Phase Angle Base Lining Study
Eastern Interconnections

NASPI Meeting

Vancouver, Canada

June 9, 2010

Sponsor : Mahendra Patel PJM

Electric Power Group Team

Bharat Bhargava, Jim Dyer, Abhijeet Agarwal, Ajay Das, Song Xue

Why Base Lining is important

Base Lining is needed to make the Synchro-Phasors tools useable in real time control room environment for use by operators

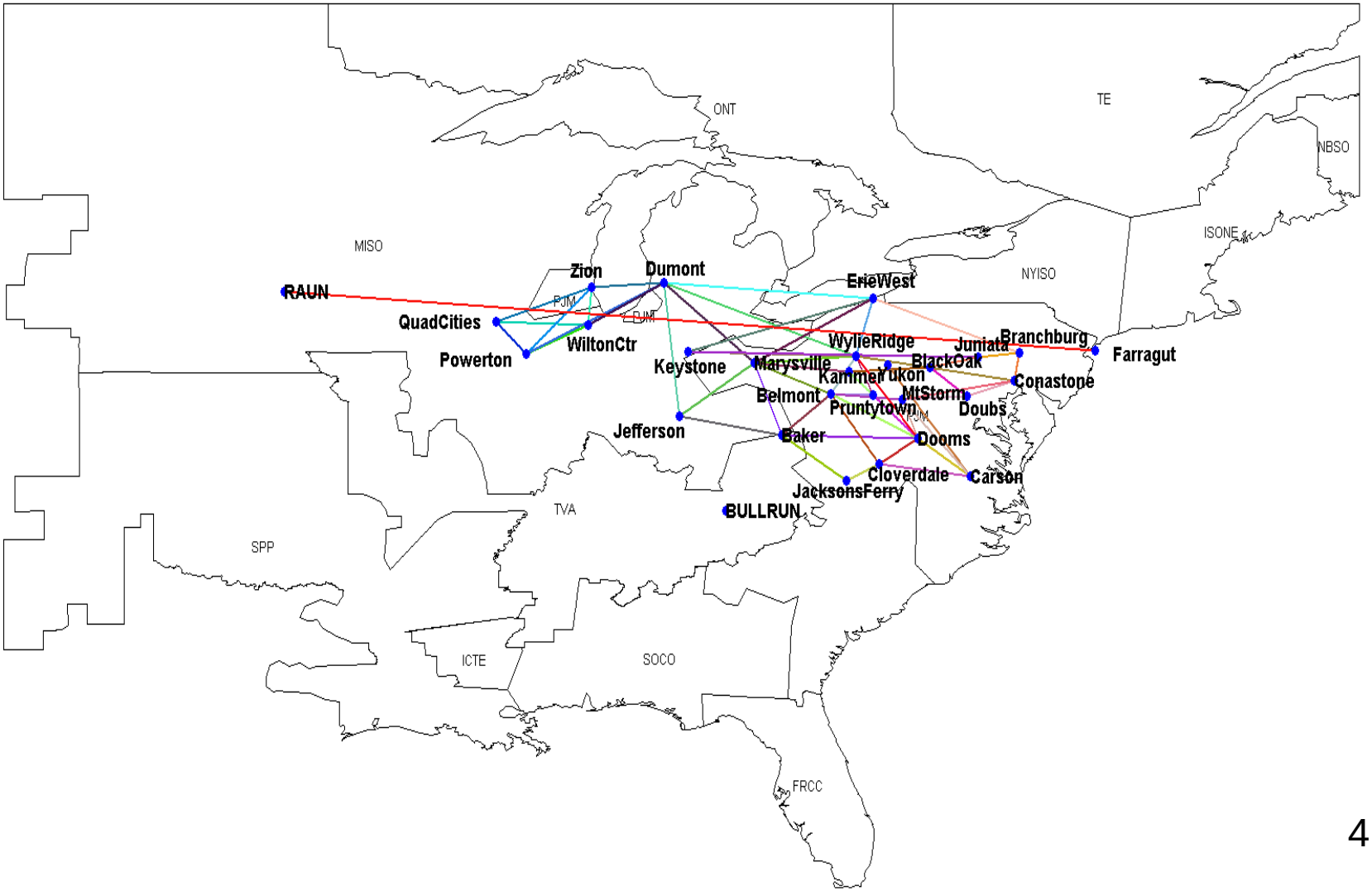
1. Understand operational norms – phase angle differences based on seasonal, on-peak, off-peak, stressed conditions etc.
2. Establish high, medium and low levels for thresholds for various angle pairs based on statistical analysis
3. Validate thresholds and models by event analysis and off-line analysis
4. Compare and validate angle limits with State Estimators or off-line power flow analysis
5. Utilize base lining results to establish meaningful alarms that can be relied upon by operators
6. Base lining is essential for all system parameters. Presently we have concentrated on Phase angle differences for selected angle pairs

Eastern Interconnection Base Lining Study

Work Accomplished:

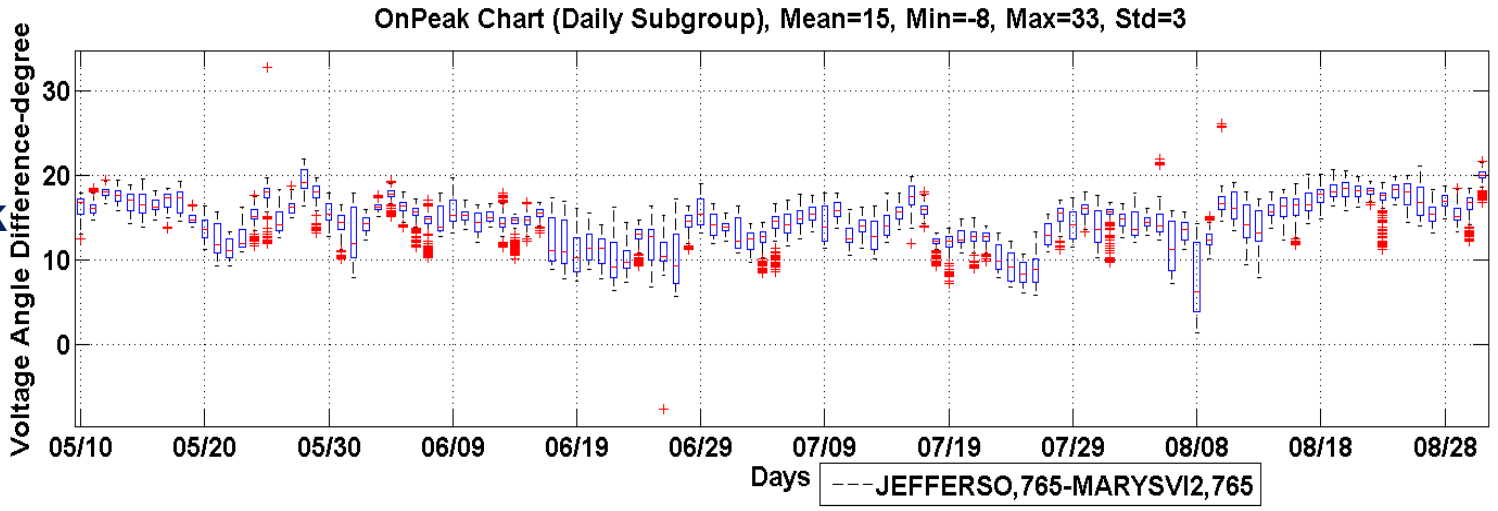
1. Analyzed 15 months of State Estimator data from PJM at 5 minute sampling interval
2. Extracted bus voltage angle and magnitude data from the State Estimator data
3. Identified angle pairs that are of interest to PJM
   - Local area (As asked by PJM)
   - Wide area (Raun-Farragut)
4. Conducted statistical analysis on the selected angle pairs for various seasons, on-peak/off-peak data for each season
5. Current Process: defining limits and validating them with system events

Selected Angle Pairs for Eastern Interconnection Base Lining

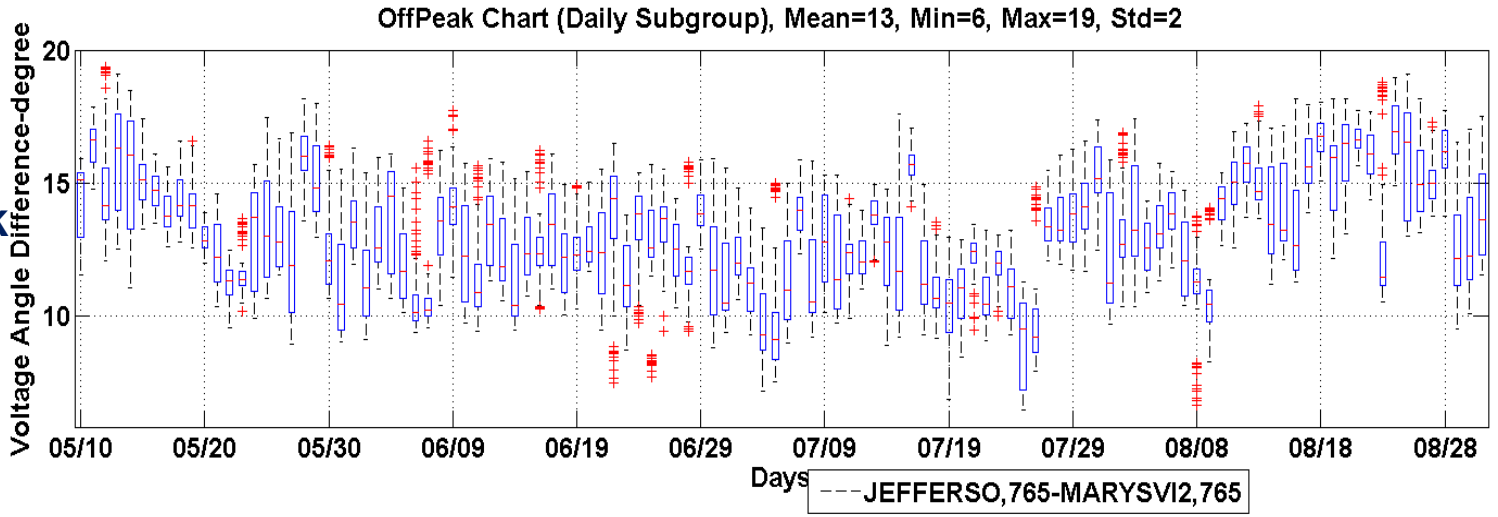


Statistical Analysis (Box-and-Whisker Plots)
Jefferson – Marysville Daily Angle Difference Data
Summer 2009

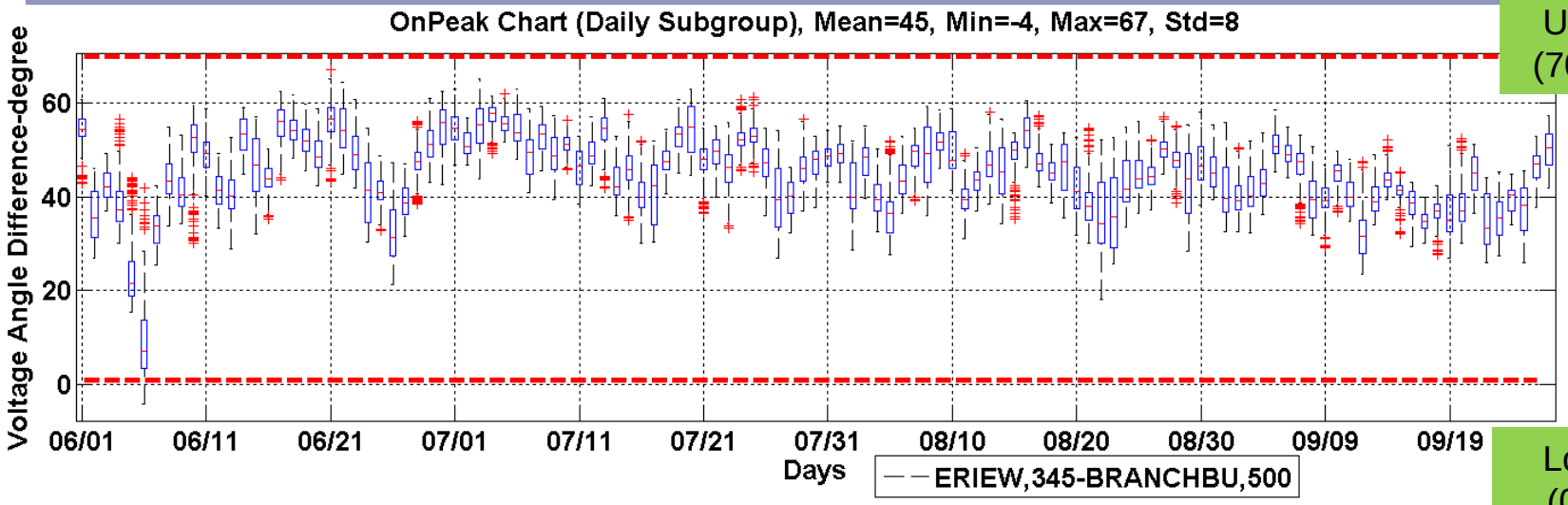
On-Peak Data



Off-Peak Data

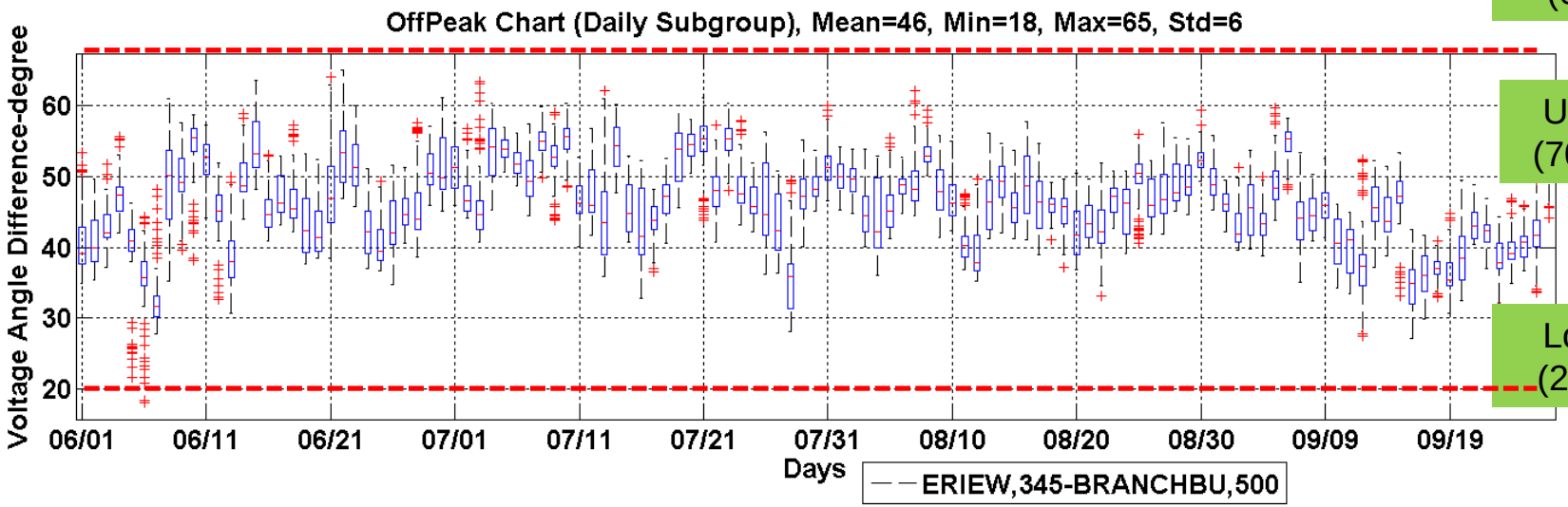


ErieWest – Branchburg Daily Angle Difference Data
Summer 2008, 5-Minute State Estimator Snapshot



Upper Limit (70 degrees)

Lower Limit (0 degrees)

