Application of EPRI PREMS II System to Solve Difficult Distribution and Customer-side Issues

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Abstract* - The Portable Radiated Emission Measurement System II (PREMS II) is an innovative new tool developed by EPRI's Power Quality Program to address "invisible" electromagnetic compatibility (EMC) issues in electric grids. By enabling utilities to quickly scan for anomalous frequency interference and potential equipment failures, PREMS II enhances the reliability of grid operations. Its integration with GIS systems allows for efficient identification of problem areas, significantly improving maintenance workflows. Utilities like TVA, SRP, ACE, Dominion, and CPS Energy have successfully applied PREMS II to resolve various issues from internet outages to malfunctioning smart home devices, to finding failing conductors, arrestors, and connections on the distribution system. The PREMS II use cases are demonstrating its critical role in preemptive maintenance, interference source mitigation, and customer satisfaction. EPRI is currently testing the use of PREMS II in helicopter inspections for quickly scanning transmission lines for issues as well.

***Index Terms* – failing equipment, interference source, outage prevention, radiated emissions**

INTRODUCTION

The Portable Radiated Emission Measurement System (PREMS II) was born out of a research project that was looking at the possible interference issues associated with the operation of a Distributed Renewable Resource (DER - Solar Farm). It was developed to address the challenges of detecting and identifying sources of anomalous radiated emissions within utility infrastructure and customer environments. These emissions, which can stem from damaged utility components, failing customer equipment, or external interference, often go undetected during standard visual inspections leading to operational issues such as service disruptions and equipment malfunctions.

The primary objective of developing the PREMS II system was to make the invisible visible, by providing a mobile solution to efficiently scan for and identify problematic emissions. Traditional methods of detecting radiated emissions involve bulky equipment and stationary spot measurements, which can be time-consuming and less effective.

RESEARCH BACKGROUND

In 2015, EPRI was asked to help a utility with a possible AM radio band issue due to the operation of a third party-connected DER system. EPRI sent a team of engineers to conduct a site survey at the DER facility. During the site survey a benchtop spectrum analyzer was used to take spot measurements near some of the solar inverters at the site. Measurements were taken at a few locations around the inverters and the site, along with GPS coordinates from a handheld phone for reference. When it came time to write the report of the findings, it was realized that the data collected was not quantifiable as to an issue being present by the applicable standards.

Given the uncertainty of what the data was telling, the EPRI engineers started looking at options of how to take these types of measurements in way that was quantified. The Team started looking at available equipment and various platforms that could be used to create a better set of data that could quantified. A robotic platform, with the capability of GPS navigation, was selected as the base platform from which to begin the process. The next step was locating a spectrum analyzer that could be used with the robotic platform. Based on other research work, a much smaller spectrum analyzer was selected to be used for data collection. After assembling the initial prototype system, some field trials were conducted to make sure that all systems were working and communicating properly. After several iterations of field trials, the platform was working according to plan and was ready for the next phase of testing. A local DER site was selected for the initial tests. After working with the site owner, the team did several test runs at the site. Measurement data was reviewed after each test and the system was adjusted until the measured data made sense for the locations measured.

The team presented their findings of the 'new' platform to the EPRI advisors, and everyone agreed with the assessment of the new platform's capabilities and demonstration. One advisor pointed out that it was a very useful tool, but they wanted something that they could put in their service vehicles and do the same type of surveys as the robotic platform. So, as part of EPRI's Program 1 Power Quality research for 2018 the research team considered options for reducing the size of the robotic platform and making able to fit in the back of a service vehicle. After two prototypes, the final design was selected and refined.

TECHNOLOGY

When planning for the initial tool to help conduct radiated emission surveys, there were several things that we wanted to be able to do. First off was a spectrum analyzer that was portable enough and capable of taking the necessary frequency measurements. The second thing was a device that would be able to provide GPS coordinates for the measurement points more accurately than a handheld phone. A way to process and store the measurement and GPS data was the next component that was needed to help accomplish the goal. The next need was a way to communicate with the system, set up the types of measurements that were needed, and check that the system was operating and taking data properly. To help accomplish this, background software had to be created to interface all of the pieces of the system together, along with a way to broadcast communications from the system to a laptop or tablet pc. The robotic platform came with an onboard computer and WiFi system for its operation, so separate software was designed to interface with the robot's system.

