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In-Line Quality Control of Lithium-Ion Battery Electrodes through Terahertz Scanning

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency; renewable energy and advanced clean generation; energy-related environmental protection; transportation; and energy transmission and distribution.

In 2011, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned electric utilities — Pacific Gas and Electric Company, San Diego Gas & Electric Company, and Southern California Edison Company — were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs to promote greater reliability, affordability, and safety for California electric ratepayers. EPIC investments advance these values by:

- Providing societal benefits.
- Reducing greenhouse gas emissions in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs, first with energy efficiency and demand response, next with renewable energy (distributed generation and utility-scale projects), and finally with a clean electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

In-Line Quality Control of Lithium-Ion Battery Electrodes through Terahertz Scanning is the final report for the project of the same title (EPC-21-035) conducted by Lookin, Inc. The information from this project contributes to the CEC Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

Lithium-ion batteries are essential to California's transition to clean energy, powering electric vehicles, grid storage, and everyday electronics. However, battery manufacturing faces a major challenge: quality control. Defects in battery electrodes often go undetected, leading to wasted materials, higher costs, and reduced reliability. Traditional inspection methods, such as x-ray and infrared imaging, are too slow or lack the precision needed for modern production lines. To address this, a California Energy Commission-funded project partnered with Lookin, Inc. to develop and test a new inspection technology using terahertz scanning. This system introduces three key innovations: highly sensitive terahertz sensors, a multipixel imaging array for fast and wide area scanning, and advanced software that uses machine learning to detect defects and measure material properties in real time.

Laboratory testing at Lookin, Inc. and the University of California, Irvine showed that the scanner can identify common electrode flaws such as uneven coatings and material clumps with micrometer-level accuracy. It also measures thickness and monitors drying processes, helping manufacturers maintain consistent quality. More than 100 samples from research and commercial sources were evaluated, confirming strong links between detected defects and battery performance. Pilot-scale testing at Navitas Systems demonstrated that the technology works under real manufacturing conditions. It detected flaws invisible to traditional optical inspection and provided near real-time analysis through a user-friendly interface.

By reducing scrap rates and improving battery reliability, this innovation supports California's clean transportation and energy-storage goals. Better quality control means safer, longer-lasting batteries at lower cost, which is critical for meeting state mandates on zero-emission vehicles and renewable energy integration.

Keywords: California Energy Commission, final report, EPIC, lithium-ion batteries, terahertz imaging, in-line quality control, roll-to-roll manufacturing, R2R manufacturing, electrode defects, capacity fade, porosity analysis

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EXECUTIVE SUMMARY

Background

Lithium-ion batteries are a critical component of California's clean energy and transportation goals, supporting electric vehicles, grid storage systems, and an expanding set of commercial and defense applications. As battery production scales, the ability to ensure consistent quality at high throughput becomes increasingly important. This project aimed to improve lithium-ion battery manufacturing by developing a real-time terahertz imaging system that can identify defects and characterize electrode quality during production.

Electrode manufacturing is one of the most defect-prone steps in the process. Roll-to-roll coating, drying, and calendering[1] can introduce agglomerates, pinholes, divots, nonuniform coatings, microcracks, density variations, and other structural defects that directly affect cycle life, energy capacity, and safety. Scrap rates during electrode fabrication can reach 10 percent, which increases production cost and limits the availability of high-performance batteries.

Despite the importance of quality control, existing nondestructive inspection tools cannot provide early, real-time feedback during electrode production. Tools and techniques such as x-ray computed tomography, infrared thermography, laser calipers, and optical imaging each capture only a portion of the relevant information. They may be limited to surface features, require long acquisition times, and lack sensitivity for subtle structural defects, or be incompatible with the speed and environment of a moving web line. As a result, many defects remain undetected until after battery cell assembly, when remediation is no longer possible.

Terahertz imaging offers a promising alternative because terahertz waves are nonionizing, penetrate many nonmetallic materials, and are sensitive to both surface and subsurface features. Terahertz waves respond to small variations in thickness, density, water content, and electrical conductivity, making them well suited for the inspection of battery electrodes. Unlike optical imaging, terahertz radiation can reveal features beneath the coating surface and provide time-domain and phase information that can be converted into thickness profiles, refractive-index maps, and porosity estimates. Unlike x-ray tools, terahertz scanners pose no radiation hazard and can be designed for continuous operation in industrial settings.

Historically, terahertz systems were limited by low sensitivity, a small field of view, and slow acquisition speeds. The innovations developed in this project address these limitations by combining plasmonic terahertz emitters and detectors, a multipixel pulsed terahertz camera, and advanced data analysis and machine learning methods. These improvements enable high-resolution, real-time imaging across a wider area, making terahertz scanning a practical tool for in-line electrode inspection.

Awarded under the Bringing Rapid Innovation and Development to Green Energy (BRIDGE) solicitation, Lookin, Inc. (Lookin) developed and validated a terahertz scanner designed

[1] Calendering involves passing the anode and cathode electrode sheets through a series of rollers to compress and densify the material.

specifically for roll-to-roll battery electrode lines. Early laboratory work performed at Lookin and the University of California, Irvine demonstrated that the technology can: detect very small defects that are difficult or impossible to see with visible imaging; measure coating thickness with micrometer accuracy; map porosity through changes in refractive index; monitor coating conductivity; and track drying processes. These results showed that terahertz scanning can characterize both geometric and material properties of electrodes in a single measurement.

The final phase of the project demonstrated the technology in production environments at Navitas Systems. The scanner successfully operated on continuous roll-to-roll lines, producing real-time maps of coating thickness, uniformity, and defect occurrence, and revealing features not detectable with conventional methods. These demonstrations confirmed that terahertz scanning can provide timely and actionable information during manufacturing, supporting higher yield, improved safety, and reduced costs in lithium-ion battery production.

The results of this project provide value to California ratepayers by improving the efficiency and reliability of lithium-ion battery production. By reducing material waste, enhancing electrode consistency, and enabling early detection of defects, the technology lowers manufacturing costs for batteries used in electric vehicles, customer-sited energy storage, and large-scale grid applications throughout the state. Increased production yields will expand access to affordable clean-energy technologies, while improved safety and performance directly support California's objectives for reducing emissions, strengthening grid reliability, and ensuring long-term energy resilience.

Project Purpose and Approach

The purpose of the project was to fund the development and validation of a terahertz-based inspection system capable of providing real-time, nondestructive quality control for lithium-ion battery electrode manufacturing. With BRIDGE funding, Lookin demonstrated a new approach to roll-to-roll electrode inspection that delivers both surface and subsurface information during production.

The project began with the design and construction of a compact and high-sensitivity terahertz imaging system that included advanced plasmonic terahertz emitters and detectors, a multipixel terahertz focal plane array, and custom electronics for high-speed waveform acquisition. The system was developed to operate on continuously moving web lines and to measure coating thickness, uniformity, porosity, drying behavior, and defect occurrence without interrupting production.

The approach combined laboratory testing, electrode evaluation studies, battery-performance correlation experiments, and multistage field demonstrations. Laboratory work at Lookin and partner universities was used to characterize the terahertz response of a wide range of anode and cathode coatings, quantify the sensitivity of thickness and porosity measurements, and identify defect types that were not detectable with optical methods. These studies provided the parameter space required to interpret terahertz signals in terms of electrode properties.