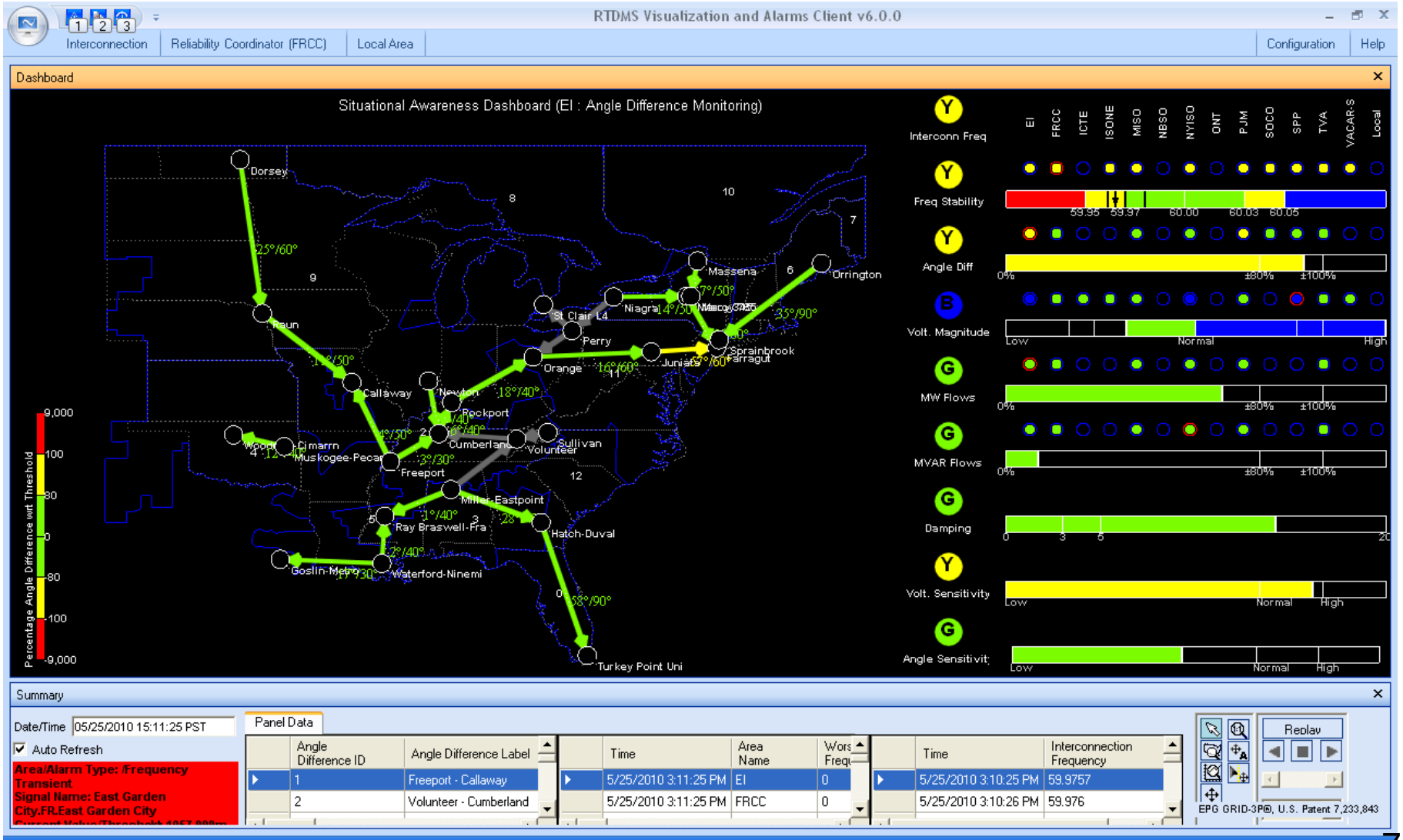


Upper Limit (70 degrees)

Lower Limit (20 degrees)

RTDMS Phase Angle Situational Awareness Dashboard

15:11:25 PM- May 25, 2010

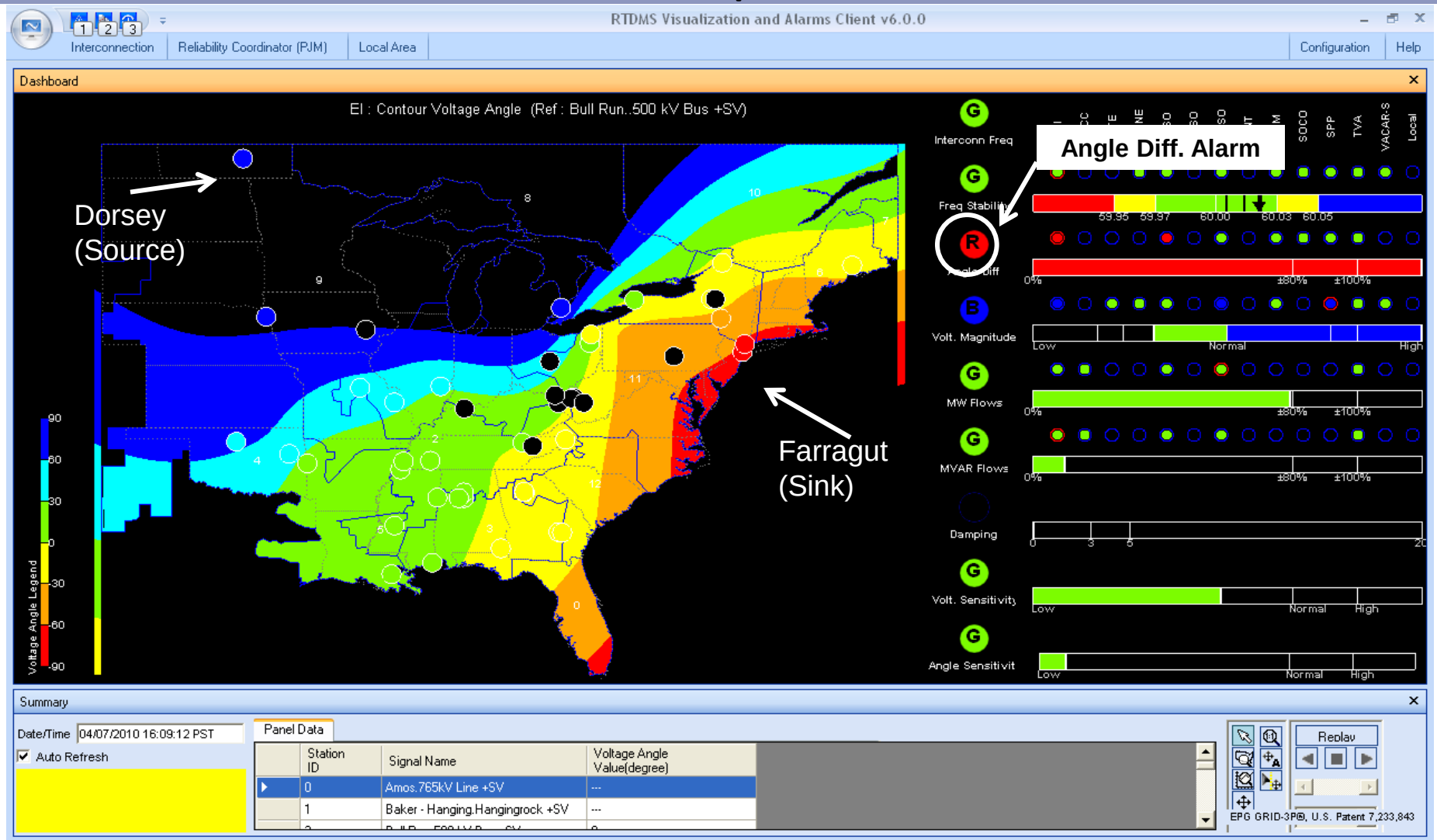


Electric Power Group

CERTS
CONSORTIUM FOR ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

RTDMS Phase Angle Contour Plot

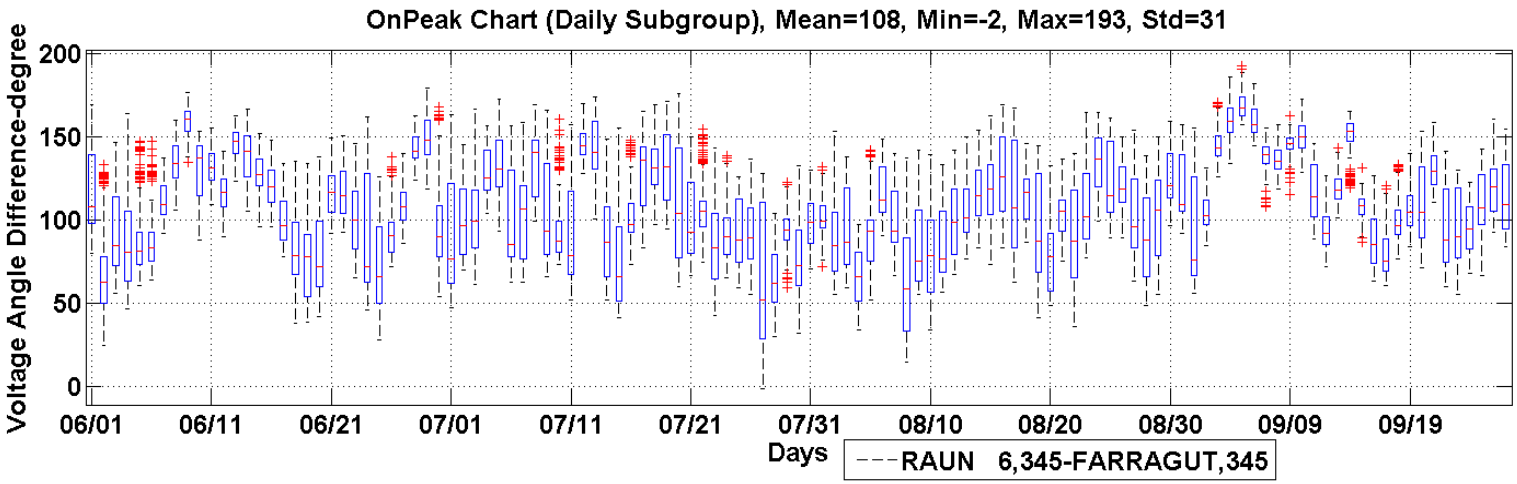
16:09 PDT April 7, 2010

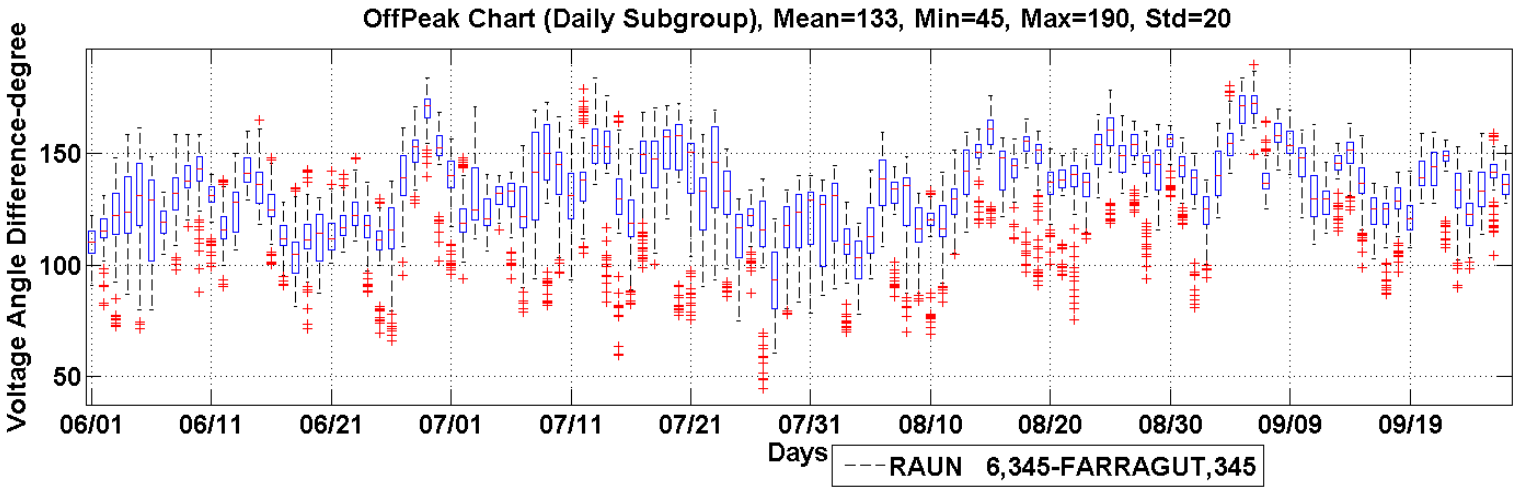


Electric Power Group

CERTS
Consortium for Electric Reliability Technology Solutions

Raun- Farragut Daily Angle Difference Data
Summer 2008, 5-Minute State Estimator Snapshot

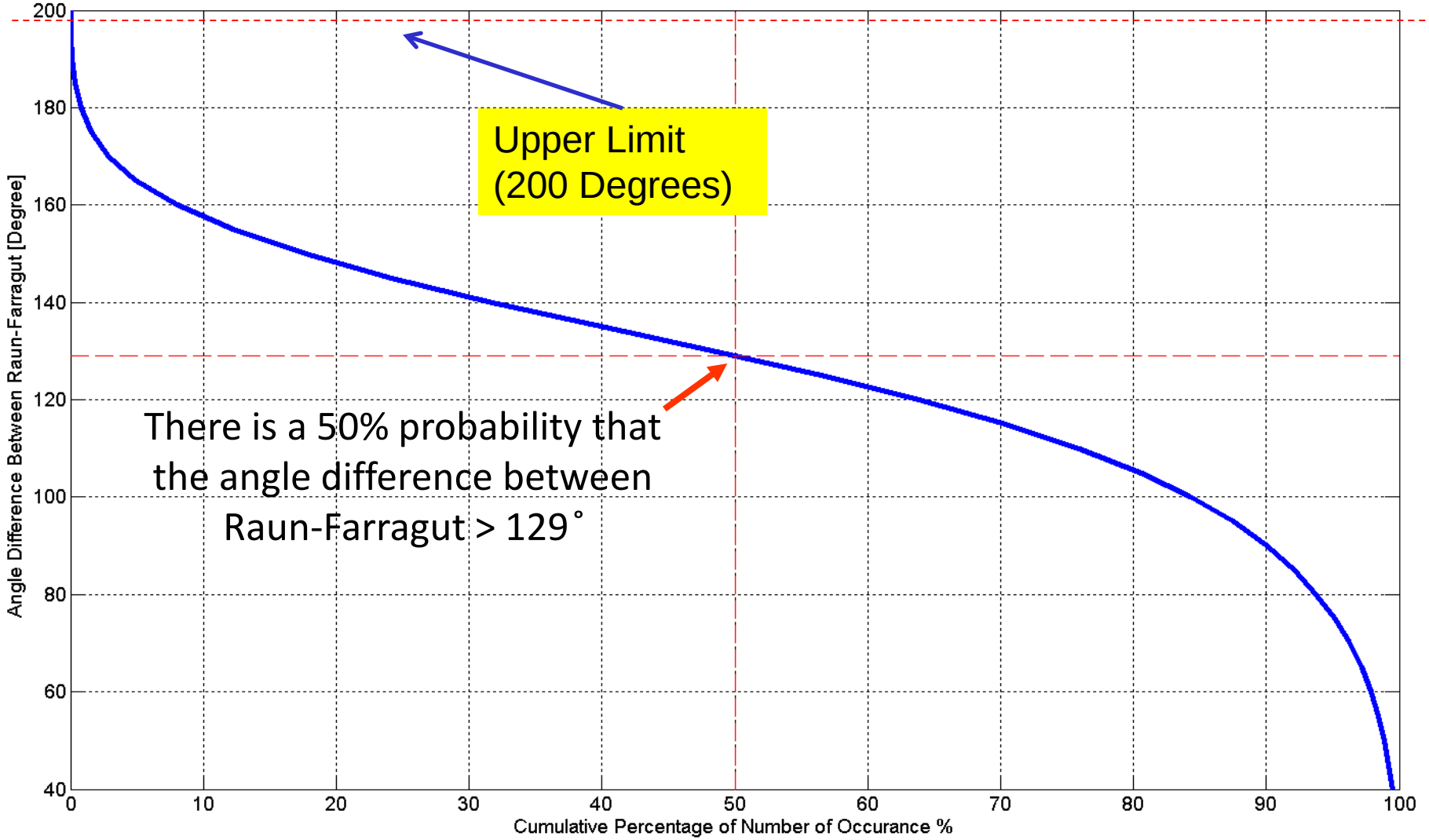




Electric Power Group

CERTS
Consortium for Electric Reliability Technology Solutions

Duration Curve: Raun-Farragut Angle Difference -- All 5 Seasons Data



Angle Difference Data (Max-Min Limits) for Summer 2009

PJM Angle Pair Summer 2009 Analysis														
			OnPeak (Degree)				Suggested Limits		OffPeak (Degree)				Suggested Limits	
Source	Sink	KV	Mean	Min	Max	Std	Max	Min	Mean	Min	Max	Std	Max	Min
QuadCities	Zion	345	24	-62	37	5	40	10	26	-2	37	4	40	10
QuadCities	WiltonCtr	345	22	-60	35	6	40	0	26	-4	36	4	40	0
QuadCities	Powerton	345	10	-69	28	7	30	-10	16	-6	29	4	30	-10
Zion	Dumont	345	7	-29	44	8	25	-30	11	-18	23	4	25	-20
Powerton	Dumont	345	21	-3	51	6	35	-5	22	5	34	4	35	5
WiltonCtr	Dumont	345	10	-12	43	4	25	-10	12	-3	18	2	20	-5
Dumont	ErieWest	345	21	-31	47	10	45	-25	24	-17	43	6	45	-20
Baker	Dooms	500	30	11	43	5	45	10	32	15	44	4	45	15
WylieRidg	Conastone	500	32	-1	51	7	50	10	28	5	47	6	50	5
Belmont	Dooms	500	25	11	39	4	40	10	28	14	42	4	40	10
JacksonsF	Cloverdale	765	4	1	42	1	10	0	5	3	15	1	8	2
Yukon	Carson	500	23	5	41	6	40	0	18	4	36	5	35	5
ErieWest	Branchbur	345	38	4	62	10	60	0	31	1	55	9	60	0
Raun	Farragut	345	124	11	194	27	190	0	125	41	189	17	190	40