We were able to locate a spectrum analyzer that was small enough to fit the robotic platform and be powered from the robot's batteries. Survey grade GPS units were used from a previous EPRI project, which gave the system an accuracy range of ±2 cm. A loop antenna from another project was used with the spectrum analyzer to be the antenna source for capturing frequencies. As noted above, this system worked very well for the initial goals that we wanted to accomplish.

The next challenge came when the EPRI engineers were asked to make a smaller measurement platform (which became PREMS II) and be able to do the same tasks. This presented several different challenges in how the system would look, how it would be powered, and how to communicate with the new system. Thus, a review became necessary to identify what components were needed to make the spectrum analyzer work in this new configuration. After all of the necessary components were determined, a footprint of these components was identified, and a portable case was selected to house those components. Initial design questions revolved around how to power this new system: would a battery be used or would the system be powered by the vehicle itself. A decision was made to use a battery, so that the system could be powered even when removed from the vehicle.

The selection of a battery brought its own set of questions: how much capacity was needed to run the system for a couple of hours, how would the battery be recharged, and how to protect the battery when the voltage dropped below a certain level? The original robotic platform was examined for an example battery option, as its batteries had a 'Smart' module that would help shut-off the output to protect the battery as it got below a certain voltage discharge level. An equivalent size battery (though a single battery instead of the three used in the robotic platform) was initially purchased to run the system, and this worked well with the addition of the proper charging system to recharge the battery.

Since the system was going to be much smaller than the robotic platform, it was determined that another type of GPS unit would be needed. The goal was to find a unit that was readily available and had an acceptable accuracy range. After looking at many different types, a small USB connected model was selected which has an accuracy range of ~3 meters (9 feet). Given that the new platform was expected to be used in a service vehicle this accuracy range was acceptable for GPS data.

During the initial build phase, the engineers also designed the interfacing software with a modular design. This was done to allow for the addition of future external sensors that may be added at some point. This would allow for more flexibility with the PREMS II design and different use cases. Another challenge with designing the software came with providing a way to combine several data sets into one for export and visualization. The software was coded so as to combine certain selectable data sets into an exportable file format for download. When examining the visualization part of the system, two options were selected to show the collected data: a geographic information system (GIS) and/or an internet-based mapping system. The recorded measurements were easily converted into a tab delimited spreadsheet which made it possible to import the data into either of these visualization options.

INITIAL PROTOTYPE VERIFICATION

After assembling an initial prototype, some minor changes were made to the overall design and software configuration. Some test trials were made with the prototype and from these trials the system was further refined. A second prototype was built and tested with some of the updates from the previous prototype tests.

In 2020, the team had the opportunity to conduct two field tests with the second prototype. The first field test helped locate an interference source that was impacting a residential homeowner's home automation system. The second field test helped to solve a DSL interference issue that had lasted 7 months.

The first field test was for a residential homeowner that automated the home with a power line carrier communication system. At some point this automation system was interrupted at various intervals that caused concern for the homeowner who was a retired radar engineer. The homeowner used some of their own test equipment and experience to locate the source of the interference and concluded that an adjacent home, then under renovation, was the cause of the interference. However, the homeowner couldn't perform a conclusive investigation to verify that this was the case. The electric power utility was asked to help in verifying the source of the interference, and the utility reached out to EPRI for assistance. EPRI used both measurement platforms to assist in the investigation. Upon examining the data collected, it was confirmed that the home under renovation was the source of noise interference. It was later learned that the renovated home was using some newer lighting technologies that were creating harmonics that flowed back up stream to the shared pad-mounted transformer. Figures 1 – 3 show examples of the PREMS II prototype being used and an example data set visualized from the surveys at the site.