The next stage involved integrating the scanner into a mobile platform suitable for transport to battery-manufacturing facilities. Lookin conducted on-site demonstrations conducted at Navitas Systems, where the terahertz scanner was installed on active roll-to-roll production lines. The system collected continuous terahertz data during coating, drying, and calendering, allowing real-time evaluation of coating quality, detection of defects, and identification of process instabilities.

Image-processing and data-analysis software were developed in parallel to enable automated defect detection, thickness mapping, drying-curve extraction, and correlation with sample conductivity and density. These tools allowed operators to view real-time quality metrics and to compare terahertz measurements with battery-performance outcomes.

Through this staged approach, the project progressed from controlled laboratory measurements to full-scale demonstrations in industrial manufacturing environments, showing that terahertz imaging can provide the continuous and quantitative feedback needed for high-yield lithium-ion battery production.

Key Results and Conclusions

This project successfully met its objectives by delivering a comprehensive solution for advanced quality control in lithium-ion battery electrode manufacturing. Key accomplishments include:

- Development of a compact, high-sensitivity terahertz scanner specifically designed for in-line roll-to-roll electrode inspection.
- Demonstration of real-time, nondestructive detection of common electrode defects such as agglomerates, pinholes, divots, microcracks, and nonuniform coatings.
- Quantitative mapping of coating thickness with approximately 1- to 3-micrometer accuracy for both anode and cathode electrodes.
- Extraction of refractive-index and porosity data from terahertz phase measurements to evaluate density variations and calendering effects.
- Continuous monitoring of water content in wet coatings to characterize the electrode drying process.
- Identification of conductivity-dependent terahertz phase signatures across electrodes with varying electrical properties.
- Development of graphics processing, unit-accelerated data processing, and an intuitive interface for real-time visualization and automated defect identification.
- Successful field validation at Navitas Systems, demonstrating stable operation at production-relevant speeds and correlation between terahertz-detected defects and electrochemical performance.
- Advancement of the scanner to a field-ready configuration suitable for integration into industrial roll-to-roll manufacturing environments.

These achievements confirm that the terahertz scanner developed provides an effective and practical platform for early-stage quality control. The system combines defect detection, thickness measurement, porosity estimation, and drying-process monitoring in a single nondestructive tool. Successful deployment in both laboratory and pilot-scale production environments demonstrates the feasibility of terahertz imaging as a high-yield quality assurance solution for electrode manufacturing lines.

Knowledge Transfer and Next Steps

Throughout the project, Lookin implemented extensive knowledge transfer activities to ensure that the advances achieved were shared with industry partners, researchers, and other stakeholders. These efforts included regular meetings with the Technical Advisory Committee, collaborative workshops with Navitas Systems during field demonstrations, and frequent data review sessions with operators and engineers to explain terahertz signal interpretation, defect signatures, and correlations with coating properties. In addition, Lookin engaged the broader energy-storage community through technical presentations, open-house demonstrations at university laboratories, and discussions with battery manufacturers, quality-control specialists, and equipment integrators. These activities helped establish terahertz imaging as a practical solution for real-time inspection in roll-to-roll electrode manufacturing.

The project also laid a strong foundation for future development and scale-up of technology. The next steps include tighter integration of the scanner with manufacturing control systems, refinement of automated defect classification algorithms, and adaptation of the platform to accommodate higher web speeds and wider electrode formats. Lookin will continue collaborating with battery manufacturers to conduct extended field trials, assess process stability improvements, and validate the impact of terahertz-based feedback on scrap reduction and electrode performance. Additional research will explore applications of terahertz imaging for other battery components and related composite manufacturing processes. These follow-on activities will support broader adoption of nondestructive, real-time quality-control tools across advanced manufacturing environments.

Benefits to California Ratepayers

California is making significant strides in advancing battery manufacturing, energy-storage systems, and electrified transportation. Achieving high-quality and consistent battery electrode production is critical for ensuring long cycle life, enhancing safety, minimizing material waste, and reducing costs across these sectors. The terahertz imaging platform developed through this project provides a nondestructive, high-resolution method for assessing key electrode properties that directly impact battery performance, including coating uniformity, thickness, moisture content, and material defects. By enabling early detection of quality issues and reducing dependence on destructive sampling and time-intensive analytical techniques, this technology has the potential to decrease manufacturing losses, improve product reliability, and accelerate the commercialization of advanced energy-storage solutions. These advancements ultimately benefit California ratepayers by fostering the development of safer, more efficient, and cost-effective energy-storage technologies that strengthen grid resilience and support the state’s clean-energy objectives.

CHAPTER 1: Introduction

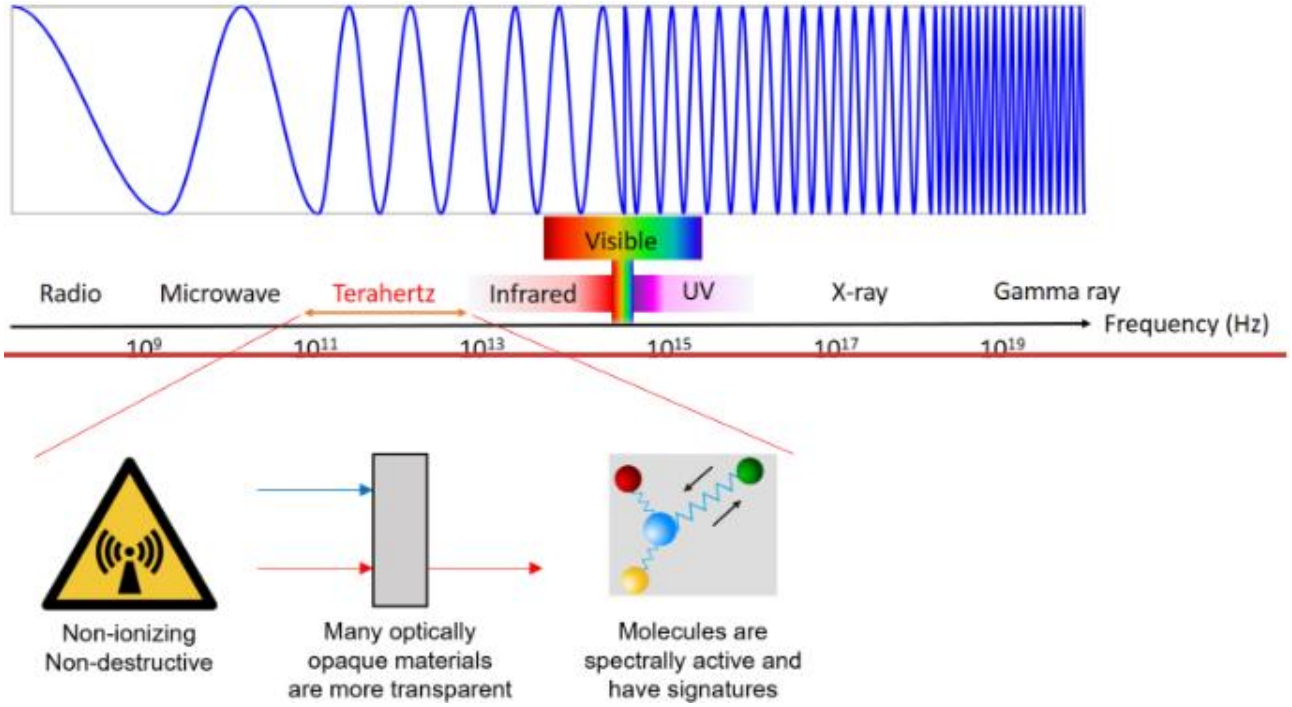
California is accelerating the adoption of clean-energy technologies, and lithium-ion batteries (LIBs) are a cornerstone of this transition. As battery-manufacturing capacity increases across the United States and globally, ensuring consistent quality in electrode production becomes increasingly important. Even small coating defects or nonuniformities introduced during roll-to-roll (R2R) electrode fabrication can lead to reduced cycle life, lower energy capacity, or safety risks such as internal short circuits or thermal runaway. Industry reports indicate that scrap rates in electrode manufacturing commonly range from 5 percent to 10 percent, and in some cases, even higher during scale-up periods, resulting in significant material waste and higher production costs.[2,3] Current inspection methods are limited in their ability to detect early-stage defects. Contact probes, laser calipers, optical inspection systems, and post-formation electrical tests provide only partial information and often identify defects only after battery cell assembly, when corrective action is no longer possible. Manufacturers, therefore, lack a noncontact, high-throughput, nondestructive method that can detect coating nonuniformities and embedded defects during the earliest stages of electrode production. This gap reduces manufacturing yield, decreases material efficiency, and affects the reliability of battery cells.