Event Summary

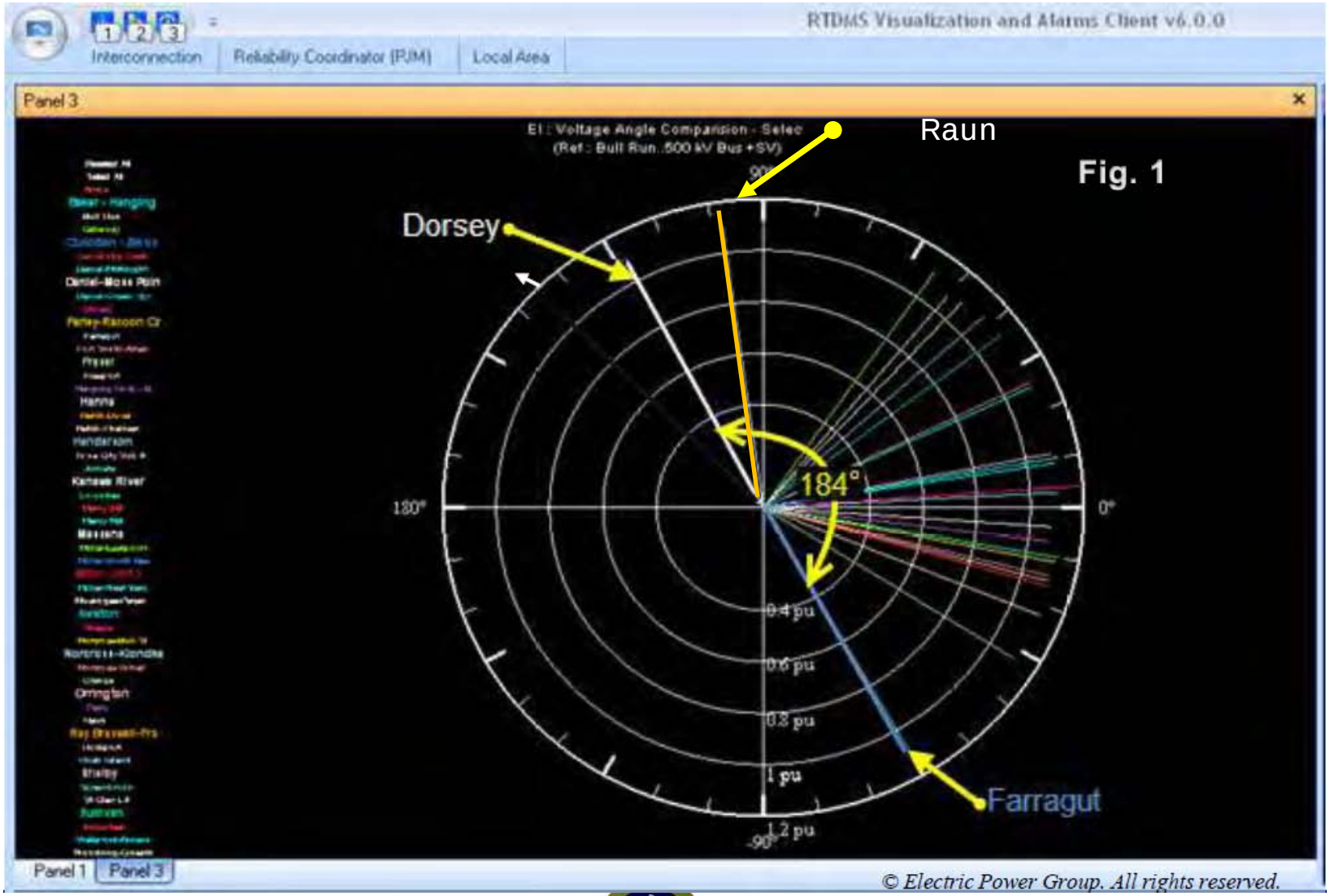
- Oscillations with low damping observed on April 7, 2010 at about 15:44-15:47 PDT
- Post event analysis shows
  - High angles difference (greater than 180^{o}) seen between Dorsey and Farragut
  - Dynamic Analysis confirmed 0.2 Hz modal frequency damping falling below 3%
  - High modal energy observed at 0.2 Hz associated with the low modal damping
  - Low damping of oscillations between Dorsey and Farragut observed in the phase angle difference plot
  - Oscillations with peak to peak amplitude of up to 4^{o}
- Analysis Data can be retrieved from RTDMS report website in .csv file format

DISCLAIMER

- Results based on real time data from TVA's NASPI PDC
- Data quality and reliability not verified or validated
- Damping and mode meter displays continue to be evaluated for validity and accuracy
- Purpose of sharing results is to invite dialogue and feedback to improve models, displays and use ability of RTDMS
- Analysis performed with off-line tools to validate observations to the extent possible
- EPG continuing to analyze mode meter performance under different operating conditions eg results may be better when damping is below 5%

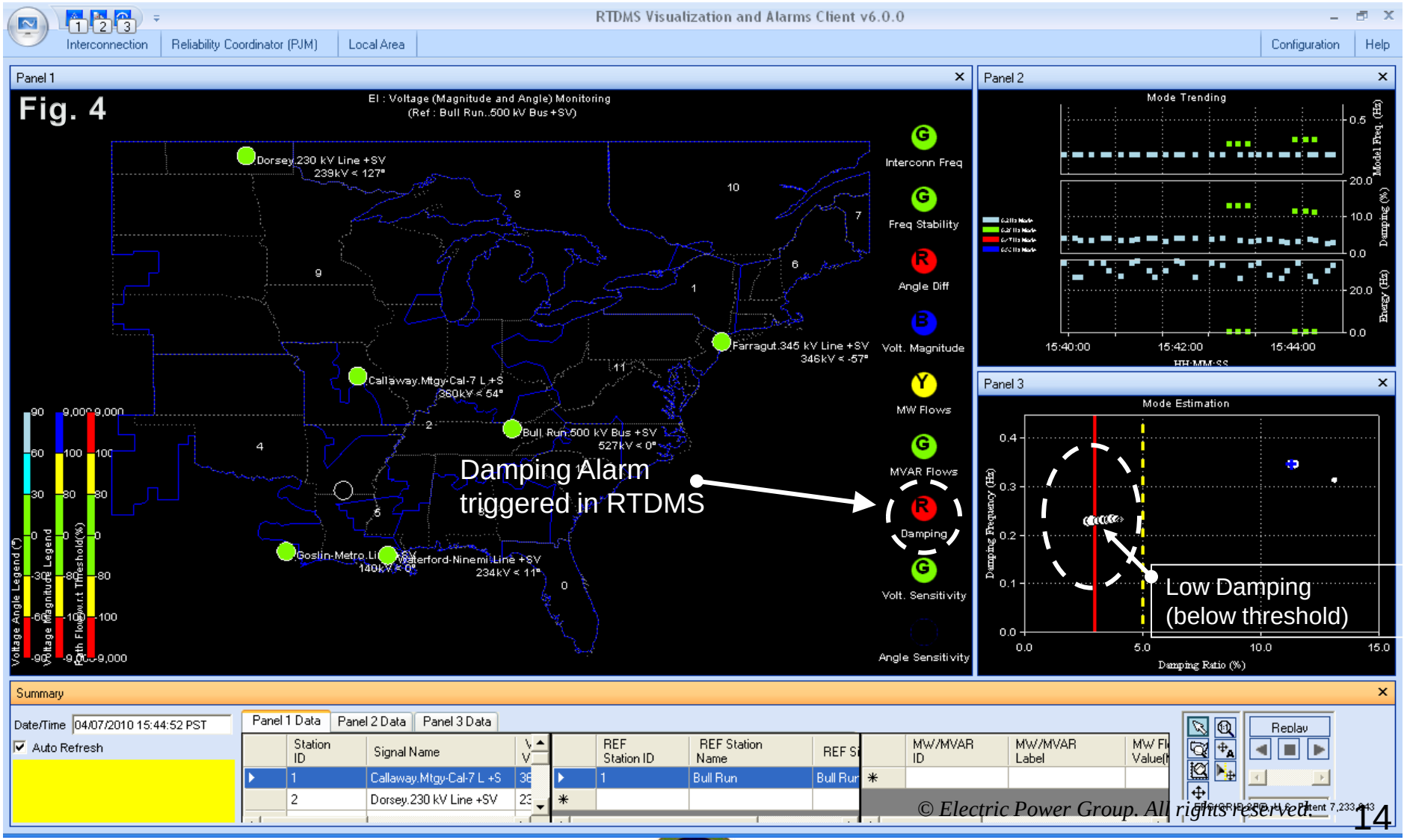
RTDMS Phase Angle Comparison

16:09 PDT April 7, 2010



RTDMS Modal Meter

16:09 PDT April 7, 2010

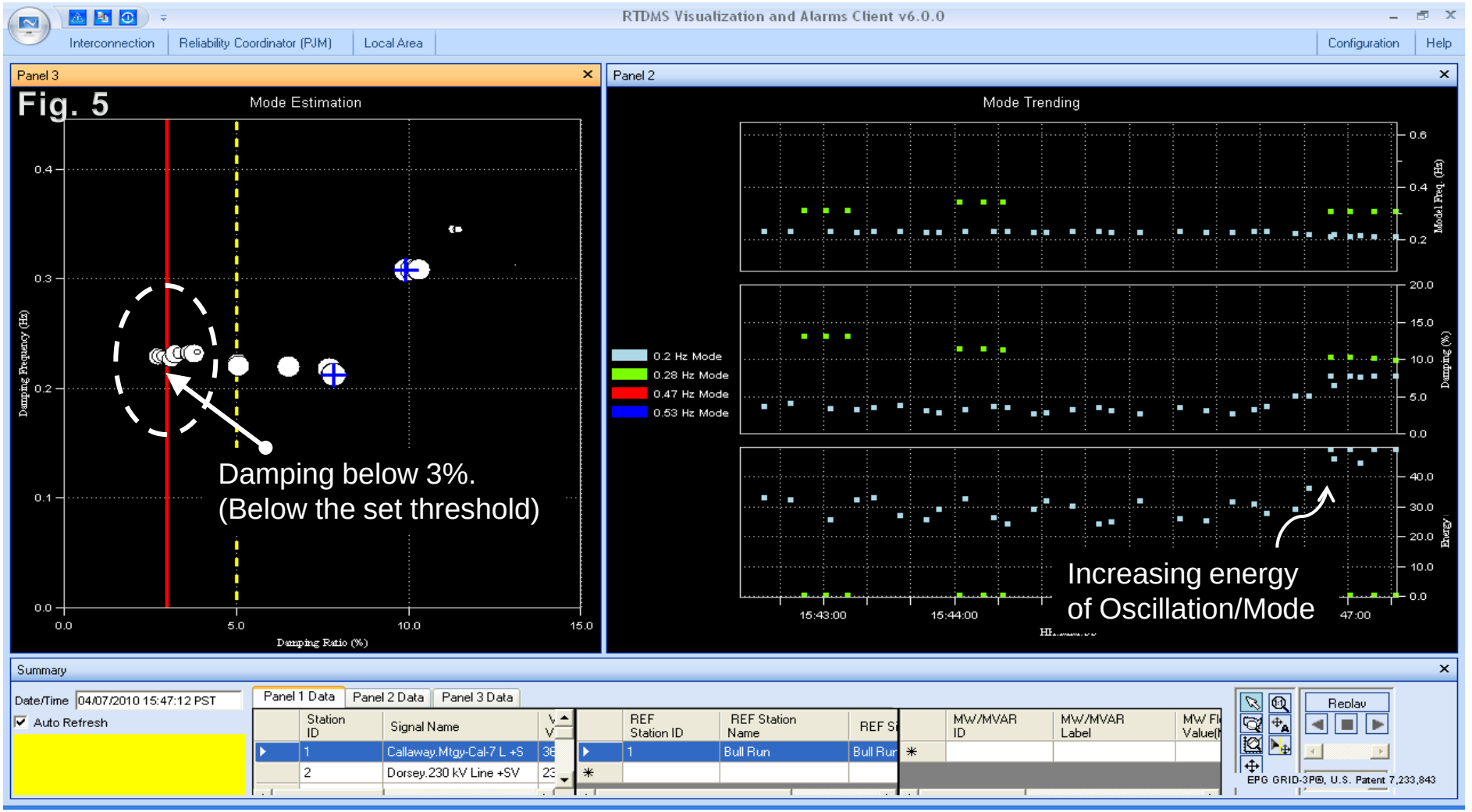


Electric Power Group

CERTS
Consortium for Electric Reliability Technology Solutions

RTDMS Modal Meter

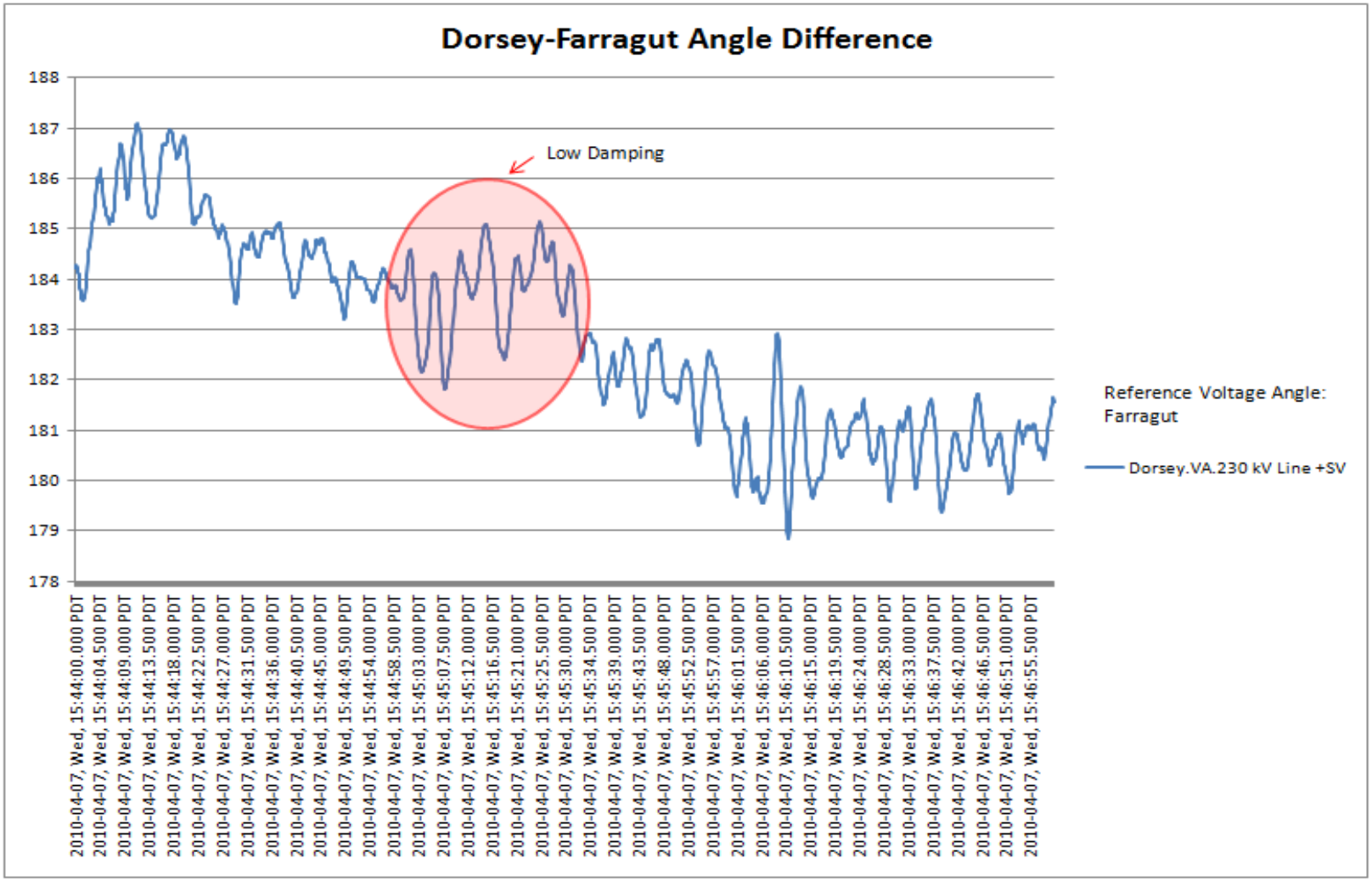
16:09 PDT April 7, 2010



Electric Power Group

CERTS
Consortium for Electric Reliability Technology Solutions

Phase Angle Difference Plot between Dorsey and Farragut showing Low Damping



Eastern Interconnection Base Lining Progress Summary

1) Completed statistical analysis of angle pairs using State Estimator data from PJM
2) Identified high stress days and correlate flowgate phase angle date with voltage and MW data
3) Results under review for use in establishing metric thresholds and comparison with power flows
4) Future analysis needed:
   a) Extend analysis to the entire eastern interconnection and other base line other system parameters
   b) Wide area stress monitoring – data available for Raun and Farragut. Would be preferable to get additional wide area angle pairs for monitoring

Thank You.

Any questions ?