FIGURE 1 PREMS II PROTOTYPE IN SERVICE VEHICLE

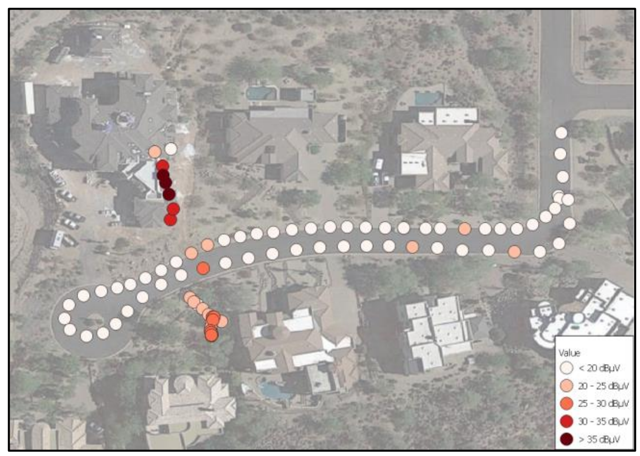

FIGURE 2 MEASUREMENTS DATA TAKEN AT 12.5KHZ

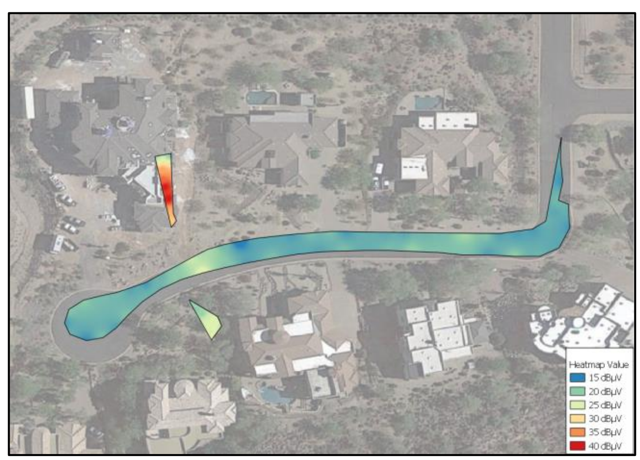

FIGURE 3 HEATMAP VISUALIZATION OF DATA AT 12.5KHZ

The second field test came in the form of helping to locate an interference source that was impacting a DSL provider and a community of 56 residential homes. These residents had experienced a service interruption to their internet service for 7 months before EPRI was asked to help locate the source of the interference. The initial assumption was the source was due to a utility's transmission lines, so EPRI did an investigative survey of those lines with help from the utility's off-road vehicle. This initial survey did not produce a location of the interference, so the next approach was to investigate along the DSL lines themselves. As the Team was surveying the DSL line, there was a point where the spectrum analyzer detected a broad band set of frequencies that were elevated above anything else that had been seen so far. That location was marked, and the rest of the line was surveyed. The next morning, a more intensive investigation took place with assistance from the local power company and the DSL provider. Prior to starting the investigation, the DSL provider checked the signal transmission of the DSL line and reported 100,000 packet errors at that point in the day. After checking two homes and several pole connections, the source of the interference was found on a branch power line off the main line. Two sources were found, the first was a cracked insulator atop a power pole and the biggest source was a damaged pole-mounted transformer at the end of the branch line. The transformer was still connected to the branch line even though its secondary wires had been cut, possibly due to a lightning strike or other damage. After resolution, the DSL provider checked the signal again and noted that there were zero packet errors. This issue was found and resolved in 1.5 days—after the DSL provider had worked for 7 months to locate the source of the interference. Figures 4 – 7 show examples from this investigation.