Terahertz imaging provides a promising solution to this problem. Terahertz waves occupy the frequency range between microwaves and infrared light, as illustrated in Figure 1, and can penetrate many nonmetallic materials used in battery electrodes. They are sensitive to variations in coating thickness, density, water content, and electrical conductivity. Terahertz radiation is nonionizing and safe for continuous use in production environments. Unlike visible-light inspection, terahertz imaging provides subsurface information. Unlike x-ray imaging, it does not require shielding or controlled areas. These characteristics make terahertz sensing well suited for real-time, in-line inspection of electrode coatings.

[2] Li, J., & Daniel, C. *Reducing Manufacturing Defects in Electrode R2R Processing*. s.l.: Department of Energy, Oak Ridge National Laboratory, 2020.

[3] Lefherz, H., Muller, M., & Peters. *Sustainability of Electrode Scrap Recycling: Quantifying the Environmental Benefit of Direct Recycling Routes for Battery Production Scrap*. s.l.: Sustainable Materials and Technologies, 2025, Vol. 36.

Figure 1: Terahertz Region within the Electromagnetic Spectrum and Unique Specifications of Terahertz Waves



Source: Lookin, Inc.

Conventional terahertz systems have historically been limited by slow scanning speeds and low sensitivity, which restricted their use in industrial settings. Recent technological advances, including plasmonic-enhanced terahertz emitters and detectors and multipixel terahertz focal plane arrays developed at the University of California, Los Angeles (UCLA), have addressed these limitations. These innovations significantly improve sensitivity and enable parallel waveform acquisition for fast imaging. This project was motivated by the opportunity to translate these laboratory advances into a practical inspection tool for battery manufacturers.

The work performed under California Energy Commission (CEC) Agreement EPC-21-035 aims to advance this new generation of terahertz scanning technology toward practical deployment in R2R battery electrode manufacturing. By enabling real-time, nondestructive detection of coating defects and structural variations, the technology has the potential to reduce scrap, increase yield, support data-driven process optimization, and improve the safety and reliability of LIBs produced in California and the United States.

Market Need for LIB Quality Control

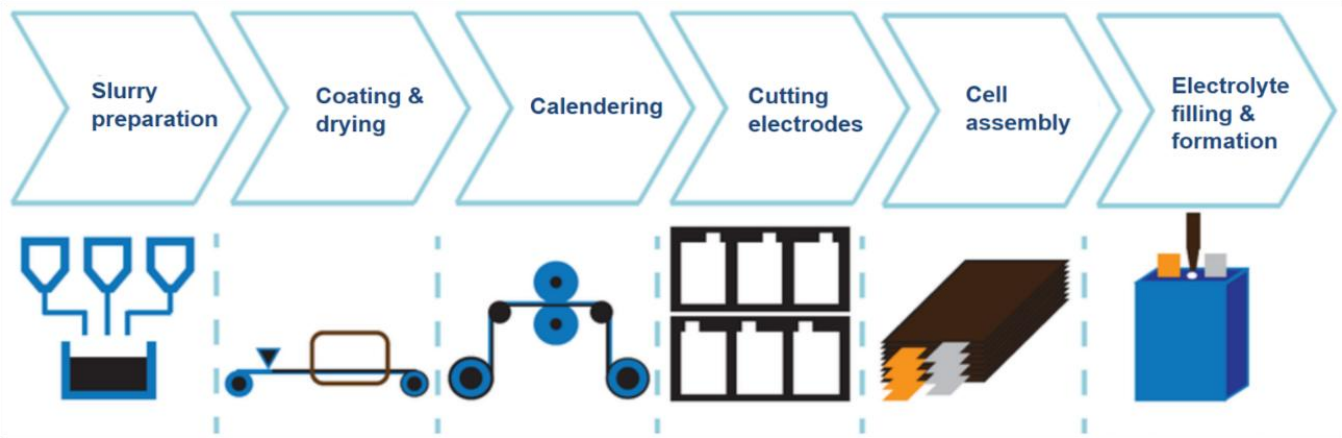
The rapid expansion of LIB manufacturing in the United States and worldwide has created a strong need for improved quality-control tools that can keep pace with modern R2R production lines. Battery demand for electric vehicles, grid-scale storage, microgrids, and consumer electronics continues to grow rapidly, and manufacturers are increasing production capacity to meet both domestic and California-specific requirements for electrification. As production

scales, even small inefficiencies in electrode quality control can result in significant material waste and reduced manufacturing yield.

Electrode fabrication remains one of the most defect-prone stages in the entire battery production chain. Coating, drying, and calendering[4] steps can introduce a variety of defects, including agglomerates, pinholes, divots, nonuniform coating thickness, microcracks, and residual moisture content. These early-stage defects often propagate into reduced energy capacity, shortened cycle life, or safety risks such as internal short circuits. Because defects frequently arise before the battery cell is assembled, manufacturers require inspection tools that can detect these issues directly on the R2R line. A conceptual representation of the LIB manufacturing chain and the defect-introduction points commonly observed in electrode production is shown in Figure 2.

Current inspection tools do not fully meet these needs. Laser calipers provide only surface-level thickness measurements. Optical cameras struggle to detect subsurface or low-contrast defects. Contact probes are slow and incompatible with wet-coating stages. X-ray systems are expensive, require shielding, and are not suited for continuous in-line monitoring. Many manufacturers rely heavily on post-formation electrical testing to identify defective cells, which only reveals issues at a late stage when material has already been consumed and remediation is no longer possible.