Phase Angle Base Lining Study
Western Interconnection

NASPI Meeting

Vancouver, Canada

June 9, 2010

Sponsor : Dmitry Kosterev, BPA

Electric Power Group Team

Bharat Bhargava, Jim Dyer, Abhijeet Agarwal, Ajay Das, Song Xue

Why Base Lining is important

Base Lining is needed to make the Synchro-Phasors tools useable in real time control room environment for use by operators

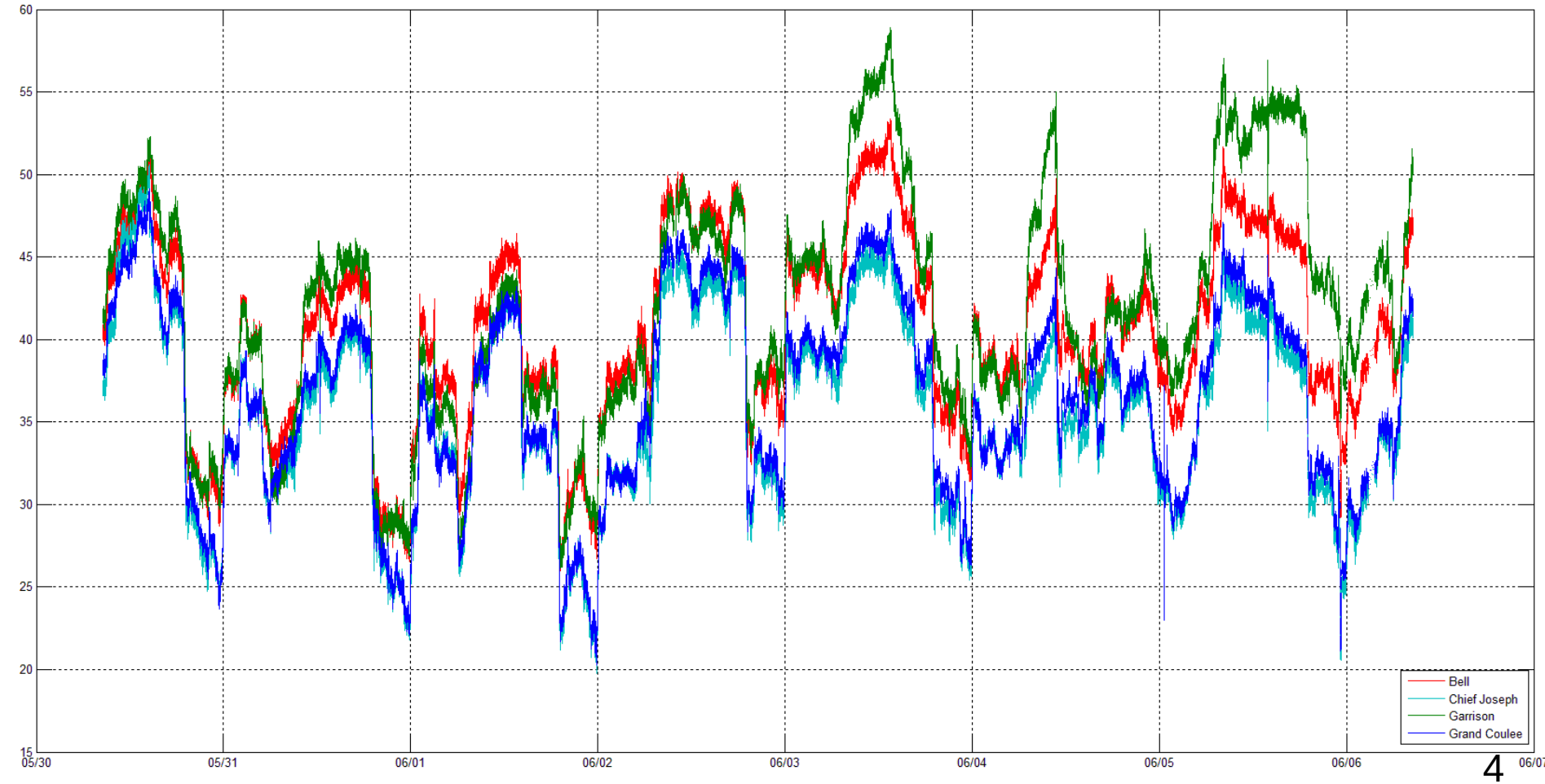
1. Understand operational norms – phase angle differences based on seasonal, on-peak, off-peak, stressed conditions etc.
2. Establish high, medium and low levels for thresholds for various angle pairs based on statistical analysis
3. Validate thresholds and models by event analysis and off-line analysis
4. Compare and validate angle limits with State Estimators or off-line power flow analysis
5. Utilize base lining results to establish meaningful alarms that can be relied upon by operators
6. Base lining is essential for all system parameters. Presently we have concentrated on Phase angle differences for selected angle pairs

Western Interconnection Base Lining study

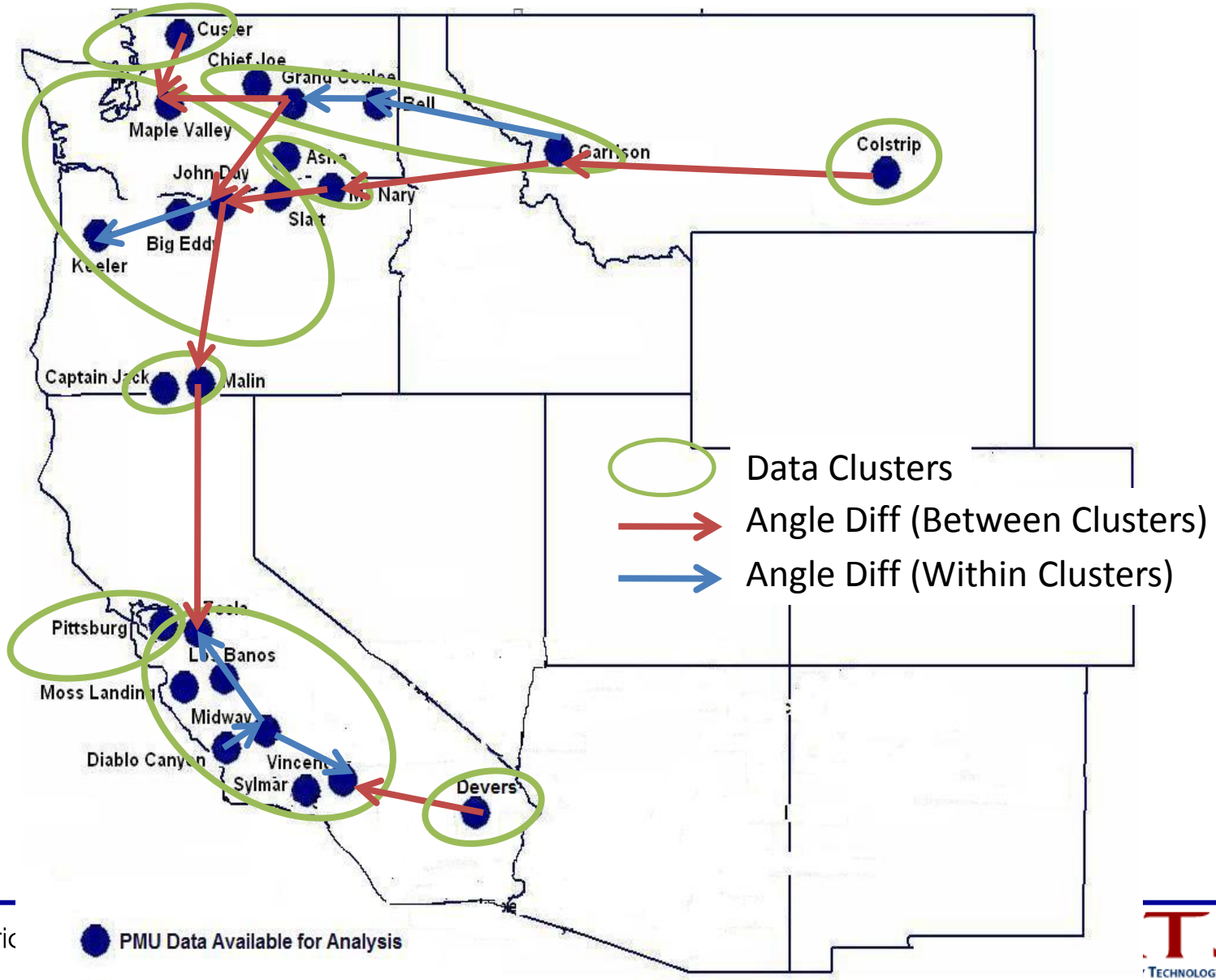
Work Accomplished:

1. Analyzed 12 months of Phasor Measurement system data received from BPA at 30 samples per second
2. Extracted bus voltage angle and magnitude data from the PMU data
3. Identified angle pairs that are of interest to BPA
   - Local area (Colstrip-Garrison, Colstrip-Grand Coulee)
   - Wide area (Grand Coulee-Malin, Grand Coulee-Tesla)
4. Conducted statistical analysis on the selected angle pairs for various seasons, on-peak/off-peak data
5. Current Process: defining limits and validating them with system events and validating with power flows

Data Clustering: Cluster 1 - Bell, Chief Joseph, Garrison, Grand Coulee

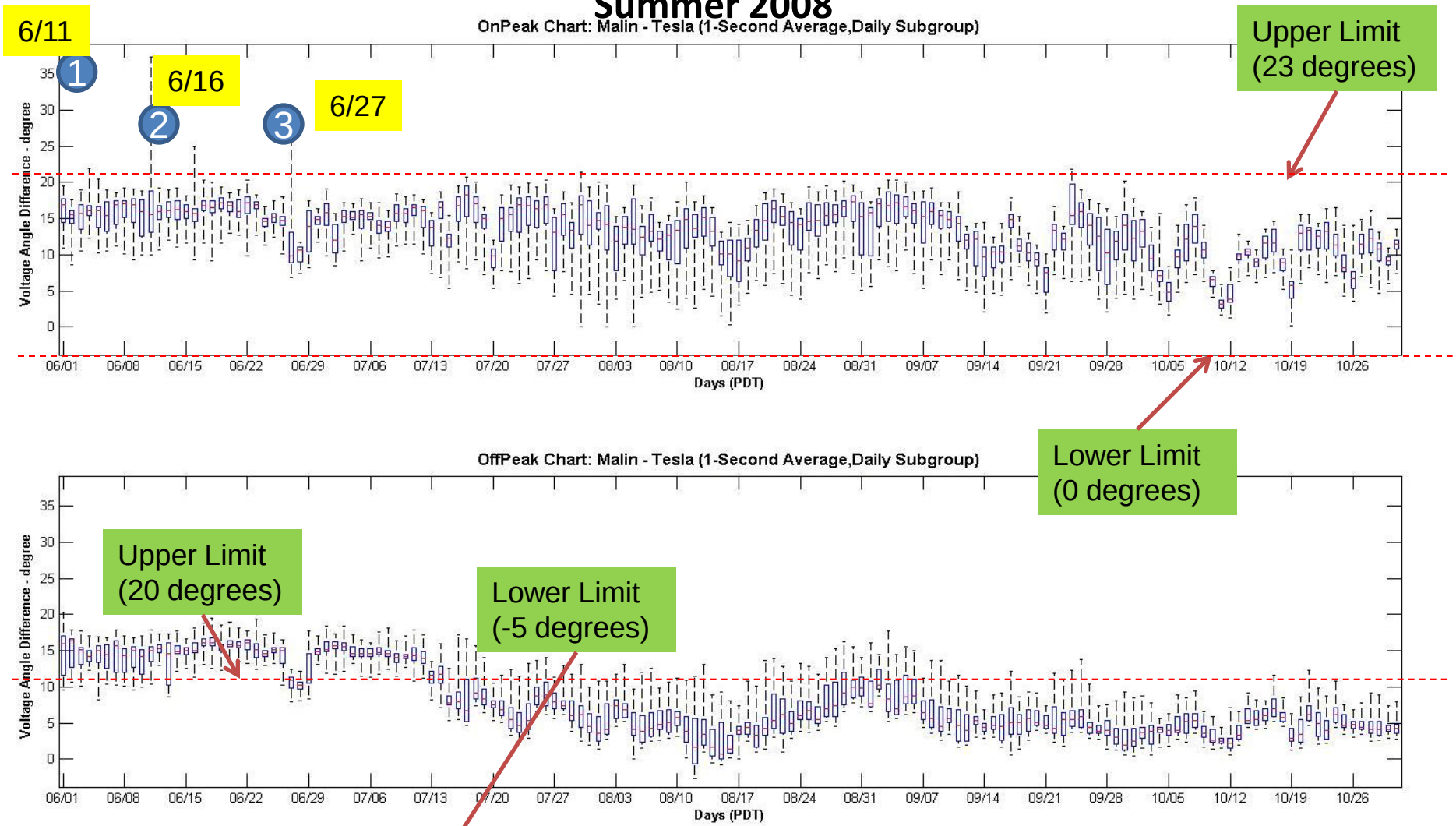


Data Clustering Results - Geographical Display of 9 Clusters



Statistical Analysis and Validation of Thresholds
Malin – Tesla Daily Angle Difference Data

Summer 2008

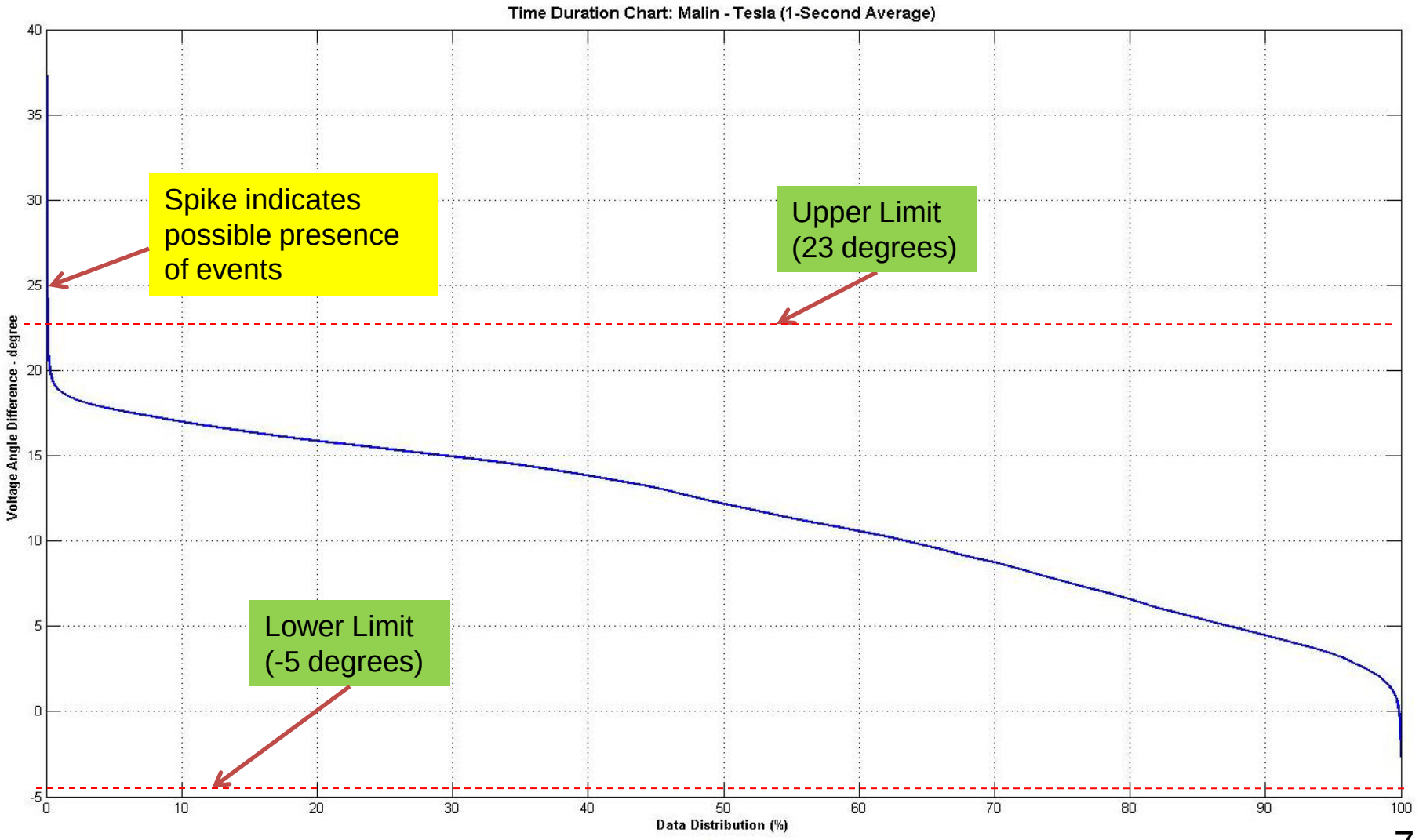


Electric Power Group

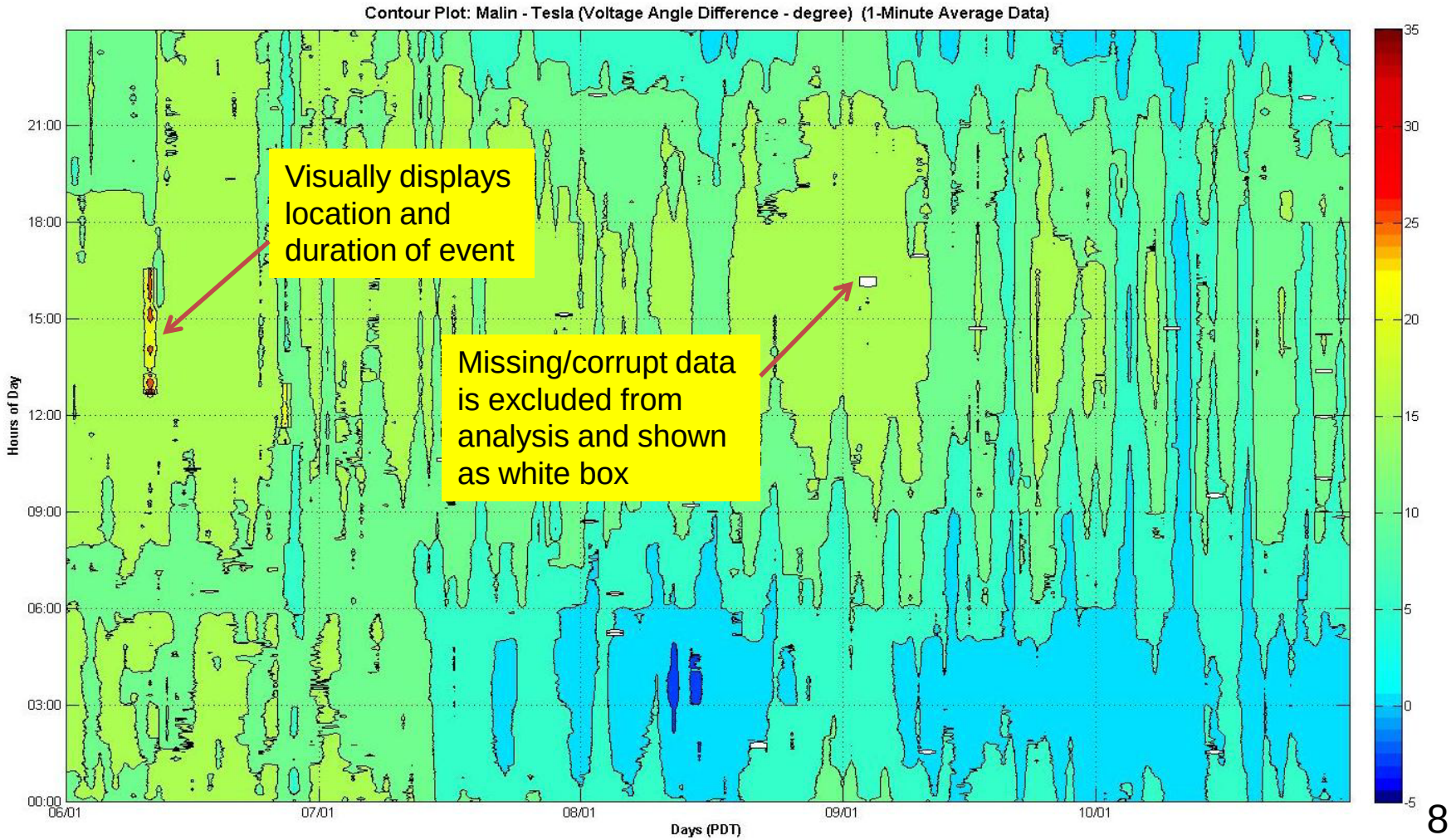
CERTS
Consortium for Electric Reliability Technology Solutions

