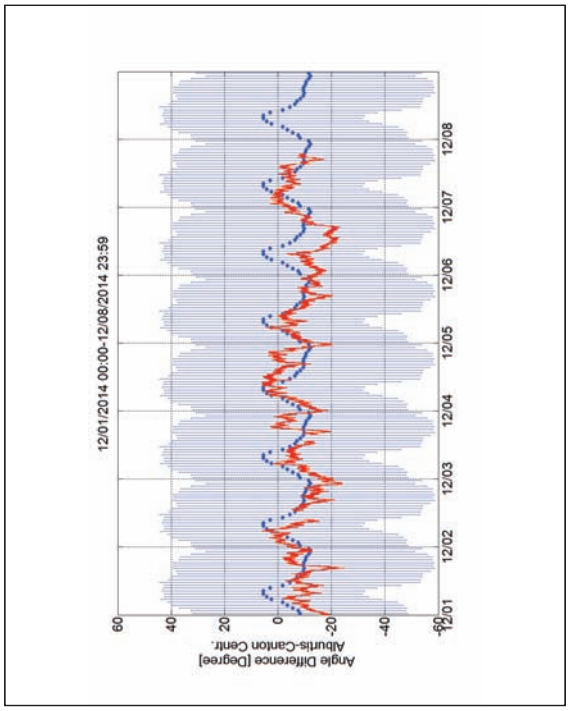

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Angle Difference [Degree]
Ramapo-Orrington
Data
Violation
Center
LCL/UCL
12
10
8
6
4
2
0
12/01
12/02
12/03
12/04
12/05
12/06
12/07

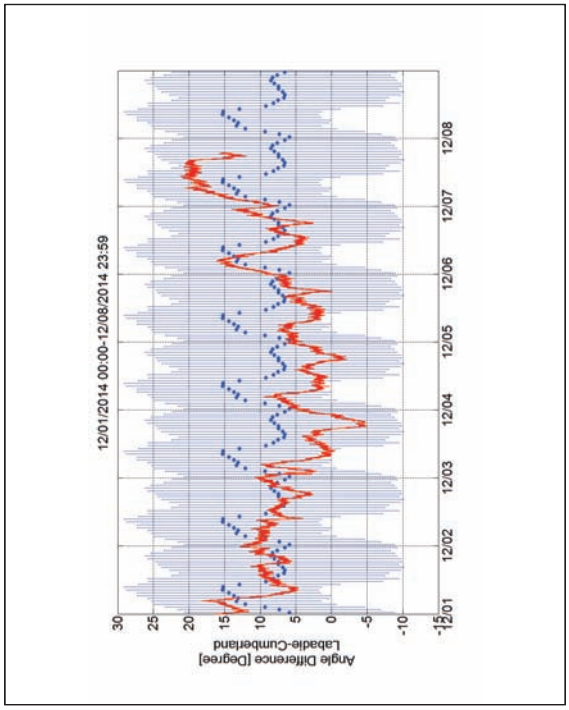

Control Plot for 1-Minute Data Range (Max-Min)
12/01/2014 00:00-12/07/2014 23:59
Angle Difference [Degree]
Arcadian-Sandy Pond
Data
Violation
Center
LCL/UCL
25
20
15
10
5
0
12/01
12/02
12/03
12/04
12/05
12/06
12/07

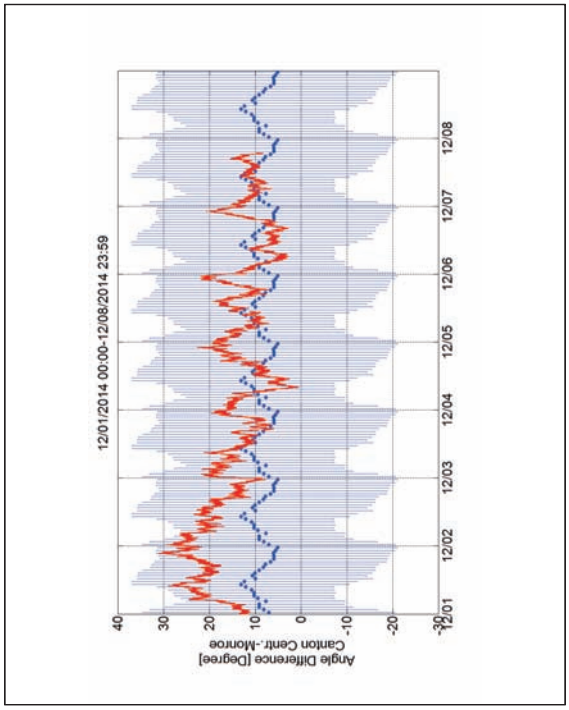
## 8.10 Angle Pair Difference Trend for for Dec 1 to Dec 7, 2014 Compared With Established Reference