Figure 2: Overview of Lithium-Ion Battery Manufacturing Process



Overview of the lithium-ion battery manufacturing process showing slurry preparation, coating and drying, calendering, electrode cutting, cell assembly, and electrolyte filling. Defects introduced during coating and calendering have the largest impact on final cell quality, and therefore represent the most critical stages for in-line quality control.

Source: Lookin, Inc.

According to multiple industry and national laboratory assessments, scrap generated during electrode manufacturing can account for 5 percent to 10 percent of processed material under stable operation and significantly more during process ramp-up or recipe changes. In high-volume plants, these losses correspond to many millions of dollars in wasted materials per

[4] Calendering involves passing the anode and cathode electrode sheets through a series of rollers to compress and densify the material.

year, along with increased energy consumption and labor costs. U.S. Department of Energy (DOE) commercialization planning studies identify manufacturing yield loss as one of the highest-cost challenges for domestic battery production. Improving early detection of coating and structural defects represents a direct path to reducing these losses.

There is, therefore, a clear and well-documented market need for an in-line, high-throughput, noncontact, nondestructive inspection method that can detect early-stage electrode defects, quantify coating uniformity, track drying behavior, and provide real-time feedback for process control. A system that operates consistently with R2R lines that delivers actionable information to manufacturing engineers has the potential to reduce scrap rates, increase process stability, improve cell-to-cell consistency, and strengthen the competitiveness of domestic battery production.

The terahertz-based inspection system developed in this project directly addresses this market gap. By providing subsurface imaging, quantitative thickness mapping, water-content tracking, and defect detection at industrial line speeds, the technology meets a pressing need identified by manufacturers and national laboratories and aligns with DOE and California Energy Commission priorities for improving the reliability, efficiency, and affordability of LIBs.

Goal of the Project

The goal of this project was to develop, validate, and demonstrate a terahertz-based inspection system capable of providing real-time, nondestructive quality control for R2R LIB electrode manufacturing. The project was designed to translate recent laboratory advances in high-sensitivity terahertz imaging into a practical tool that can operate directly on industrial web lines. The specific objectives included:

1. Develop a compact, high-sensitivity terahertz scanning system suitable for noncontact, real-time inspection of electrode coatings, with the ability to measure coating thickness, uniformity, porosity, drying behavior, and defect occurrence.
2. Characterize the terahertz response of anode and cathode materials through laboratory testing and electrode evaluation studies to establish quantitative relationships between terahertz signals and electrode structural properties.
3. Design and implement a field-ready platform capable of deploying the terahertz scanner inside battery-manufacturing facilities, including integration with R2R lines and compatibility with industrial production speeds.
4. Demonstrate the system in operational environments through multistage field testing at Navitas Systems to evaluate performance under real manufacturing conditions and assess correlation with battery-performance outcomes.
5. Develop automated data-processing tools that enable defect detection, thickness mapping, drying-curve tracking, and material-property inference in real time through a user-friendly interface.

6. Assess the impact of terahertz-based inspection on scrap reduction, process stability, and overall manufacturing efficiency, and identify pathways for broader adoption in the battery industry.

These objectives collectively support California's need for advanced, data-driven manufacturing tools that can improve the quality, reliability, and cost-effectiveness of LIBs produced in the state.

Project Benefits to California

This project provides several important benefits to California by supporting the development of advanced manufacturing tools that improve the quality, safety, and competitiveness of LIB production. As California expands the use of electric vehicles, distributed energy resources, and grid-scale storage, the availability of high-quality batteries becomes increasingly important for both economic and environmental objectives.

Improved in-line quality control can reduce scrap generation during electrode manufacturing. Scrap rates of 5 percent to 10 percent are common in electrode-coating processes, and reductions in material waste directly lower production costs. Because the most expensive inputs in battery manufacturing include active materials, conductive additives, binders, solvents, and energy required for drying and calendering, reducing scrap has a meaningful impact on the cost of batteries used by California ratepayers. Lower-cost batteries contribute to more affordable electric vehicles, reduced cost of energy-storage systems, and decreased financial barriers for clean-energy adoption.

Enhanced quality control also supports improved battery reliability and safety. Early detection of defects such as agglomerates, pinholes, divots, microcracks, and nonuniform coatings can reduce the likelihood of battery cell failures. More consistent electrode manufacturing results in longer cycle life and more stable field performance for electric vehicles and stationary storage installations across the state. These improvements help reduce maintenance costs, increase system uptime, and support California's grid-reliability goals.

The technology developed in this project strengthens California's innovation ecosystem by advancing a next-generation sensing platform created at UCLA. The project supports the translation of university research into commercial hardware and software, contributing to high-technology job creation and workforce development in the state. By demonstrating the feasibility of terahertz-based inspection in real manufacturing environments, the project also improves the competitiveness of domestic battery production and reduces reliance on imported inspection equipment.

Finally, this work supports California's climate goals. Higher-yield manufacturing reduces energy consumption associated with reprocessing, remanufacturing, and scrap handling. Improved battery quality extends lifetime and reduces the frequency of replacements, lowering lifecycle emissions. More affordable and reliable batteries facilitate wider deployment of electric transportation and renewable energy storage, both of which are central to meeting California's emission-reduction targets.

CHAPTER 2:
Project Approach

Technical Approach

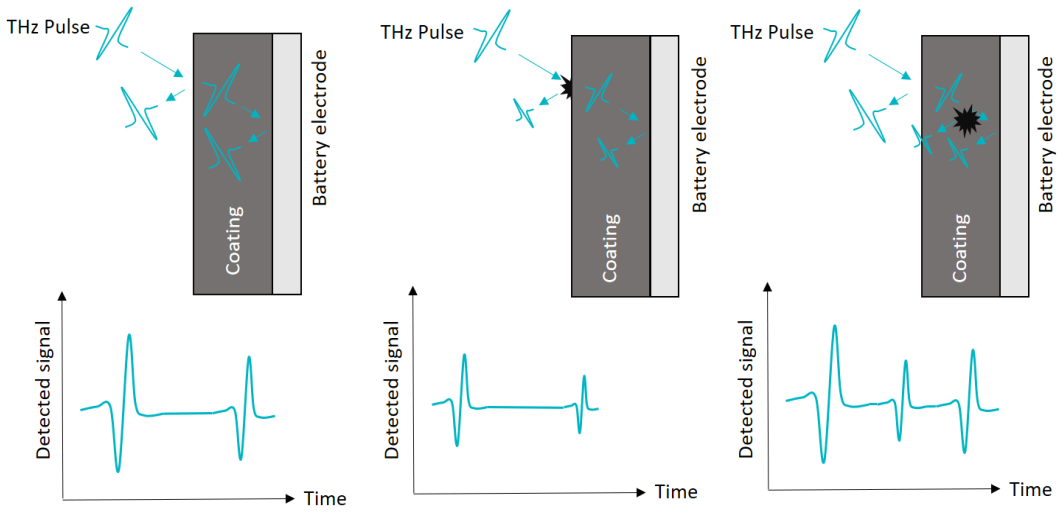
The technical approach for this project focused on developing a practical terahertz-based inspection system capable of operating directly on R2R LIB electrode lines and providing real-time, nondestructive measurements of coating quality. The work combined laboratory materials characterization, advancements in terahertz time-domain imaging, sensor and hardware engineering, development of a high-throughput data-processing framework, and field deployment at a manufacturing facility. The approach was designed to address the historical limitations that prevented terahertz imaging from being used in industrial environments and to translate recent scientific advances into a field-ready inspection platform.