Duration Curve: Malin – Tesla Angle Difference Data

Summer 2008



Contour Plots
Malin Tesla Angle Difference Data (Hour of Day)
Summer 2008

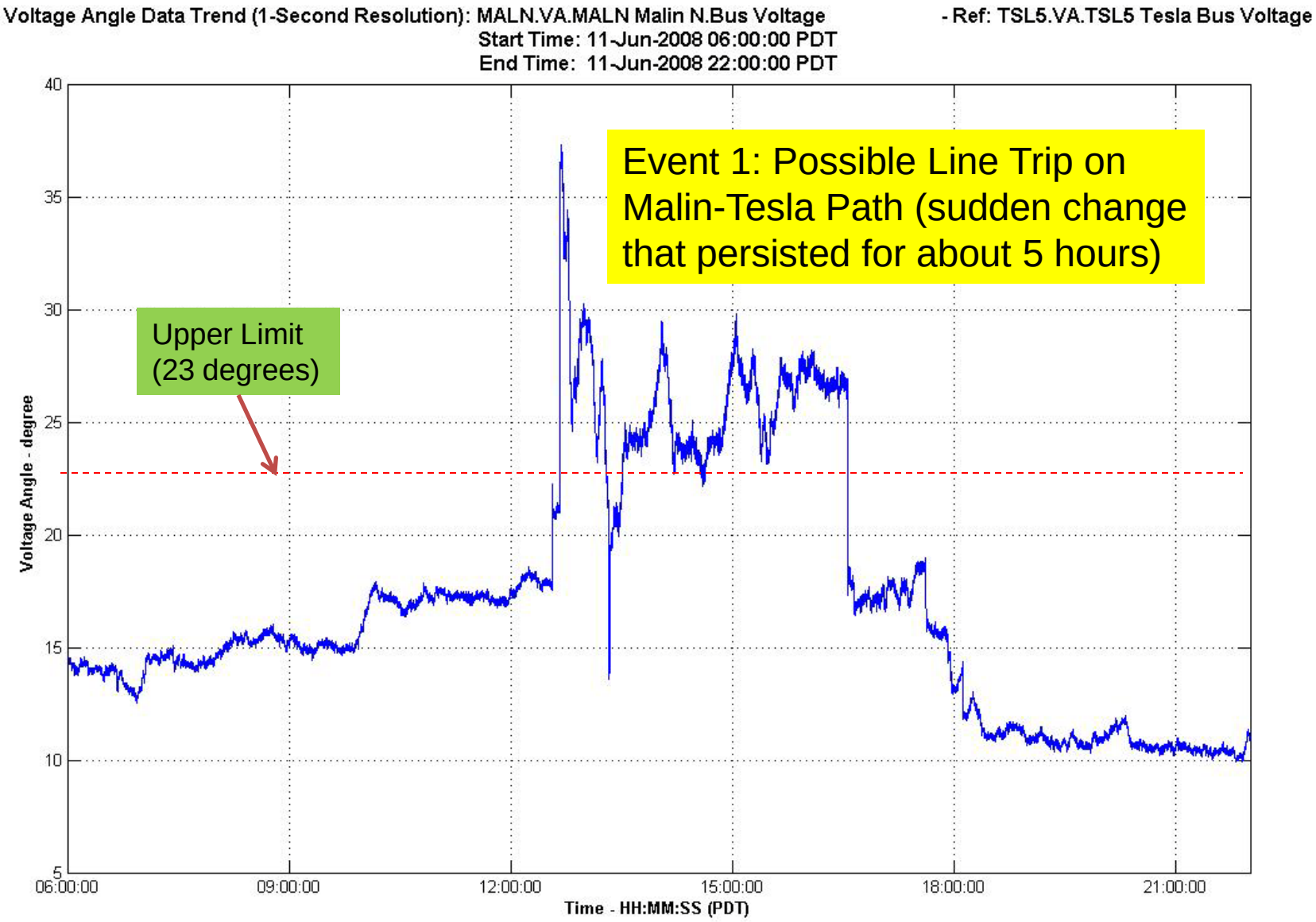


Electric Power Group

CERTS
Consortium for Electric Reliability Technology Solutions

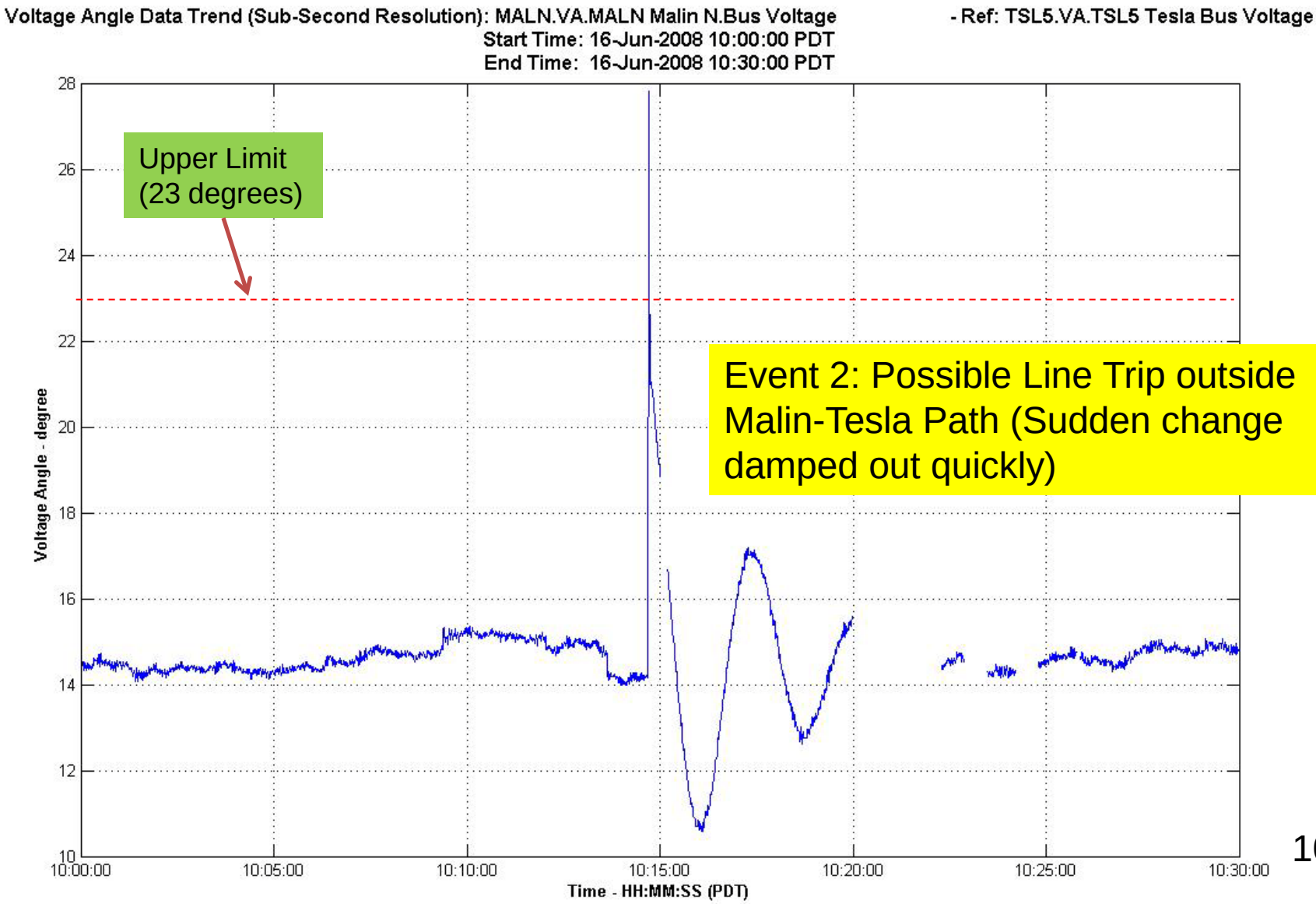
Validation of Thresholds with Disturbance Data

Event 1: Malin-Tesla 06/11/08 (on-peak hours)



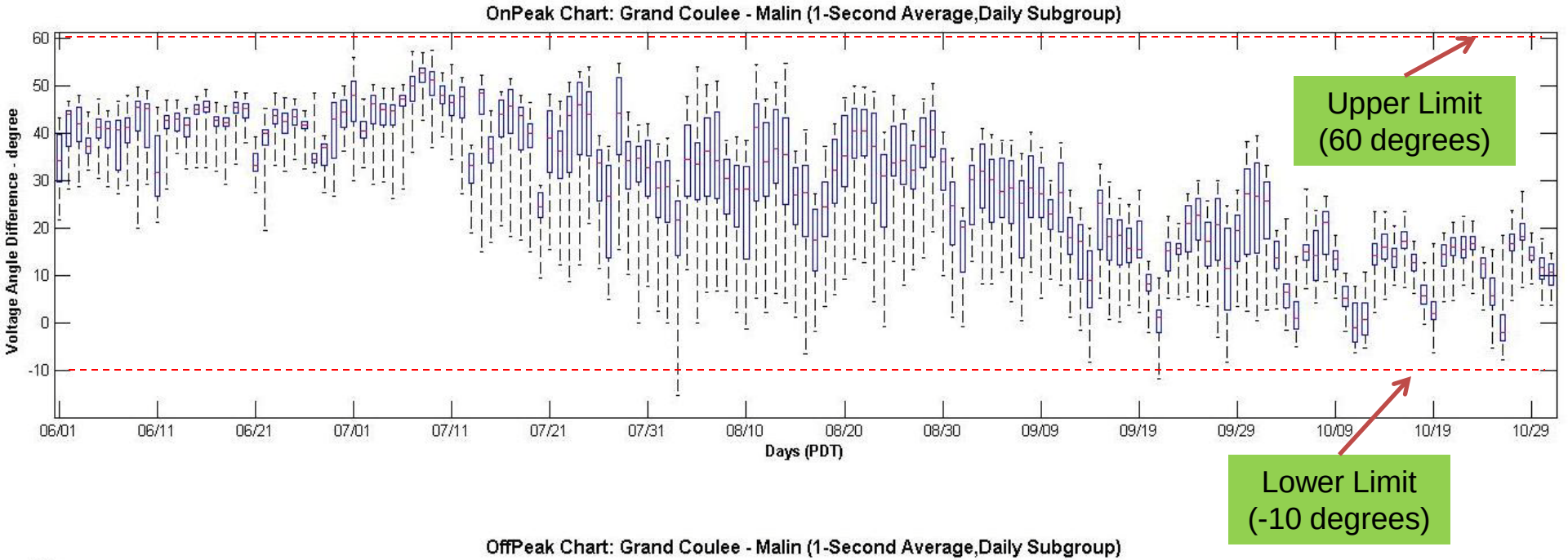
Validation of Thresholds with Disturbance Data

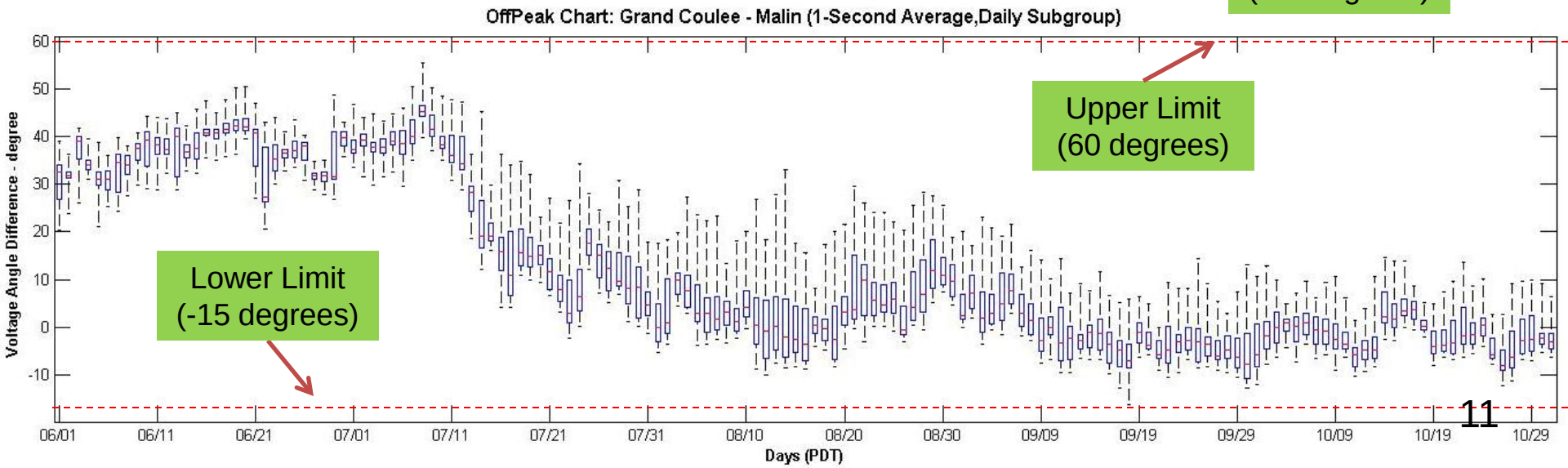
Event 2: Malin-Tesla 06/16/08 (on-peak hours)



Grand Coulee – Malin Angle Difference Data

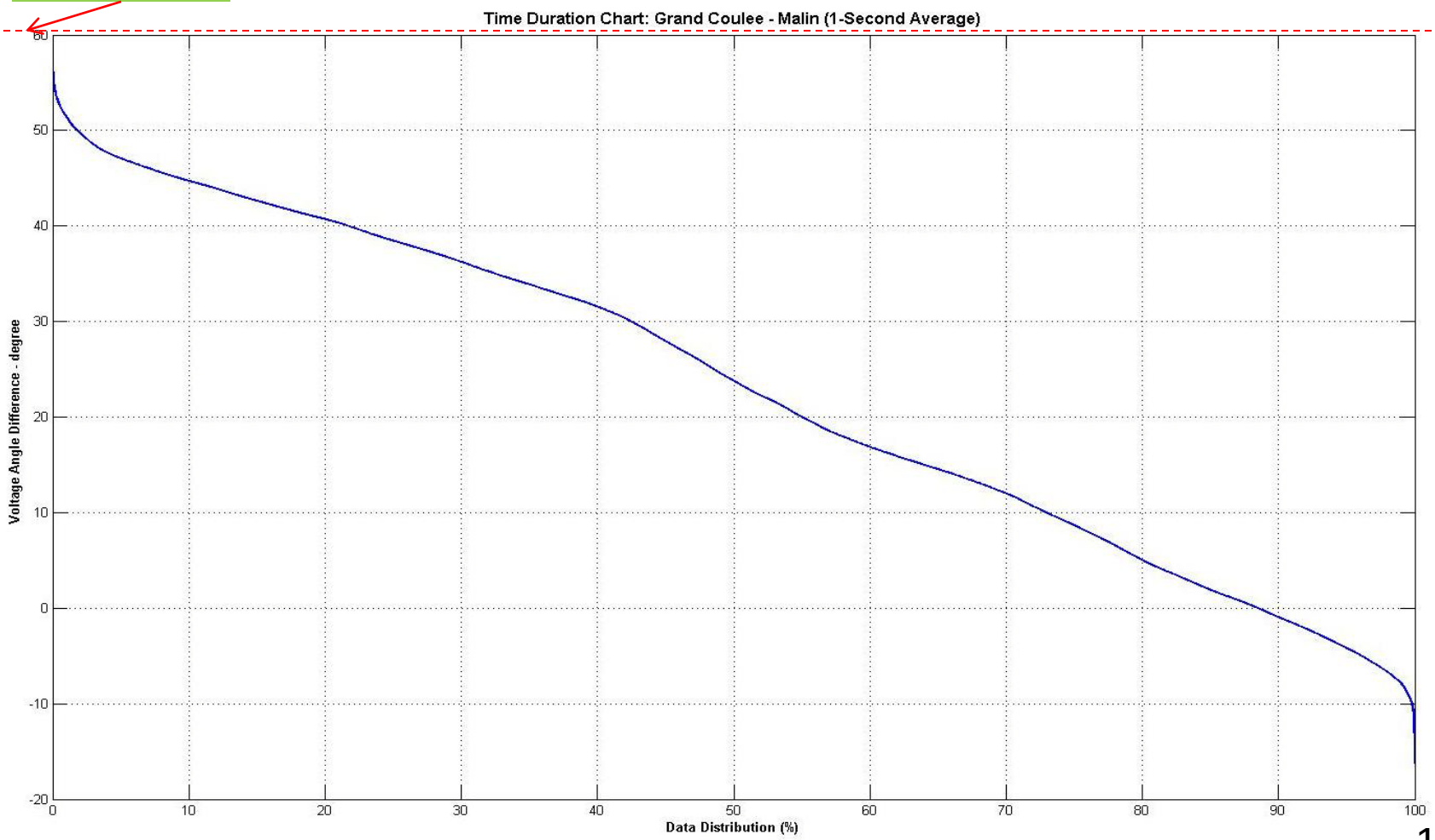
Summer 2008





Duration Curve: Grand Coulee – Malin Angle Difference Data Summer 2008

Upper Limit
(60 degrees)