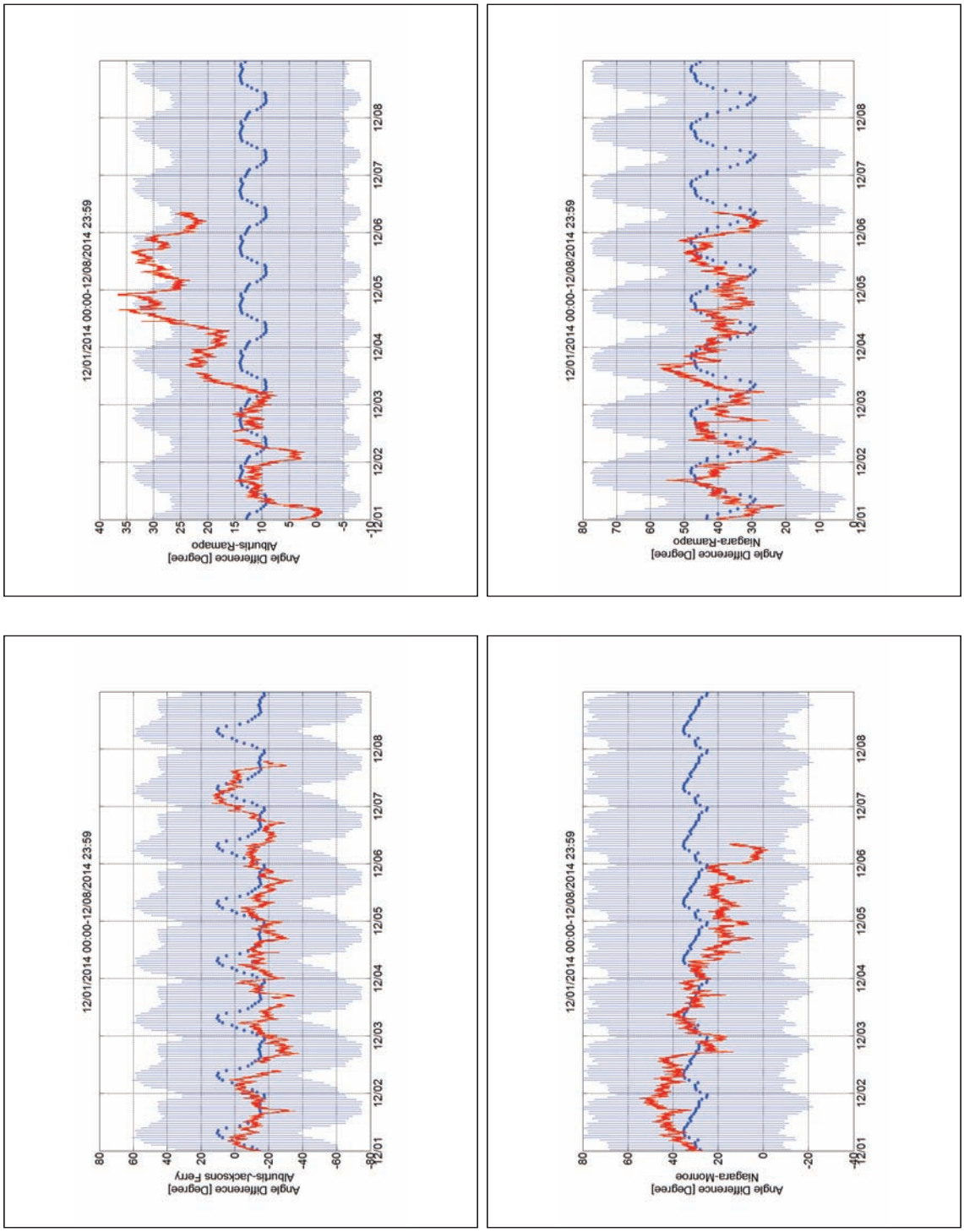


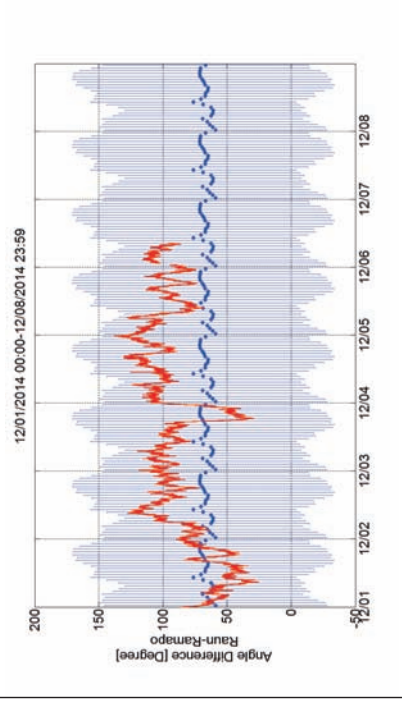

12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Jacksons Ferry-Cumberland
10
0
-10
-20
-30
-40
-50
-60
-70
12/01
12/02
12/03
12/04
12/05
12/06
12/07
12/08

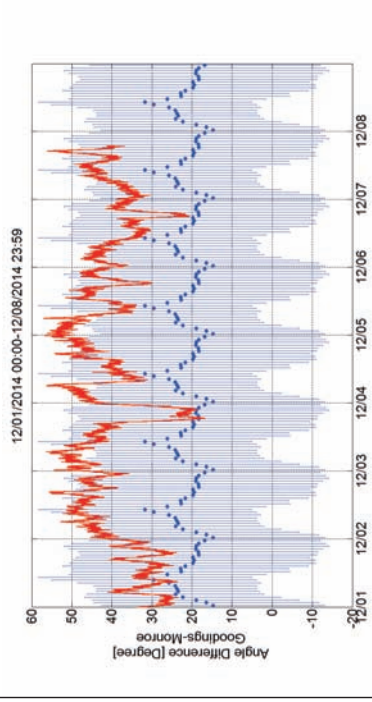

12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Alburtis-Canton Centr.
60
40
20
0
-20
-40
-60
12/01
12/02
12/03
12/04