Conventional terahertz systems were not suitable for industrial R2R manufacturing because they relied on single-pixel detectors and mechanical raster scanning that produced very low throughput, a small field of view, and long acquisition times. Traditional systems lacked the sensitivity required to analyze thin electrode coatings, were prone to misalignment in vibration-heavy environments, and were typically mounted on large optical tables unsuitable for integration with production lines. These limitations prevented manufacturers from using terahertz for real-time, in-line inspection, even though the underlying physics offered strong potential for detecting coating defects, thickness variations, subsurface nonuniformities, and moisture content.

Recent advances developed at UCLA addressed these barriers. Plasmonic-enhanced terahertz emitters and detectors increased signal amplitude and detection sensitivity by more than an order of magnitude, enabling the detection of thin coatings and subtle density variations. In parallel, multipixel terahertz focal plane arrays made it possible to capture multiple waveforms simultaneously, significantly increasing the field of view and throughput. These innovations provided the foundation for a new type of compact, high-sensitivity terahertz scanner capable of operating at speeds compatible with industrial R2R manufacturing.

The imaging method used in this project is terahertz time-domain imaging, which generates short pulses of terahertz radiation and records the time-varying electric field reflected from the electrode surface and internal interfaces. A representative example of a terahertz time-domain measurement and imaging output is shown in Figure 3. Each waveform contains amplitude and phase information that depends on coating thickness, refractive index, porosity, moisture content, and internal structure. The time delay between echoes corresponds to coating thickness. The phase shift provides the refractive index. Amplitude changes and spectral dispersion provide information about porosity and density. Absorption and relaxation signatures reveal water content and drying behavior. Scattering patterns and multipeak features identify agglomerates, embedded particles, voids, and other structural defects. By acquiring waveforms across the web using a multipixel array, the system forms two-dimensional maps of these properties with micrometer-scale sensitivity.

Figure 3: Terahertz Time-Domain Waveform and Imaging Outputs

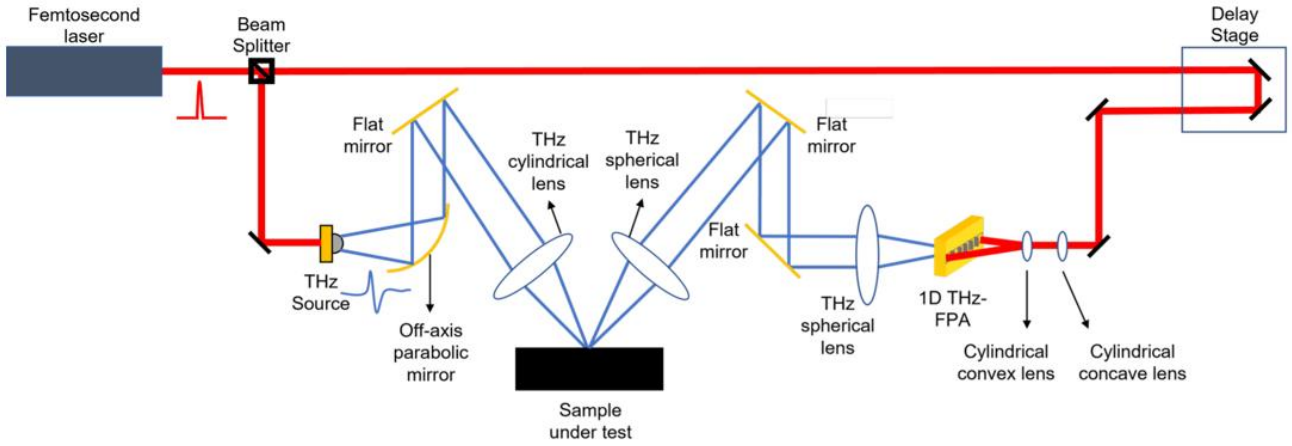


Representative terahertz time-domain waveform and imaging output from electrode samples. The waveform shows reflections from the coating surface and coating-foil interface, while the corresponding image illustrates coating-thickness variations, density differences, or defect locations revealed by terahertz time-of-flight and phase analysis.

Source: Lookin, Inc.

Hardware engineering efforts produced a compact terahertz scanner optimized for industrial conditions. The scanner architecture is shown in Figure 4. It included plasmonic-enhanced terahertz emitters and detectors, a multipixel focal plane array, high-speed waveform acquisition electronics, and a rigid mechanical frame designed to maintain alignment during continuous operation. The optical components were enclosed in dust-resistant and solvent-resistant housings to protect the system near coating and calendering equipment. Adjustable mounting interfaces allowed the scanner to be installed above or below the moving web and adapted to different coating widths and line geometries.

Figure 4: Diagram of Terahertz Time-Domain Imaging Scanner



Simplified block diagram of the terahertz time-domain imaging scanner developed in this project, including the plasmonic terahertz emitter, delay line, imaging optics, multipixel terahertz focal

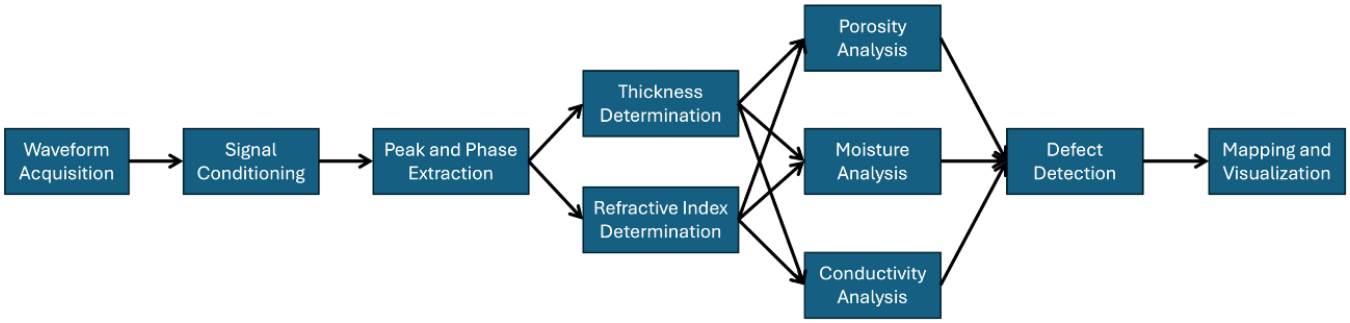
plane array, and high-speed waveform acquisition electronics. The configuration supports real-time, nondestructive analysis of R2R lithium-ion battery electrodes.

Source: Lookin, Inc.

To support on-site deployment, the team developed a mobile platform that allowed rapid installation on existing manufacturing lines. The platform incorporated adjustable optical paths, precision alignment fixtures, and interchangeable mounting modules. This configuration provided flexibility for integration with different R2R systems and ensured that the scanner could be deployed quickly for field testing.