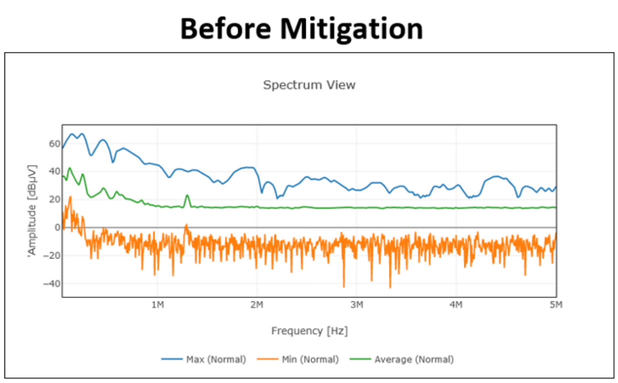

FIGURE 4 SPECTRUM MEASUREMENT OF ELEVATED FREQUENCIES

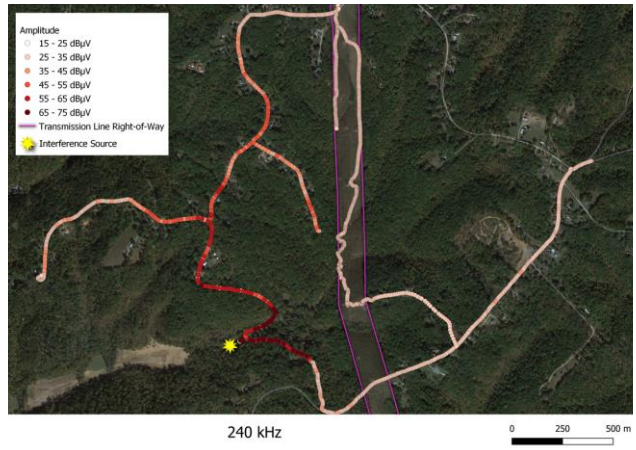

FIGURE 5 MAP IMAGE OF MEASUREMENT POINTS AND MAXIMUM FREQUENCY MEASUREMENTS

FIGURE 6 LOCATION OF CRACKED INSULATOR AND DAMAGED TRANSFORMER

FIGURE 7 SPECTRUM MEASUREMENT AFTER MITIGATION OF THE INTERFERENCE SOURCES

PREMS II Users' Case Studies

After these two successful field verification trials, the decision was made to offer the opportunity to collaborate with electric utilities and offer them a PREMS II system. This was an opportunity to continue the research of the system as a tool to help with locating and detecting radiated emission issues. At the time of this paper being written, six utilities have participated in this effort and are using their PREMS II to help locate various interference sources. The next few sections will present some examples of the use cases from some of the partnering utilities and their findings.

I. Utility Case Study #1

A few of the utilities have been very active with their PREMS II system and have incorporated it into a regular power line survey tool. One utility noted to EPRI that the PREMS II had become a very important tool in their regular line surveys. This utility was using a different type of spectrum analyzer system but found the PREMS II to be more useful with detecting interference sources as well as being able to combine GPS data with the measurement points and then export the measurement data and overlay the measurements in their GIS system.

Ham radio operators seem to be the biggest source of information for the utilities using a PREMS II system. These operators appear to be quick to let the electric utilities know when there is an interference source that is impacting their communications. As an example, one radio operator notified the electric utility about a very, strong interference source impacting their communications. The utility, using the PREMS II, conducted a survey around the ham radio operator's area starting at a radius of ½ miles. In this initial radius sweep, the PREMS II users detected and located some minor sources of frequency noise associated with the power line system. As the sweep radiated out at further distances, at 1.5 – 2 miles sweep a very large interference source was detected. This source was attributed to the electric utility's lightning arrest. A repair crew was dispatched to the location to inspect and make repairs. The crew ended up doing the repairs on three lightning arrestors at that location. As the leads were lifted on the 3 arrestors the frequency emissions were immediately cleared. This PREMS II user reported that there have been 12 -15 other noise sources that have been found and mitigated—due to reports from different ham radio operators—while using the PREMS II.