12/05
12/06
12/07
12/08

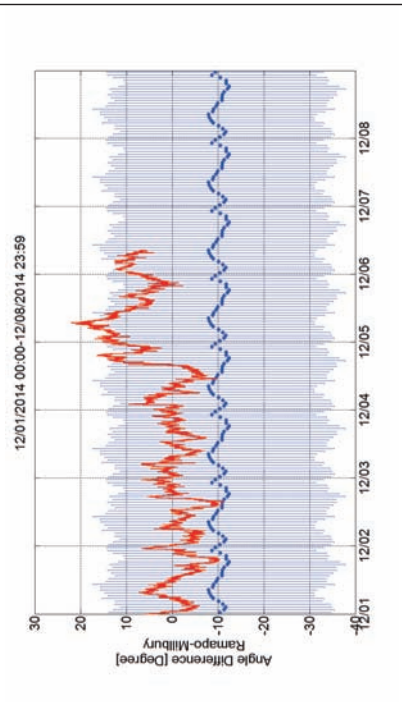

12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Labadie-Cumberland
30
25
20
15
10
5
0
-5
-10
-15
12/01
12/02
12/03
12/04
12/05
12/06
12/07
12/08

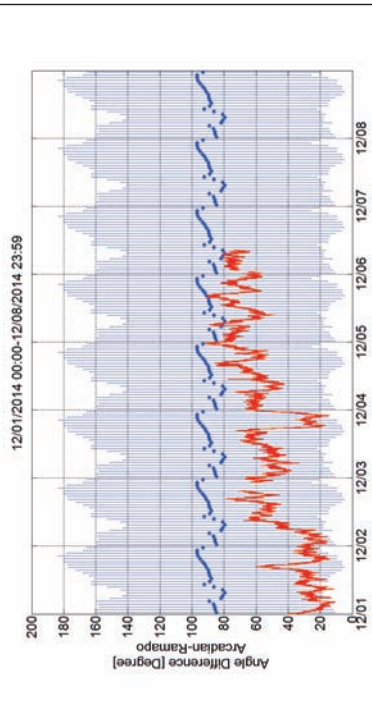

12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Canton Centr.-Monroe
40
30
20
10
0
-10
-20
-30
12/01
12/02
12/03
12/04
12/05
12/06
12/07
12/08