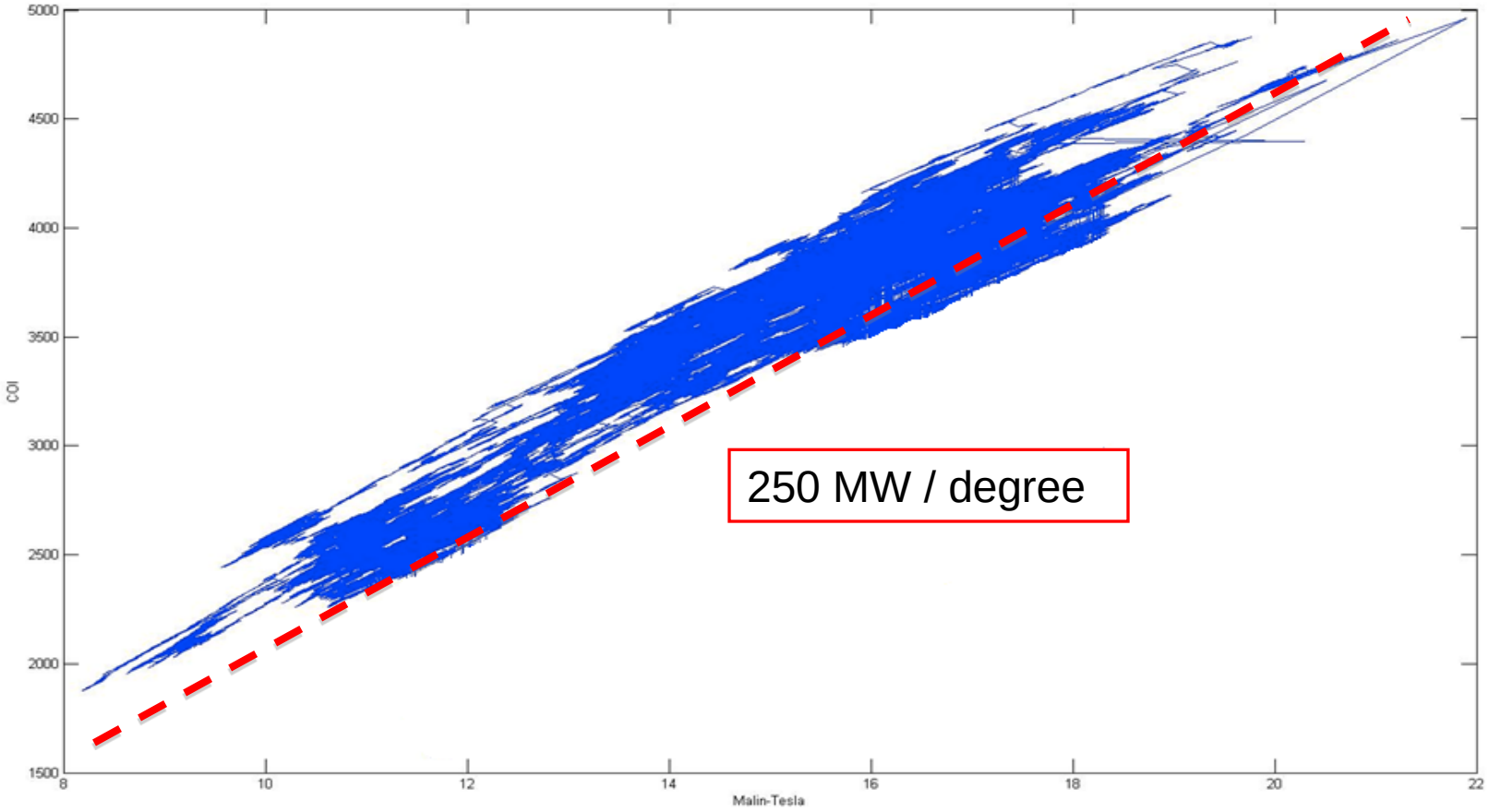


Base Lining Study Results: Angle Difference Alarm Limits

Summer 2008

Angle Difference Pair	On Peak High	On Peak Low	Off Peak High	Off Peak Low	Suggested Limit
Colstrip-Garrison	30	-4	30	0	30
Garrison-Bell	40 (25)	-5	40 (25)	-5	30
Garrison-McNary	35	0	35	0	35
McNary-JohnDay	15	0	15	0	15
Bell-GrandCoulee	11	-2	12	-2	12
GrandCoulee-JohnDay	35	-15	35	-15	35
GrandCoulee-MapleValley	25	6	23	6	25
Custer-MapleValley	15	-15	15	-16	15
JohnDay-Keeler	20 (15)	-7	16	-3	20
JohnDay-Malin	25	-2	25	-5	25
Malin-Tesla	23	0	20	-5	25
Grand Coulee - Malin	60	-10	60	-15	60

Performance Metric - Angle Sensitivity
Power–Angle Curve: COI (MW) Vs. Malin-Tesla (Deg)

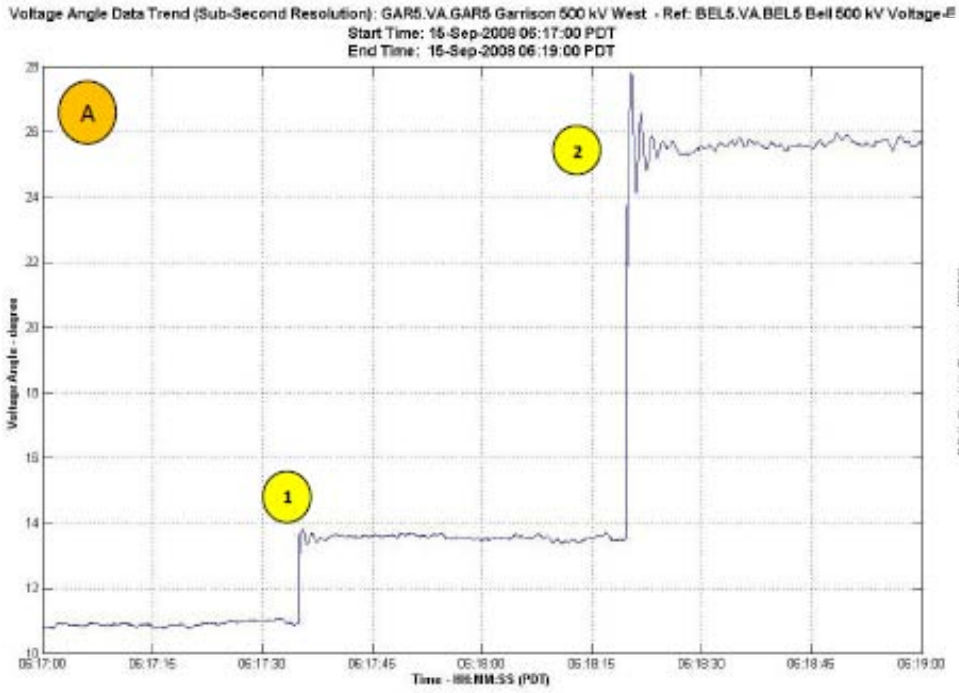


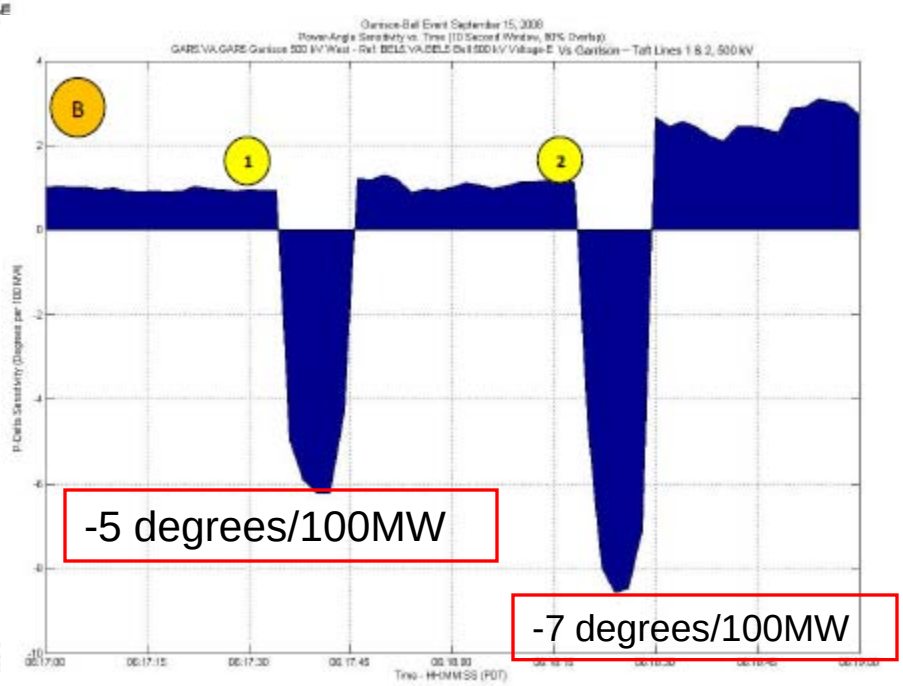
Angle Difference – Malin-Tesla (Degrees)

14

1 Week Data

Event Detection using Angle Sensitivities During Transient System Conditions





Voltage Angle Difference between Garrison-Bell for events 1 & 2

Power-Angle Sensitivity over time (Garrison – Bell)

Angle Sensitivities used to identify abnormal system conditions

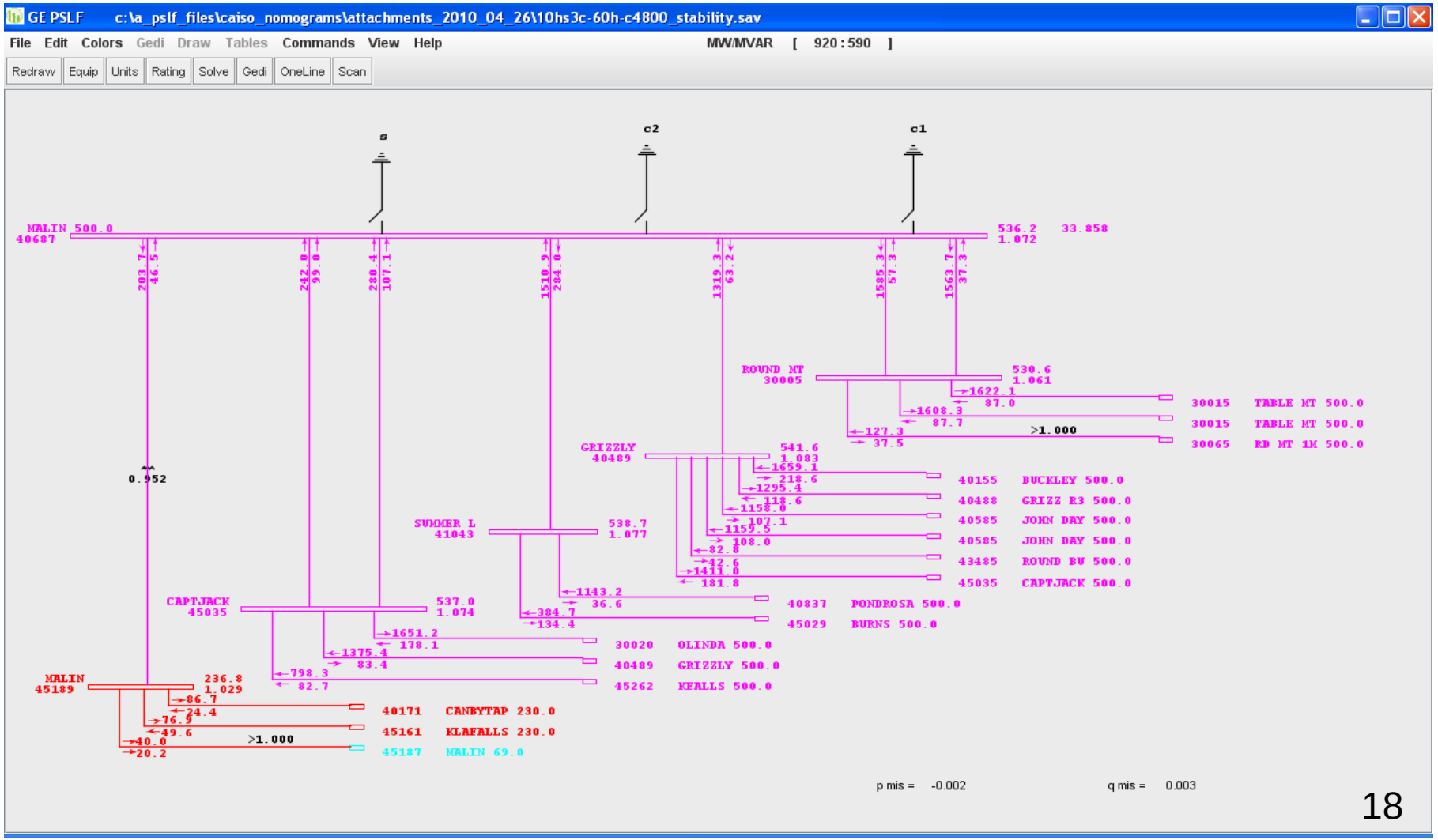
Western Interconnection Base Lining Studies

Comparison/Validation of 2008 Base Lining Results with 2010 Heavy Summer (HS) Stressed Power Flow Case

2010 Heavy Summer Stressed Base case Power Flows on Major Paths

Pacific AC Interties	4,800 MW
Pacific DC Intertie	3,100 MW
Midway-Vincent Path 26	3,712 MW
Devers-Palo Verde	1,585 MW
Colstrip Gen	1,938 MW
Diablo Cyn. Generation	2,273 MW
SONGS Generation	2,150 MW
Palo Verde Generation	4,029 MW

Power Flow screen shot – Malin substation



Comparison of Angle Difference Pairs

Angle Difference Pairs	2010 Heavy Summer	2008 Base Lining
Colstrip - Garrison	24.63	30
Garrison - Bell	2.954	30
Garrison - McNary	20.64	35
McNary - John Day	12.89	15
Bell - Grand Coulee	0.973	12
Grand Coulee - John Day	32.56	35
Grand Coulee - Maple Valley	11.18	25
Grand Coulee – Malin	56.67	60
Custer - Maple Valley	15.18	15
John Day - Keeler	2.516	20
John Day - Malin	24.11	25
Malin - Tesla	20.12	25

Western Interconnection Base Lining Study Summary / Conclusions

- Based on review of one year synchro-phasor data from BPA
- Results compared with 2010 HS Stressed Power flow case
- The results can be used for real-time monitoring and alarming
- The data can be used to establish low, normal, high, or abnormal loading conditions
- Limits evaluated for
  - Different important paths within BPA system
  - Wide Area angle pairs analysis needs to be performed

These studies need to be extended to include data for the entire Western Interconnection, and should be an ongoing process as the system is constantly changing because of the addition of wind generation, transmission lines, and changing market conditions

Thank You.

Any questions ?