A high-throughput data-processing and visualization framework was created to convert raw terahertz waveforms into actionable quality metrics. The workflow is illustrated in Figure 5. The processing pipeline included waveform conditioning, peak and phase extraction, time-of-flight thickness mapping, refractive-index estimation, porosity analysis, moisture tracking, and automated defect detection. Computation accelerated by graphics processing units (GPU) allowed these operations to be performed in real time. A user-friendly interface displayed thickness maps, defect locations, moisture distributions, and other quality metrics during production, enabling operators to evaluate coating uniformity as the web moved through coating, drying, and calendering stages.

Figure 5: Data-Processing Workflow



Data-processing workflow for the terahertz time-domain imaging system used in this project. The pipeline begins with waveform acquisition and signal conditioning and continues through peak and phase extraction, thickness and refractive-index determination, porosity and moisture analysis, conductivity estimation, defect detection, and real-time mapping and visualization for use in R2R lithium-ion battery electrode manufacturing.

Source: Lookin, Inc.

The final component of the technical approach was a series of multistage field demonstrations at Navitas Systems. The scanner was installed on active R2R electrode lines and operated during real coating and drying processes. Continuous measurements were collected at production-relevant speeds, demonstrating the ability to detect coating nonuniformities, thickness variations, embedded defects, drying gradients, and density changes. The system showed stable performance during extended operation and maintained alignment despite line vibrations and thermal fluctuations. These demonstrations confirmed that the terahertz scanner could operate reliably in a manufacturing environment and provided real-time data that complemented operator observations and downstream inspection methods.

Through this integrated technical approach, the project advanced terahertz time-domain imaging from a laboratory research tool into a field-ready platform capable of supporting practical, in-line quality control for R2R LIB electrode manufacturing. The combination of plasmonic-enhanced emitters and detectors, multipixel terahertz focal plane arrays, compact mechanical design, high-speed data processing, and successful field deployment provides a clear path toward broader industrial adoption.

Terahertz Scanner Design and Specifications

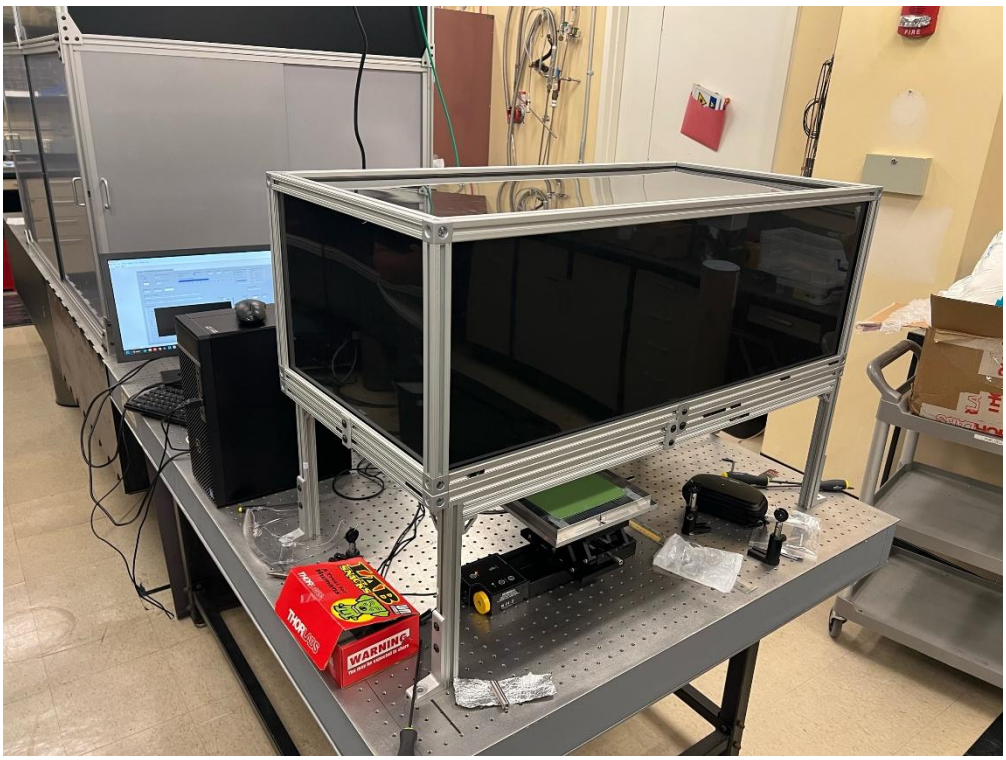
The terahertz scanner developed in this project was designed to provide high-sensitivity, high-throughput, nondestructive imaging of LIB electrodes in R2R manufacturing environments. The system integrates plasmonic-enhanced terahertz emitters and detectors, a multipixel terahertz focal plane array, and vibration-tolerant optical and mechanical assemblies to ensure stable operation during extended measurements.

The scanner uses a mode-locked femtosecond laser that is split into a terahertz generation path and a sampling path (Figure 4). In the generation arm, the laser excites a plasmonic photoconductive emitter that produces broadband terahertz pulses with significantly higher conversion efficiency than conventional photoconductive antennas. The emitted terahertz radiation is routed through a series of off-axis parabolic mirrors and beam-steering elements to illuminate the electrode surface. Reflected terahertz pulses are collected by a second optical path and imaged onto a multipixel terahertz focal plane array. Each pixel operates as an independent detector, capturing its own terahertz time-domain waveform and enabling parallel, high-throughput imaging across the field of view.

Plasmonic-enhanced emitters and detectors substantially improve the system's signal-to-noise ratio, enabling clear detection of thin coating layers and subtle variations in density, porosity, moisture content, and internal structure. The broadband response of the devices supports time-of-flight, phase, and spectral analysis. These capabilities enable the scanner to extract coating thickness, refractive index, porosity-related contrast, and water-absorption signatures from a single measurement. The increased sensitivity and multipixel detection architecture together overcome the fundamental throughput and field-of-view limitations that previously prevented terahertz systems from being deployed on industrial R2R lines.

The optical assembly is housed in an aluminum-frame enclosure with blackout side panels and dust shields to provide a stable measurement environment and reduce the impact of ambient light, dust, and air currents. Mechanical components include rigid optical rails, fixed mirror mounts, and adjustable detector mounts designed to maintain alignment in vibration-heavy environments. The prototype scanner assembly is shown in Figure 6. The enclosure also includes removable side panels for quick maintenance and an adjustable-height mounting interface to accommodate varying web geometries during deployment.

Figure 6: Prototype of the Terahertz Scanner



Prototype of the terahertz scanner, including the protective enclosure, optical assembly, focal plane array mount, data-processing workstation, and alignment platform. The enclosure provides a stable environment for long-duration terahertz measurements.

Source: Lookin, Inc.

The focal plane array includes 64 detector pixels with an 800-micrometer pitch, providing a lateral spatial resolution of approximately 800 micrometers by 1 millimeter across the web. The high-speed waveform acquisition system supports sampling rates up to 100 hertz (Hz) and is synchronized with the motion of the moving electrode surface. The resulting field of view is approximately 5 centimeters by 800 micrometers, with depth resolution below 2 micrometers. These specifications allow the scanner to operate effectively on web speeds below 36 meters per second, which is compatible with typical electrode manufacturing lines. A summary of the scanner prototype specifications is provided in Table 1.