This same PREMS II user noted that during a 2023 investigation, an elevated noise signature was detected around a power distribution substation. After driving around the area, it was suspected that there was something within the substation that was creating this interference source. A request for a substation crew was made, a crew arrived and inspected things in the substation, and it was suspected that the source of the interference was within the Control House. The substation crew made a repair, and the strong interference signal disappeared and has not returned. Figure 8 shows part of the scans for this case.

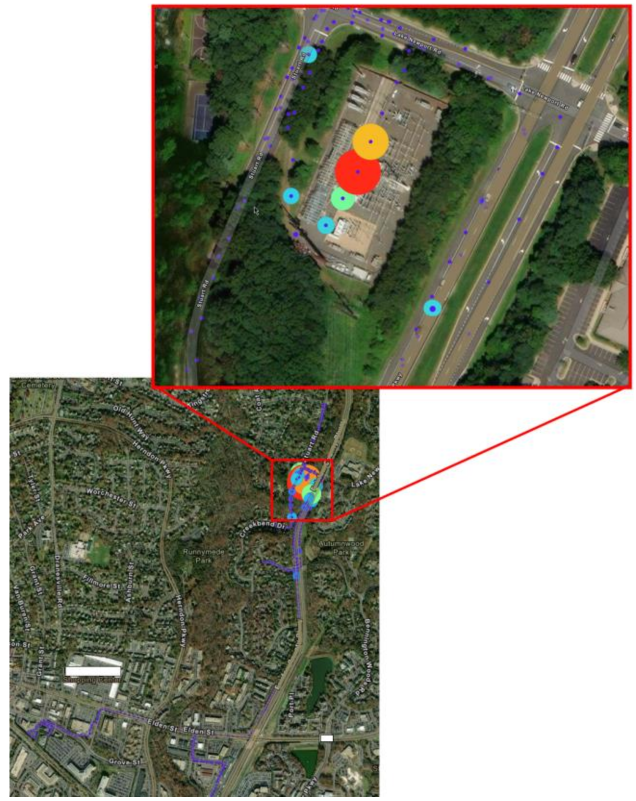

FIGURE 8 SUBSTATION SURVEY SCAN FOR POSSIBLE INTERFERENCE SOURCE

II. Utility Case Study #2

Another PREMS II user has experienced many different issues on several of their power line feeders. These different issues created line inspections and work for their line crews. Upon receiving a PREMS II system, an active program was implemented in conducting line surveys across several of their most problematic feeders. During some of their initial line surveys, a second verification was made using a thermal imaging camera, and a large majority of the detected locations were confirmed by the thermal camera's imagery. This gave them confidence in using the PREMS II system to investigate larger sections of the feeders.

During one of these line surveys, the PREMS II user detected an elevated signature near a substation that was feeding several different line feeders. As the user was submitting a repair ticket for this substation, they received a call from one of the power line crews that a transformer primary feeder *at the same substation* had burned off and created a fire in the substation.

On a separate investigation, the PREMS II user noted that there have been several other issues that they have detected on some of their power lines that were not expected. One of these issues was bad connections on their feeder gateway devices. Figure 9 shows a survey scan of this line inspection with the bad connections marked by highlighted circles.

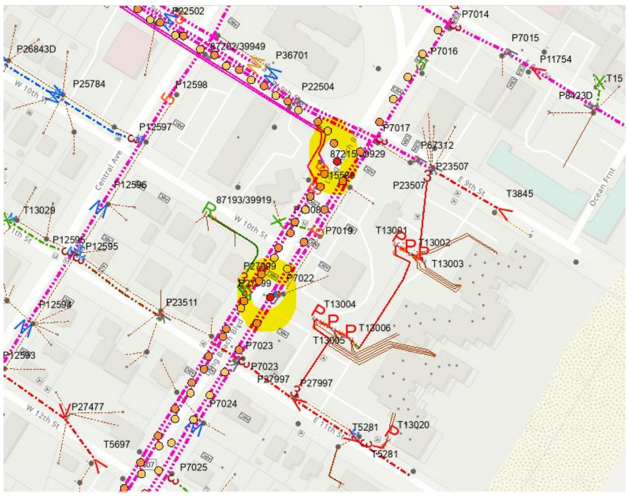

FIGURE 9 HIGHLIGHTED BAD GATEWAY CONNECTIONS DETECTED DURING LINE SURVEY

This PREMS II user also noted the efficiency of conducting line surveys with the PREMS II system. They noted that on one occasion they were able to scan an 18-mile feeder completely in about 4 hours. During this scan there were ~12 areas that were noted as needing further investigations for possible issues.