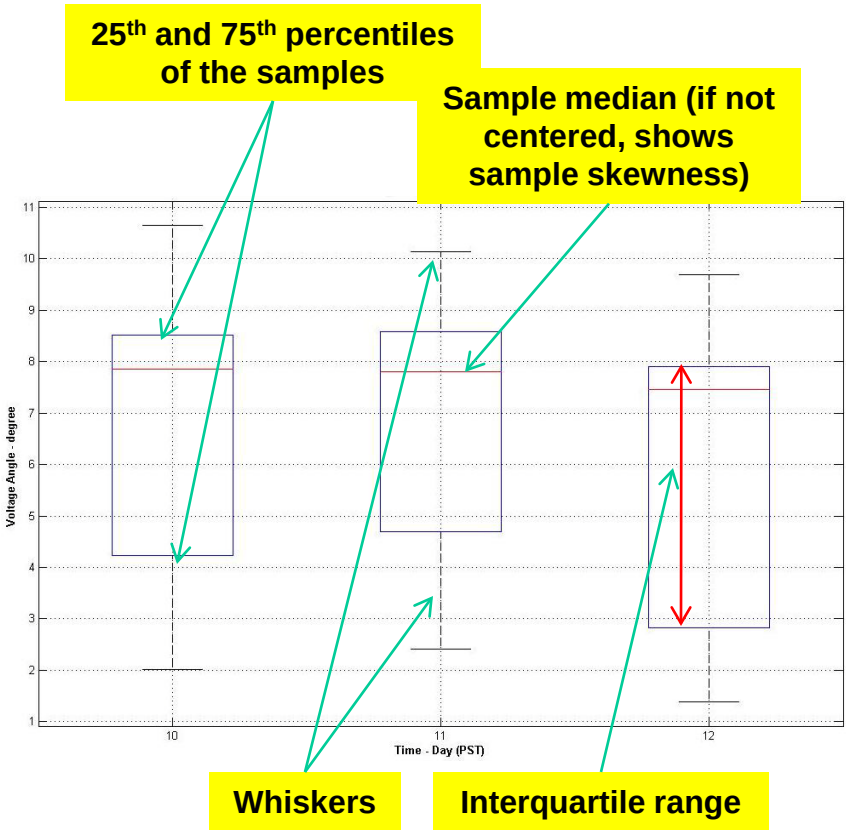
Western & Eastern Interconnection Base lining Studies

Process Flow of Study:

1. Identify Data Clusters
2. Define Angle Difference Pairs
3. Statistical Analysis of Angle Differences for the Angle Pairs (seasonally, hourly, etc.)
4. Establish Metric Thresholds
5. Validate Thresholds with Disturbances and offline studies
6. Analyze System Performance using Sensitivities

Box-Whisker Charts

- Daily box-whisker charts:
  - Data is grouped by on-peak and off-peak hours for each day.
  - Shows the data distribution for each day and its variation over the analysis duration.
  - Helps in setting alarm limits and flag any unusual behavior of data.
- Hourly box-whisker charts:
  - Data is grouped by each hour of day and days separated into weekdays and weekends.
  - Shows the data variation between hours of day and data distribution within same hour over all weekdays and weekends in analysis duration.
  - Helps understanding hourly variation in voltage angle data.



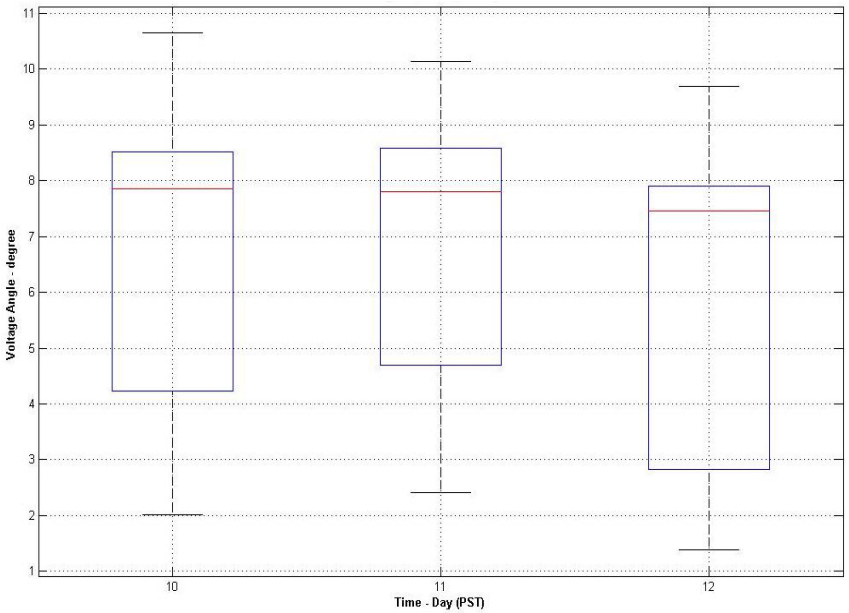
Time Duration Charts

Daily box-whisker charts:

- Data is grouped by on-peak and off-peak hours for each day.
- Shows the data distribution for each day and its variation over the analysis duration.
- Helps in setting alarm limits and flag any unusual behavior of data.

Hourly box-whisker charts:

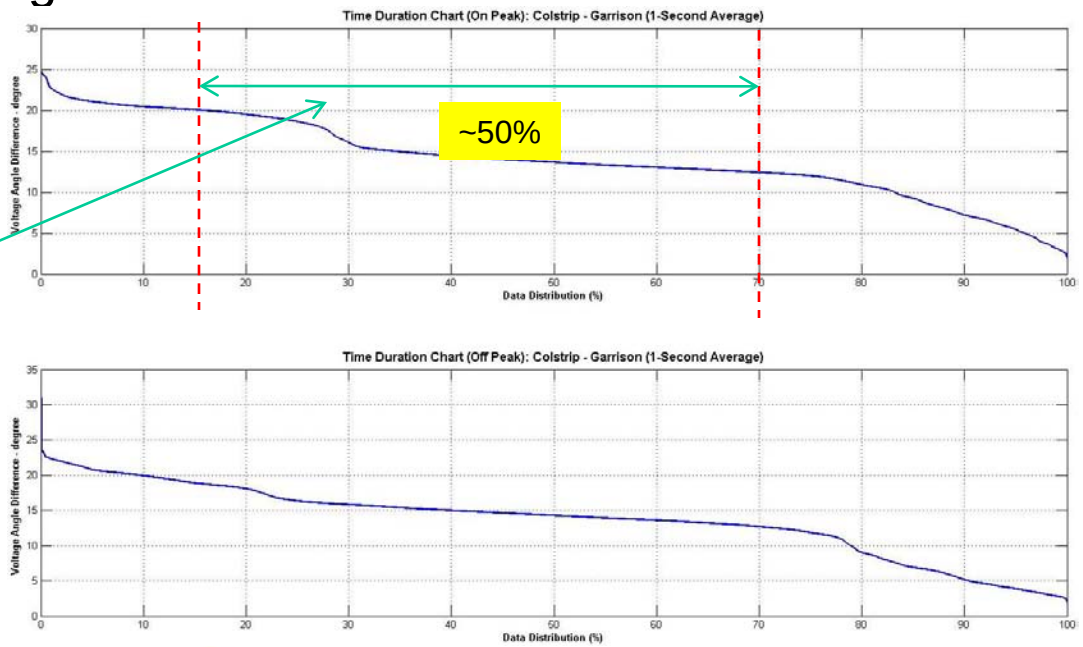
- Data is grouped by each hour of day and days separated into weekdays and weekends.
- Shows the data variation between hours of day and data distribution within same hour over all weekdays and weekends in analysis duration.
- Helps understanding hourly variation in voltage angle data.



Time Duration Charts

- The data is split into on-peak and off-peak hours, which is then sorted and plotted from maximum to minimum value.
- The chart displays the data distribution percentage between the maximum and minimum data values during on-peak and off-peak hours.
- The data can be visually grouped to determine the percentage of data between desired data range.

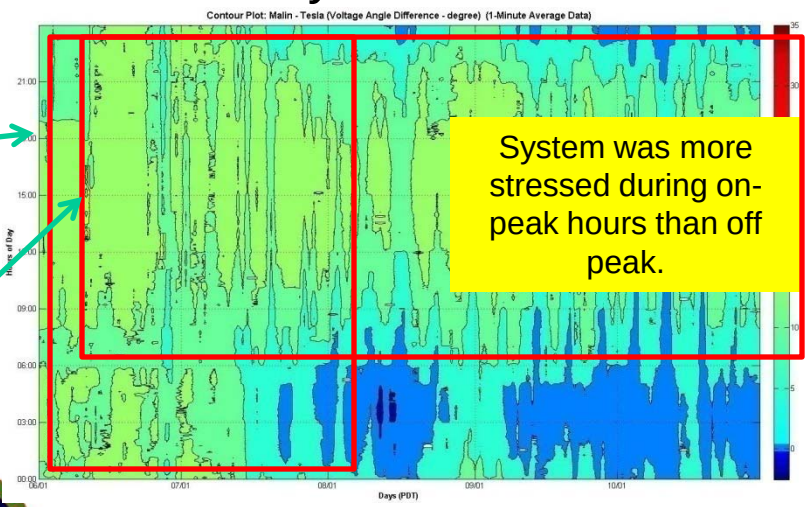
On-peak angle difference between Colstrip to Garrison remained between 10-15 degrees for about 50% of the time



Contour Plot

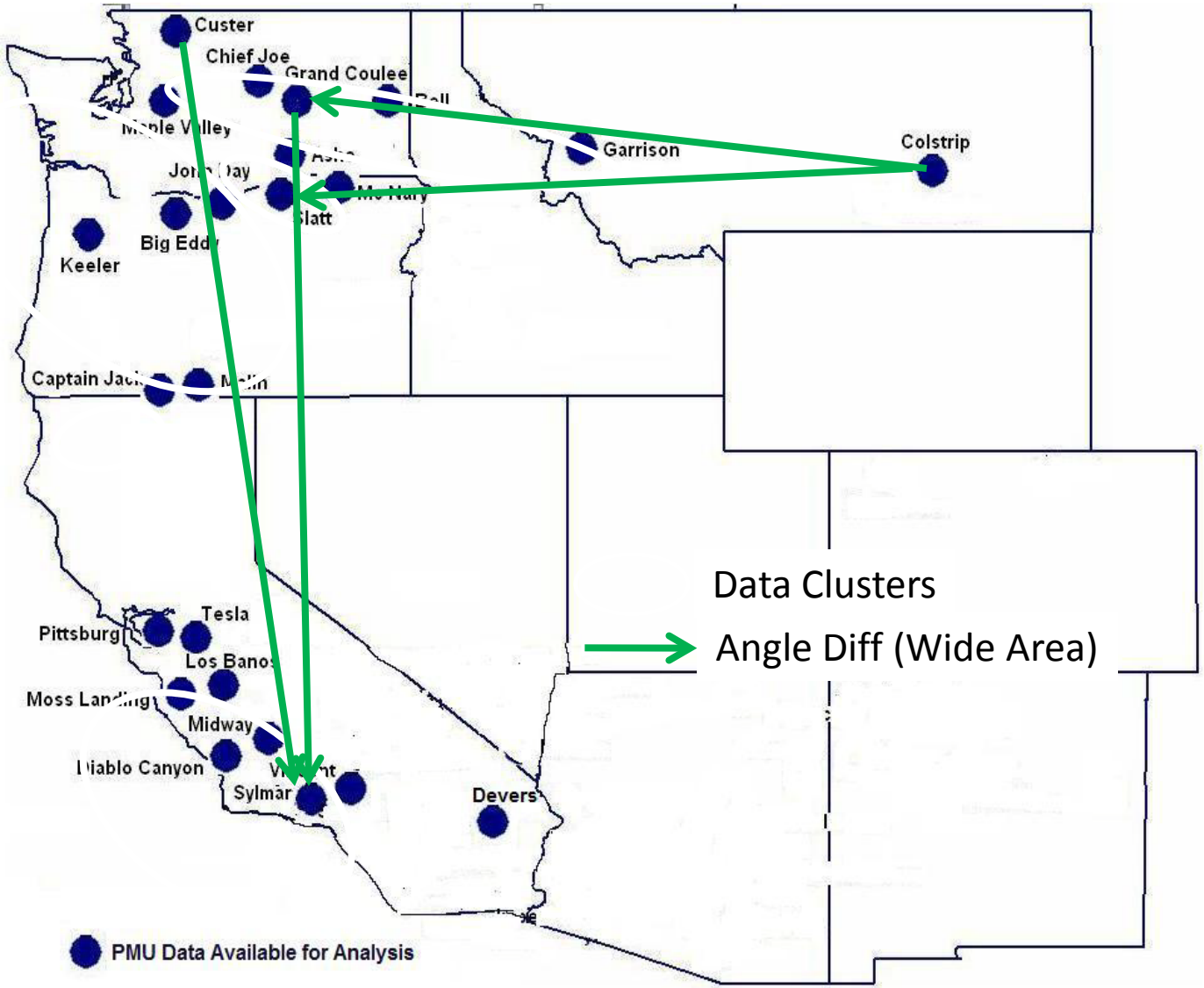
- For the 2-D contour plot, the data was grouped by days and plotted with days on x-axis and time on y-axis.
- 1-minute average data is used due to higher computational requirements when 1-second average data was used. The analysis results were not affected by using lower resolution data.
- Voltage angle difference values were used to draw contour lines and colored accordingly with gradient from blue (low) to red (high) .
- This plot provides capability of visually analyzing how voltage angle difference varies within a day and across days and months. Highly stressed days and long-term events can be easily identified and further investigated.

Contour plot for summer (Jun-Oct) for Malin to Tesla angle difference data reveals that system was more stressed during months of June and July.



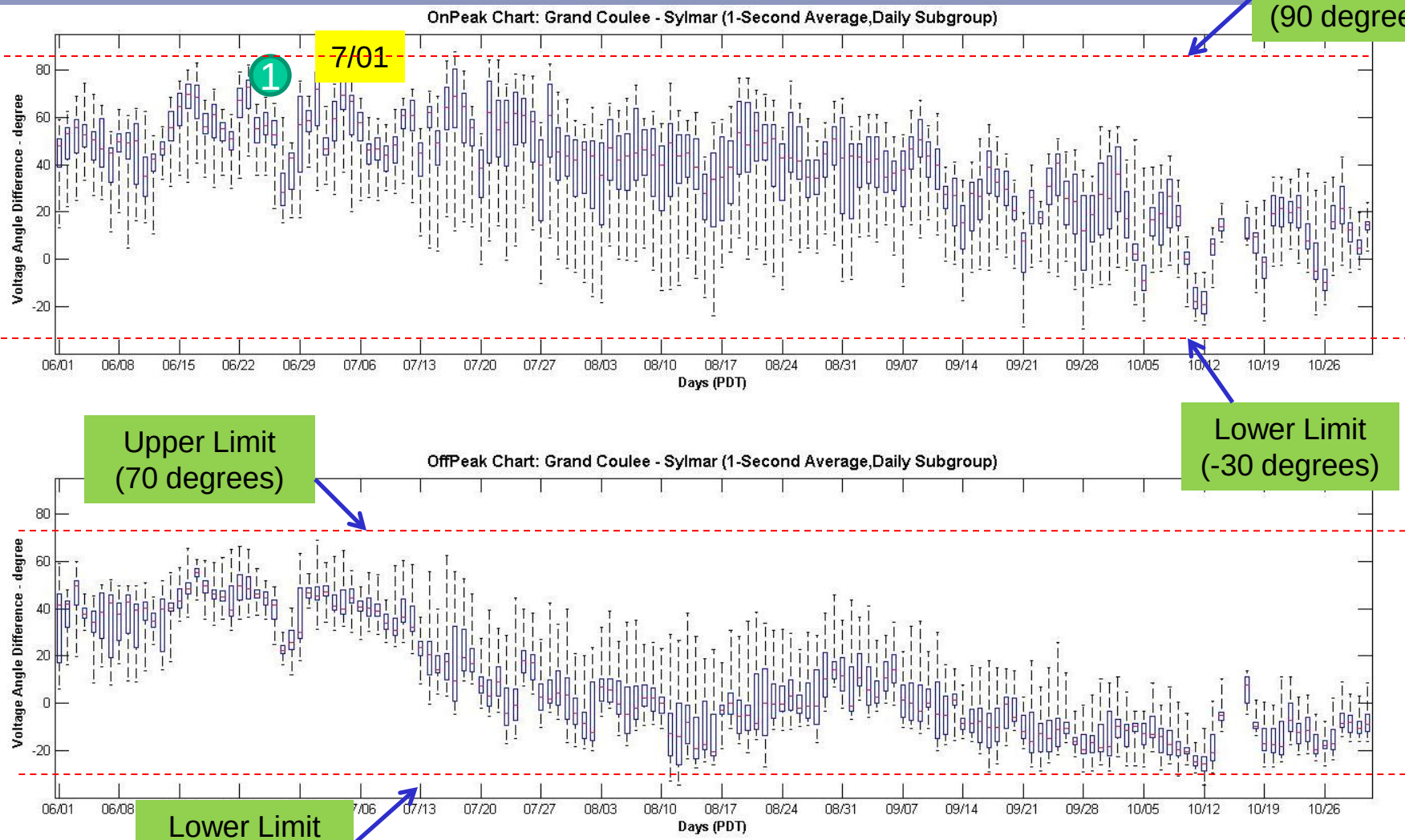
June 11th ,2008 line trip event can be observed visually.