Table 1: Terahertz Scanner Prototype Specifications

Pixel count	64
Pixel pitch size	0.8 mm x 0.8 mm
Field of view	5 cm x 0.8 mm
Depth resolution	< 2 µm
Spatial resolution	800 µm
Scan rate	100 Hz
Applicable R2R speed	36 m/min

Signal-to-noise ratio	70 dB at center, 55 dB at edge
Bandwidth	0.1-3 THz at center, 0.1-1.5 THz at edge
Prototype dimension	40″ x 20″ x 12″
Prototype weight	30 kg

Source: Lookin, Inc,

The complete system includes high-speed digitizers, timing electronics, system-health monitors, and a computer workstation for real-time acquisition and visualization. Fiber-coupled laser delivery stabilizes alignment and reduces sensitivity to mechanical disturbances. Environmental sensors monitor temperature, enclosure status, and operating conditions to ensure stable long-term performance. The scanner is mounted on a modular platform that enables rapid installation near coating, drying, or calendering equipment during field demonstrations.

Through this design, the scanner provides spatial resolution, depth accuracy, and data throughput required for real-time electrode inspection. The combination of plasmonic terahertz devices, multipixel detection, and mechanical robustness supports the transition of terahertz imaging from research laboratories to industrial in-line quality-control environments.

Experimental Methods and Test Plan

The experimental methods and test plan were designed to evaluate the terahertz imaging system in progressively more realistic environments, beginning with controlled laboratory testing at Lookin, followed by dynamic R2R emulation experiments conducted at Lookin and the University of California, Irvine (UCI), and culminating in full-field demonstrations at the partner manufacturing facility, Navitas Systems.

The first phase of the project focused on laboratory-based electrode evaluation at Lookin's terahertz development lab. Representative anode and cathode samples with varied coating thicknesses, porosities, drying conditions, and calendering levels were provided by project partners and commercial suppliers. These samples were placed on a precision translation stage beneath the terahertz scanner, and terahertz time-domain waveforms were collected across each electrode surface using the multipixel focal plane array. Extracted parameters included coating thickness, refractive index, porosity indicators, moisture signatures, and defect-related scattering features. These results were compared with reference measurements such as micrometer readings, mass-loading information, optical microscopy images, and caliper-based measurements. This phase established baseline sensitivity, validated the accuracy of the thickness and refractive-index models, and provided parameters required for algorithm calibration.

The second phase involved stability, repeatability, and robustness testing, also performed at Lookin's laboratory. Controlled experiments evaluated temporal drift, signal-to-noise ratio as a function of averaging time, and the effects of environmental variables such as ambient temperature and airflow. Additional tests were performed by introducing controlled perturbations, including changes in electrode tilt, lateral displacement, and small alignment

offsets. These experiments confirmed that the enclosure and mechanical design provided sufficient stability for long-duration measurements and that the system maintained alignment and sensitivity under realistic disturbances.

To assess performance under motion, a series of dynamic scanning experiments was carried out at Lookin and UCI. In these tests, electrode strips were translated beneath the terahertz scanner using programmable linear stages to mimic the motion of R2R manufacturing lines. Measurements were taken at multiple speeds ranging from slow laboratory motion to speeds approaching those used in commercial electrode coating lines. The purpose of this phase was to verify that the multipixel terahertz system could acquire waveforms at 100 Hz and maintain accurate thickness and porosity extraction during motion. These tests demonstrated consistent measurement accuracy and minimal motion-induced distortion, validating the system's suitability for high-throughput operation.

The final phase consisted of field demonstrations at Navitas Systems. The scanner was installed on a mobile deployment platform and positioned near the coating, drying, and calendering units of the electrode production line. Several test sequences were executed, including static measurements of freshly coated electrodes, real-time measurements during active coating runs, and scans of electrodes after drying and calendering. The terahertz system was used to map coating thickness, detect nonuniformities, identify residual moisture patterns, and observe structural variations linked to process adjustments. Measurements were compared with operator observations, mass-loading data, and downstream inspection results.

These field demonstrations provided a realistic assessment of scanner performance under manufacturing vibration, temperature variations, and environmental noise. The system maintained stable operation throughout extended runs and produced consistent, high-quality data at production-relevant web speeds. The results confirmed that terahertz time-domain imaging can be deployed in real manufacturing environments and can deliver actionable quality-control metrics during electrode production.

Overall, the experimental methods and test plan formed a structured progression from controlled laboratory evaluation to full-scale industrial testing. Each phase validated key aspects of system performance, ultimately demonstrating that the terahertz scanner can support in-line quality control for R2R LIB electrode manufacturing.

Data-Analysis Framework

A comprehensive data-analysis framework was developed to support high-throughput terahertz imaging and to ensure consistent, repeatable data collection during laboratory and field experiments. The framework consists of two major components: an automated acquisition platform and a scalable post-processing pipeline.

On the acquisition side, a Laboratory Virtual Instrument Engineering Workbench (LabVIEW) application was created to integrate and control all system hardware, including the laser, delay line, waveform digitizers, and multichannel data acquisition modules. This approach eliminated the need for multiple independent programs and reduced the time between successive measurements. The software also logged instrument parameters and positional information for

each scan, ensuring that waveform reconstruction and sample alignment were consistent across extended experiments.

A separate post-processing and visualization pipeline was implemented in Python. This pipeline performs signal conditioning, waveform identification, normalization, background correction, and feature extraction. Processing is parallelized across all detector channels and uses GPU acceleration to support real-time or near real-time operation during dynamic scanning. The pipeline generates charts, maps, and quality metrics that allow operators to assess coating thickness, structural features, and uniformity. These capabilities were packaged into an interactive graphical user interface that allows users without programming experience to navigate datasets, visualize results, and export analysis reports.