III. Utility Case Study #3

During other PREMS II user scans, various effects have been found at different frequencies. It's been noted that each user has developed their own method and manner of using the system to detect issues. Some are scanning at lower frequencies, while others are scanning at higher frequencies. A few scans are based on input from the ham radio operators. One such investigation was conducted with help from a radio operator who had noted they were experiencing an issue in the 50-MHz band, and they even were able to provide a direction for the interference source. A general survey through several different residential blocks was conducted until elevated levels were detected in the 50-MHz range in the general direction provided by the radio operator. Figure 10 shows an image from that scan.

FIGURE 10 SCAN LOOKING FOR A 50-MHZ INTERFERENCE SIGNAL IMPACTING A HAM RADIO OPERATOR

Elevated color readings are seen in the bottom left of the above scan image. This location contained a power pole that had several connections and circuit protection devices. A line crew was not available at the time of the investigation, so this one was not confirmed at the time of the initial investigation. Figure 11 show pictures of the power pole and all of its connections.

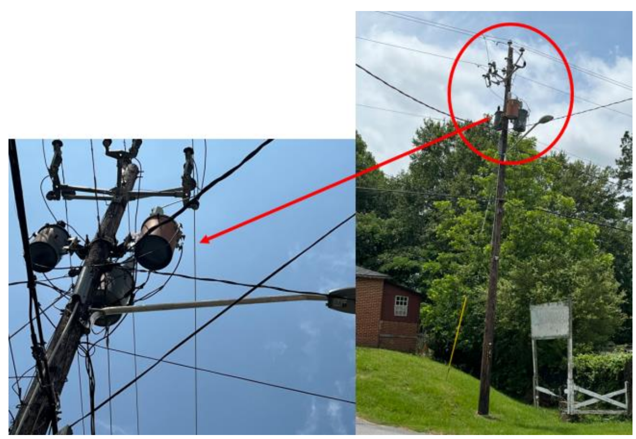

FIGURE 11 POTENTIAL SOURCE(S) OF INTERFERENCE AT 50 MHZ

IV. Utility Case Study #4

On several occasions, EPRI engineers have explored numerous opportunities to utilize PREMS II for scanning and investigating power lines. These inquiries have ranged from integrating PREMS II into power line surveys conducted via helicopter to deploying the system on drones. Each approach has presented unique challenges, particularly in terms of timing and logistics, with drone usage posing the greatest difficulty due to size constraints.

Last year, an opportunity arose to collaborate with an electric utility to incorporate PREMS II into a helicopter line survey. This endeavor introduced unexpected challenges, such as determining the optimal location for mounting the antenna on the helicopter and obtaining GPS data during flight. Both issues were successfully resolved, allowing measurements to be taken across several sections of power lines.

To address the antenna mounting, a specific external mount on the helicopter required a custom fixture to attach the antenna securely. Additionally, the GPS unit had to be relocated to the front of the cockpit area to ensure reliable reception. Figure 12 provides example photos from this project.

FIGURE 12 IMAGES FROM THE HELICOPTER FLIGHT SURVEYS

One of the greatest challenges of this project came with the large amount of data collected from each flight over the different power lines. The challenge was in how to quickly process this large set of data in the most efficient and effective way. To help with this, the EPRI team leveraged machine learning (ML) algorithms to assist in filtering through the large data sets looking for those anomalies that deviate from the 'normal' measurement for each power line section.