Geographical display of wide area angle difference pairs



Grand Coulee – Sylmar Daily Angle Difference Data

Summer 2008



2010 WECC Heavy Summer Stressed Base case
Angle difference summary - Wide Area

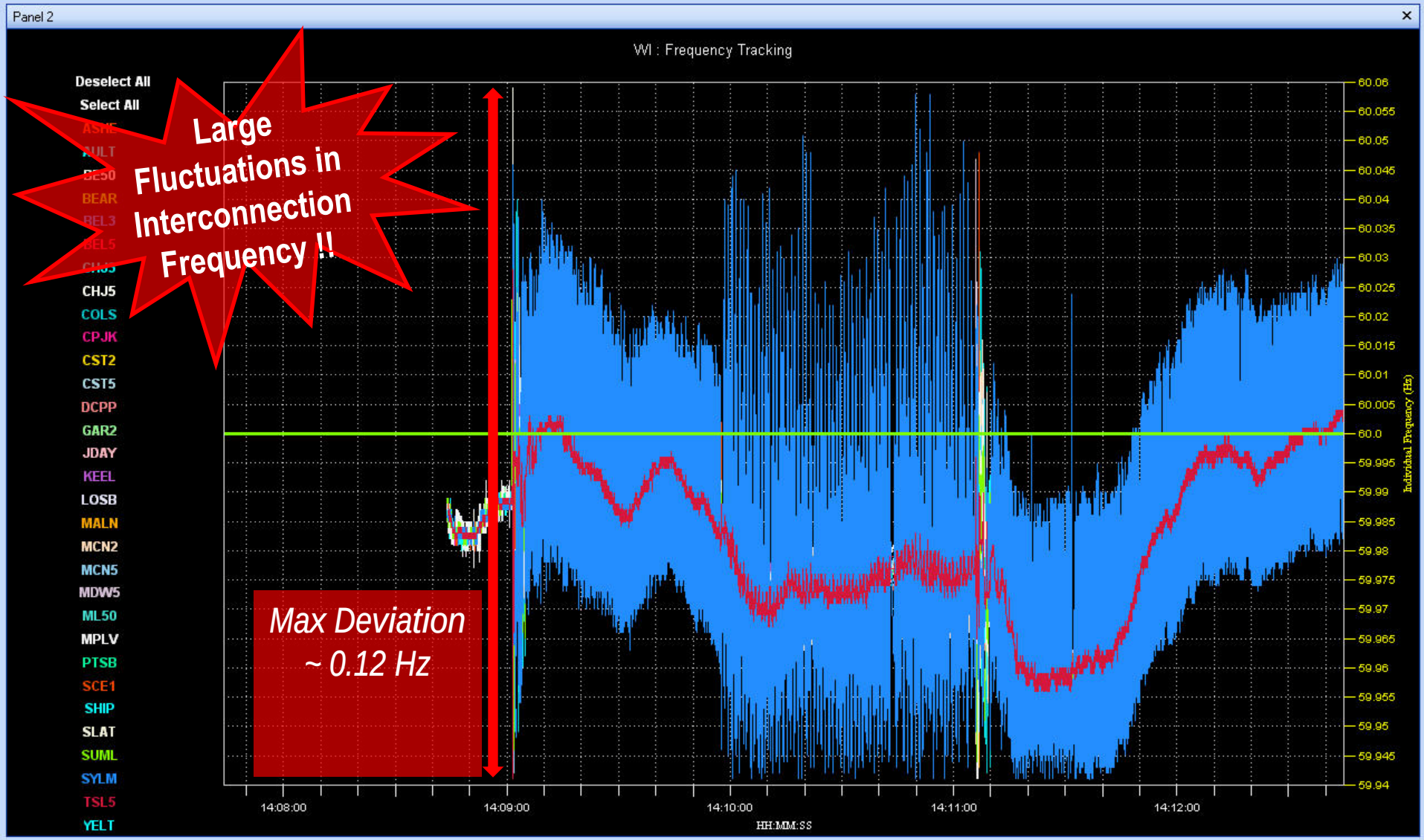
BC Hydro – BPA

- Kimano (Transmission) - Grand Coulee (Load) 46.29
- Gordon Shrum (Generation) - Grand Coulee (Load) 50.45

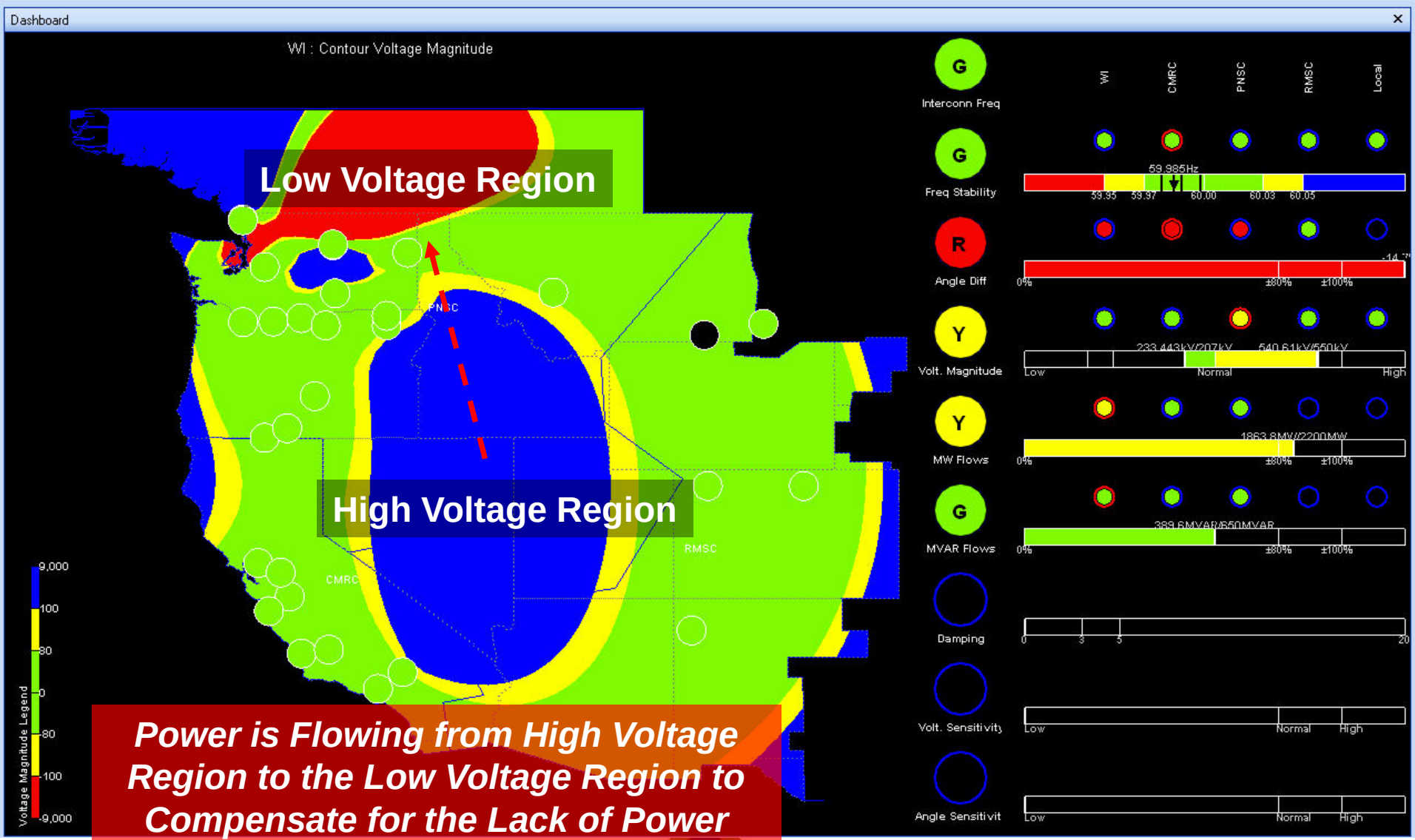
BPA/BCH – Southern California

- Kimano (Transmission) - Vincent (Load) 133.88
- Colstrip (Generation)– Vincent (Load) 127.0
- Grand Coulee (Transmission) - Tesla (Load) 76.89
- Grand Coulee (Transmission) - Vincent (Load) 87.59
- Grand Coulee (Transmission) - Devers (Load) 94.87
- Grand Coulee (Transmission) - Sylmar (Load) 95.77
- Custer (Transmission) - Sylmar (Load) 99.78

Interconnection Frequency Vs. Time Plot
January 26, 2008 – WECC HVDC event



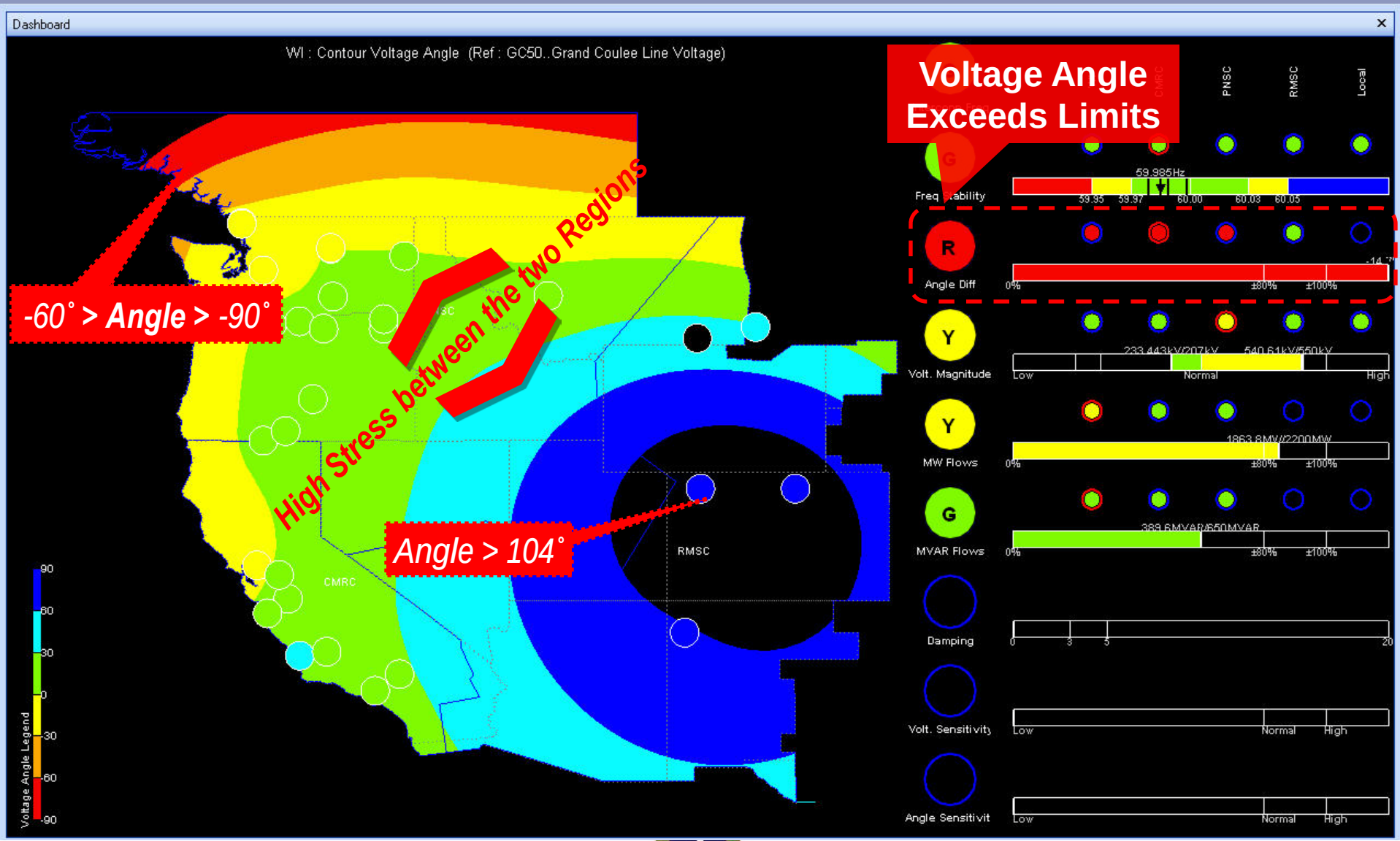
Voltage Magnitude Contour Plot
January 26, 2008



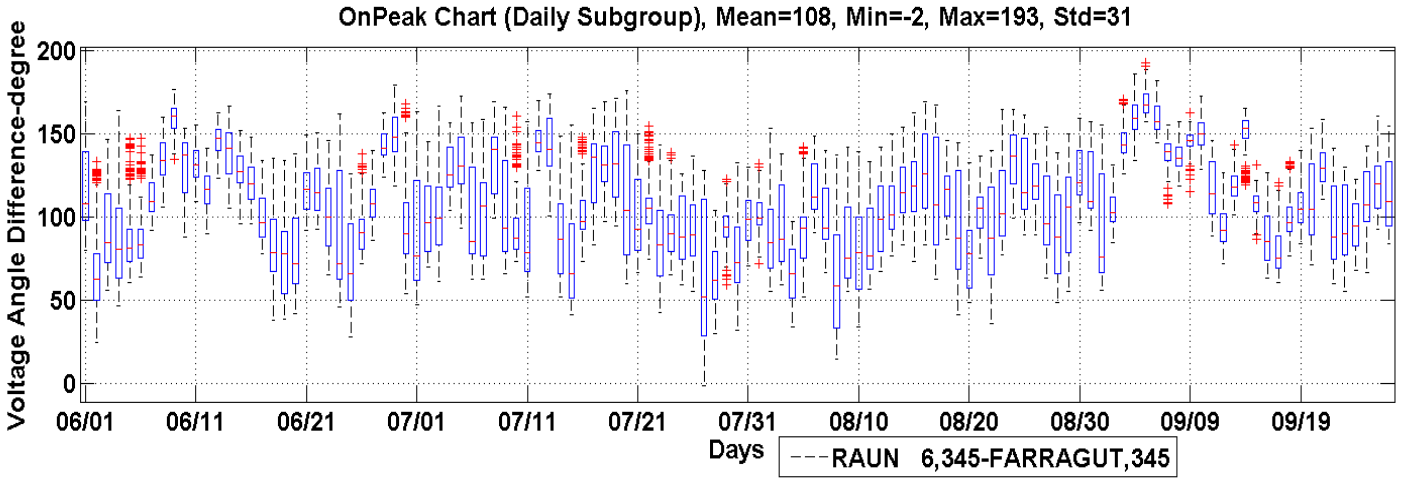
Electric Power Group

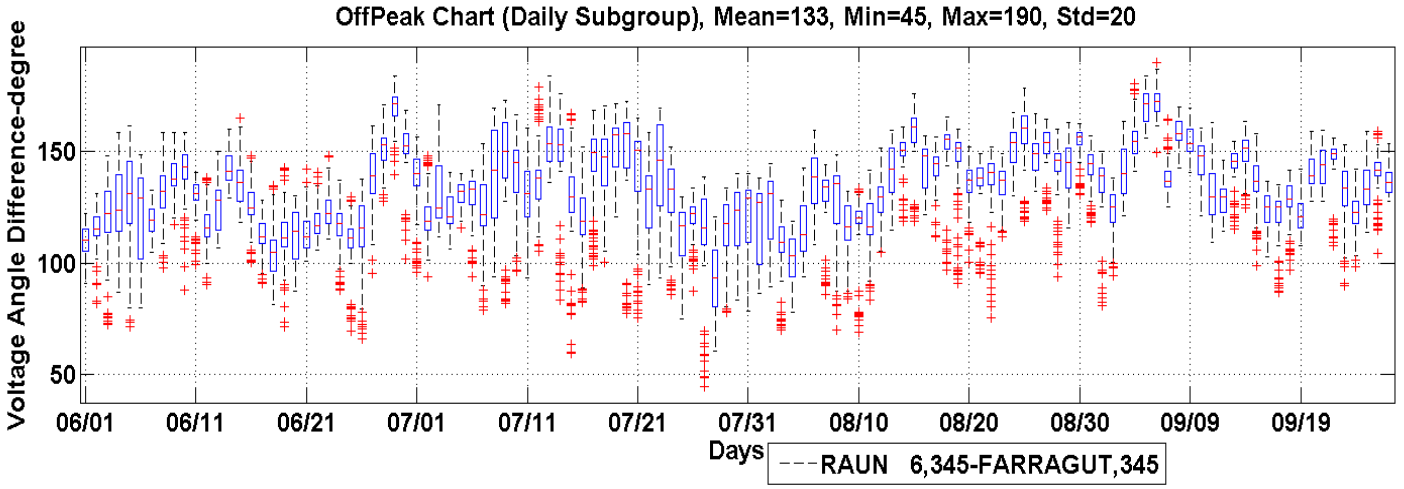
CERTS
Consortium for Electric Reliability Technology Solutions

Voltage Angle Contour Plot
January 26, 2008



Raun- Farragut Daily Angle Difference Data
Summer 2008, 5-Minute State Estimator Snapshot





Angle Difference Data (Max-Min Limits) for Winter 2009

PJM Angle Pair Winter 2009 Analysis														
			OnPeak (Degree)				Suggested Limits		OffPeak (Degree)				Suggested Limits	
Source	Sink	KV	Mean	Min	Max	STD	Max	Min	Mean	Min	Max	STD	Max	Min
QuadCities	Zion	345	25	0	40	7	40	0	26	2	41	6	40	0
QuadCities	WiltonCtr	345	19	-16	38	9	40	-20	24	-5	40	7	40	-10
Dumont	ErieWest	345	26	-14	54	11	50	-10	30	-8	52	8	50	-10
Jefferson	Baker	765	13	-4	43	4	30	-10	15	3	26	3	30	0
Baker	Dooms	500	31	3	60	6	50	0	34	13	57	5	50	10
WylieRidg	Pruntytown	500	5	-3	49	3	15	-5	6	-1	29	3	15	-5
WylieRidg	Conastone	500	39	21	63	5	55	20	36	16	52	6	50	15
Belmont	Pruntytown	500	11	2	64	3	20	0	11	3	39	3	20	0
Belmont	MtStorm	500	23	7	65	4	40	5	24	11	45	4	35	15
Belmont	Dooms	500	28	6	60	5	45	5	32	16	49	5	50	15
Belmont	Cloverdale	500	20	4	46	4	40	0	25	11	43	5	40	10
WylieRidg	Dooms	500	21	1	45	5	40	0	27	8	43	5	45	0
ErieWest	Branchbur	345	45	16	66	9	70	10	39	10	62	9	60	10
Raun	Farragut	345	131	9	204	30	190	0	136	17	192	23	190	0