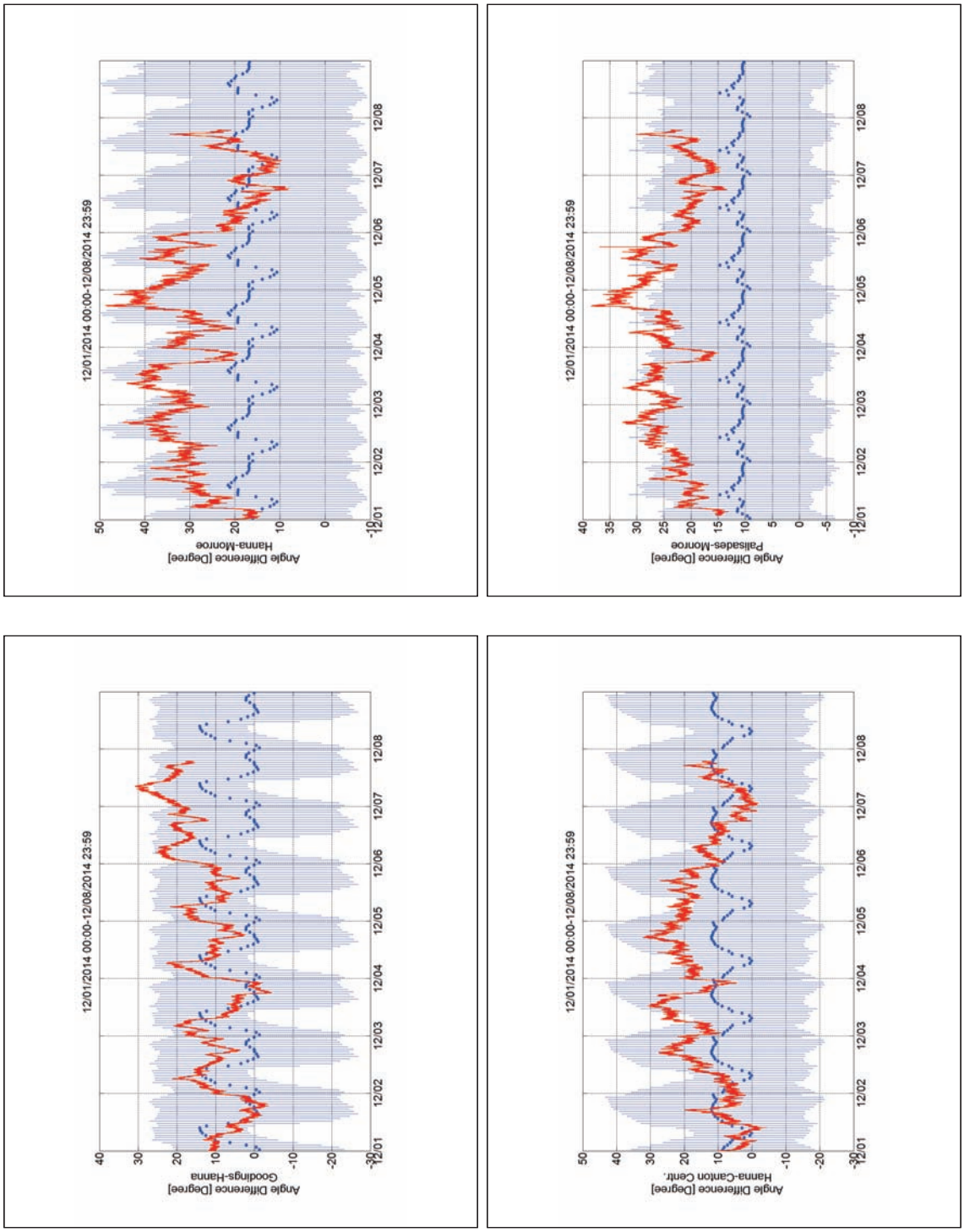

12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Alburiis-Ramapo
12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Niagara-Ramapo
12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Alburiis-Jacksons Ferry
12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Niagara-Monroe
12/01 12/02 12/03 12/04 12/05 12/06 12/07 12/08