To process the millions of data records associated with the entire spectral data set, a data pipeline was created to:

- import data from CSV files, where each file represented a different transmission line survey,
- compute aggregated statistics (i.e. min, max, and average) for each measurement location,
- perform principal component analysis (PCA) to reduce the dimensionality from 2048 to 2,
- perform k-means clustering on the PCA data,
- perform anomaly detection on the PCA data using elliptical envelope and local outlier factor algorithms, and
- create a list of measurement locations which were flagged as anomalies based on the anomaly detection algorithms mentioned above.

For the elliptical envelope method, the resulting measurements can be seen in Figure 13 where slight differences in amplitudes can be seen in the lower frequency range of 9 kHz to 100 kHz. Figure 14 shows the result of the elliptic envelope algorithm flagging measurement locations based on principal component analysis. The same process was conducted using the local outlier factor method, and its results can be seen in Figure 15 and Figure 16, respectively.

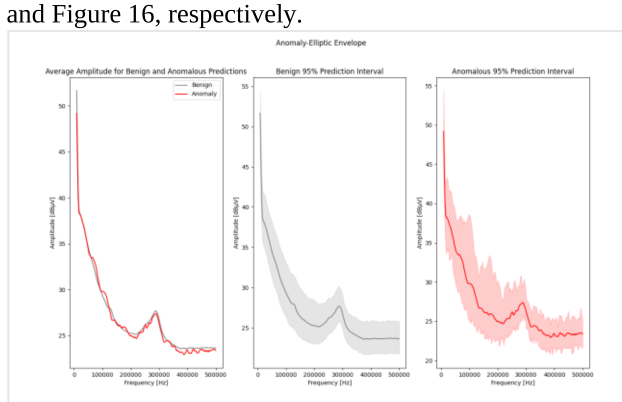

FIGURE 13 AVERAGE AMPLITUDES OF PREDICTED BENIGN AND ANOMALOUS MEASUREMENTS (LEFT), BENIGN MEASUREMENT RANGE (CENTER), AND ANOMALOUS MEASUREMENT RANGE (RIGHT) FOR THE ELLIPTIC ENVELOPE METHOD.

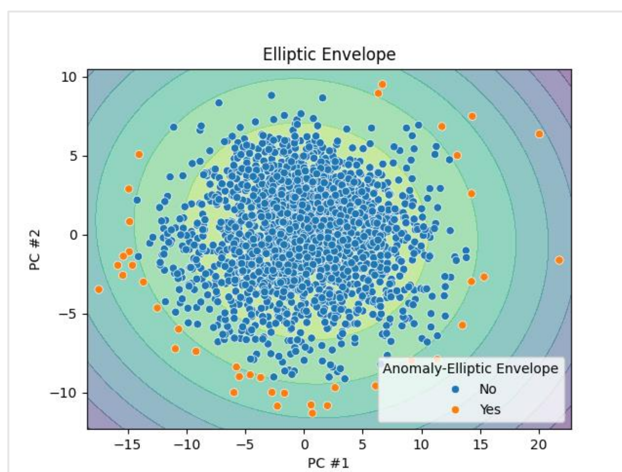

FIGURE 14 ELLIPTIC ENVELOPE ALGORITHM RESULTS FOR ALL MEASUREMENT LOCATIONS. THE ENTIRE SPECTRUM IS REDUCED TO TWO DIMENSIONS.

by other devices or tools. The case studies above give some examples of what the system has been able to help locate and detect. Given the current direction of the system, it is believed that its capabilities are just starting. The system, through data collection and visualization, has made what was invisible, visible.

Future research will continue with further exploration of its use on a helicopter for line inspections and another potential area that is being considered is its use as a tool for Wildfire Mitigation. A tool for Wildfire Mitigation is an idea that PREMS II can help detect overgrowth of vegetation into power lines that potentially result in a fault that leads to a fire. This capability is still a "What if?" idea at this point and will require more tests and research to see if it is even possible. A third area of future research involves further reducing the system and incorporating its sensing capabilities into a drone platform. There are questions about being able to incorporate this with other thermal or imaging technologies that are used with drones as part of a ground level line survey by electric utilities or possible third parties on behalf of an electric utility. Another opportunity for future improvements would be to update the user interface with additional visualization options. Currently, the user has to manually visualize the data using their own GIS system, which takes considerable amounts of time to do for each field study. By having mapping functionality built into PREMS II, the user would be able to quickly see potential interference source locations. Additionally, the system could benefit by integrating the machine learning methods previously described earlier in this paper. By automatically performing PCA and anomaly detection within the PREMS software, the user could potentially be alerted in the user interface whenever an anomalous measurement is detected.

PREMS II started as an idea of combining several, different, readily available components to develop a tool that can bring value to its users. Through lots of research and development hours, a tool has been created that has brought value to its users. A few of the users have reported finding different sources that they weren't even looking for on their utility system with the PREMS II. As interest continues to grow in the PREMS II system, there are other research opportunities to continue advancing its capabilities going into the future. Now with the advances in Artificial Intelligence (AI), there is interest in incorporating certain aspects of it into the data processing to improve the speed and efficiency of locating radiated sources that are impacting a Utility's customers.

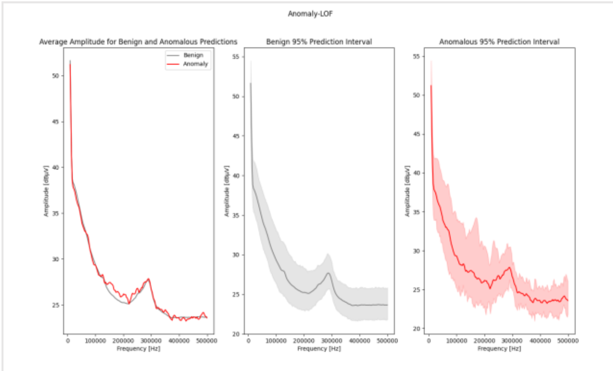

FIGURE 15 AVERAGE AMPLITUDES OF PREDICTED BENIGN AND ANOMALOUS MEASUREMENTS (LEFT), BENIGN MEASUREMENT RANGE (CENTER), AND ANOMALOUS MEASUREMENT RANGE (RIGHT) FOR THE LOCAL OUTLIER FACTOR METHOD.

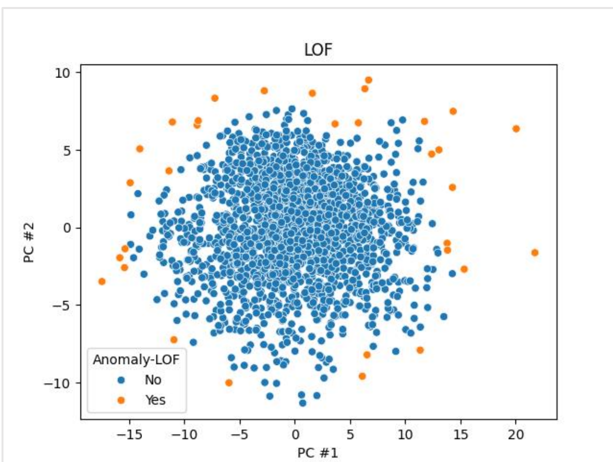

FIGURE 16 LOCAL OUTLIER FACTOR METHOD RESULTS FOR ALL MEASUREMENT LOCATIONS. THE ENTIRE SPECTRUM IS REDUCED TO TWO DIMENSIONS.

CONCLUSION

PREMS II started out with an idea and goal of developing a tool that could be used to help find radiated frequency (noise) sources that cause interference issues for equipment. To date, the initial challenges of developing this tool have been solved and overcome. PREMS II has now gone beyond the initial goals for this tool and has become a tool that has shown its value in helping to find failing equipment, equipment experiencing issues, and locating sources of interference that have not been detected