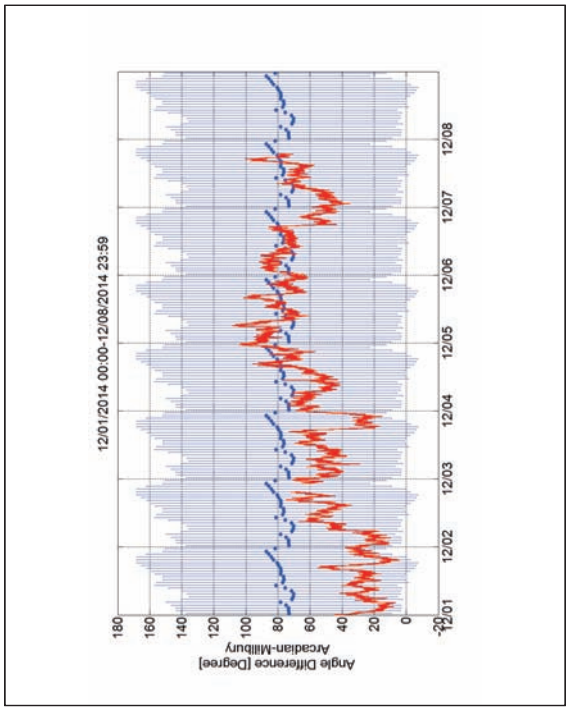

12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Raun-Ramapo
200
150
100
50
0
-50
12/01
12/02
12/03
12/04
12/05
12/06
12/07
12/08

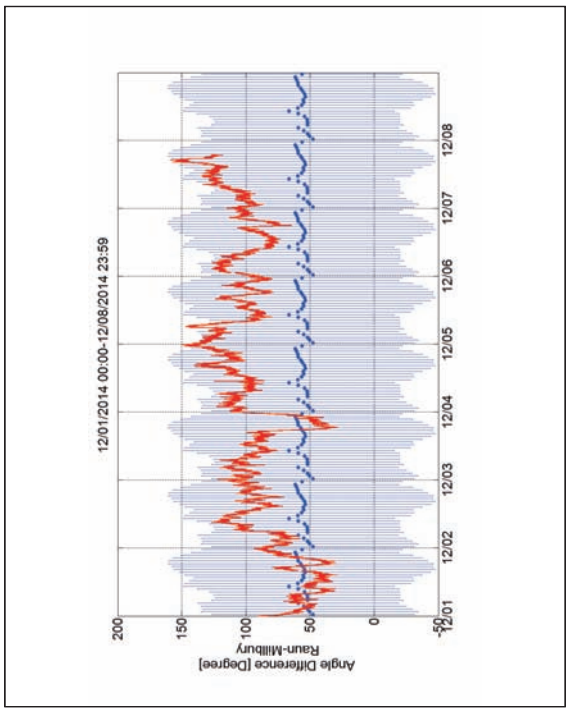

12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Goodings-Monroe
60
50
40
30
20
10
0
-10
-20
12/01
12/02
12/03
12/04
12/05
12/06
12/07
12/08


12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Ramapo-Millbury
30
20
10
0
-10
-20
-30
-40
12/01
12/02
12/03
12/04
12/05
12/06
12/07
12/08


12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Arcadian-Ramapo
200
180
160
140
120
100
80
60
40
20
0
12/01
12/02
12/03
12/04
12/05
12/06
12/07
12/08


12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Hanna-Monroe
12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Palisades-Monroe
12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Goodings-Hanna
12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Hanna-Canton Centr.


12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Arcadian-Millbury
180
160
140
120
100
80
60
40
20
0
-20
12/01
12/02
12/03
12/04
12/05
12/06
12/07
12/08


12/01/2014 00:00-12/08/2014 23:59
Angle Difference [Degree]
Raun-Millbury
200
150
100
50
0
-50
12/01
12/02
12/03
12/04
12/05
12/06
12/07
12/08