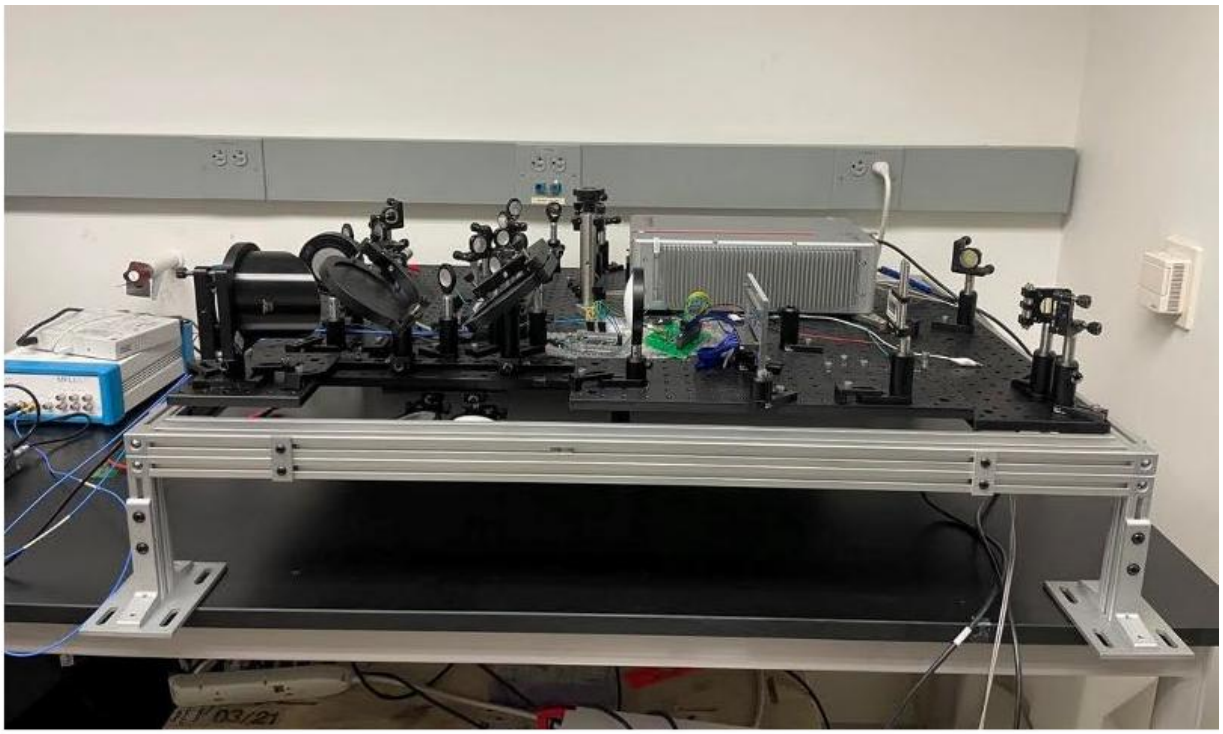
The combination of automated acquisition and scalable post processing ensured that the terahertz scanner could operate reliably in laboratory settings, during motion-based experiments, and during field demonstrations. The framework also provides a foundation for integration with future in-line quality-control systems.

CHAPTER 3:
Results

Prototype Development and Laboratory Validation

The development of the terahertz scanner prototype progressed through several stages during the project period, beginning with early optical and electronic architecture and culminating in a compact, integrated, multipixel system suitable for laboratory evaluation and initial field deployment. The first version of the prototype, developed in early 2023, focused on validating the core functionality of the plasmonic terahertz focal plane array detectors and establishing baseline signal-to-noise performance. These early results confirmed the viability of multipixel time-domain imaging using plasmonic photoconductive devices and provided the foundation for system-level improvements made later in the project. Figure 7 shows an image of the first prototype.

Figure 7: First Prototype



Source: Lookin, Inc.

The first prototype used a free-space optical layout with separate control software for the laser, delay stage, and waveform digitizer. This configuration enabled initial measurements on electrode samples but required substantial manual setup time and was sensitive to laboratory alignment changes. Laboratory tests performed during this period demonstrated the first successful acquisition of multipixel terahertz waveforms, early thickness measurements on cathodes and anodes, and preliminary defect identification. These experiments verified that the basic detector architecture could capture repeatable measurements across all pixels and

that the terahertz signals contained sufficient temporal and spectral content for material-parameter extraction.

As the project progressed, the team consolidated the optical layout into a more compact and robust configuration. They shortened the optical path, reduced the number of free-space elements, and added an adjustable enclosure to improve environmental stability. These changes increased system alignment stability, reduced noise due to ambient infrared and visible light, and improved repeatability of waveform acquisition.

At the same time, the team implemented significant upgrades in the data acquisition hardware. A higher-speed, multichannel acquisition module capable of synchronously recording signals from all pixels replaced the original digitization system. This upgrade reduced timing jitter, improved waveform fidelity, and allowed reliable operation at higher scan rates. Calibration routines were introduced to account for pixel-to-pixel variations in gain and phase, enabling more accurate reconstruction of thickness and refractive-index maps.

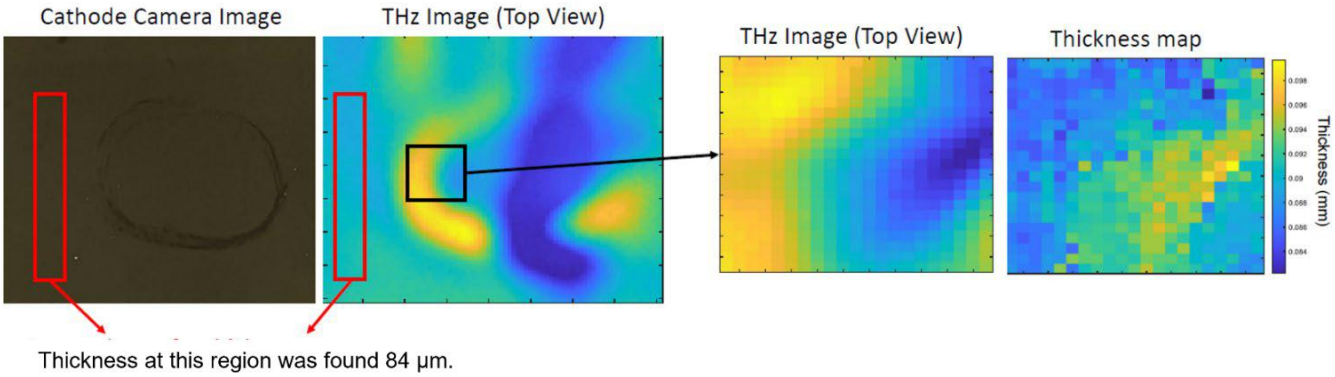
Laboratory validation efforts focused on quantifying the performance of the upgraded system through controlled measurements on a wide range of electrode materials. These tests included cathodes with different coating weights, anodes with varying porosity levels, dry-coated and slurry-coated films, and samples both before and after calendering. A series of thickness validation experiments demonstrated that the system could reliably measure layer thickness with approximately micrometer-level accuracy over the full field of view.

Laboratory samples also validated material-parameter extraction. By analyzing the time-domain waveforms and their associated frequency-domain spectra, the system could estimate refractive index, absorption coefficients, and other dielectric properties relevant to coating density and porosity. Controlled moisture-exposure experiments demonstrated that the terahertz signals were sensitive to small changes in water content, enabling the identification of partially dried or insufficiently dried regions in coated electrodes.

Defect-detection capabilities were examined through imaging of samples containing scratches, pinholes, embedded particles, and coating nonuniformities. The prototype system detected defects that were not visible under optical inspection and identified subsurface features that would otherwise go unnoticed until later stages of battery manufacturing. These laboratory tests verified that the terahertz focal plane array approach provides complementary information to optical and x-ray-based methods.

As an example, Figure 8 shows the top-view image obtained with a phone camera and Lookin's terahertz scanner, respectively. In this part of the sample, the project team intentionally created a defect by scratching the coating material with a thin blade. From the terahertz image, the team could clearly observe the impact of the scratching, not only on the ring but also in its peripheral region, which is not observable with a camera image. Additionally, Figure 8 shows the top-view and thickness map.

Figure 8: Camera Image and Terahertz Amplitude Image



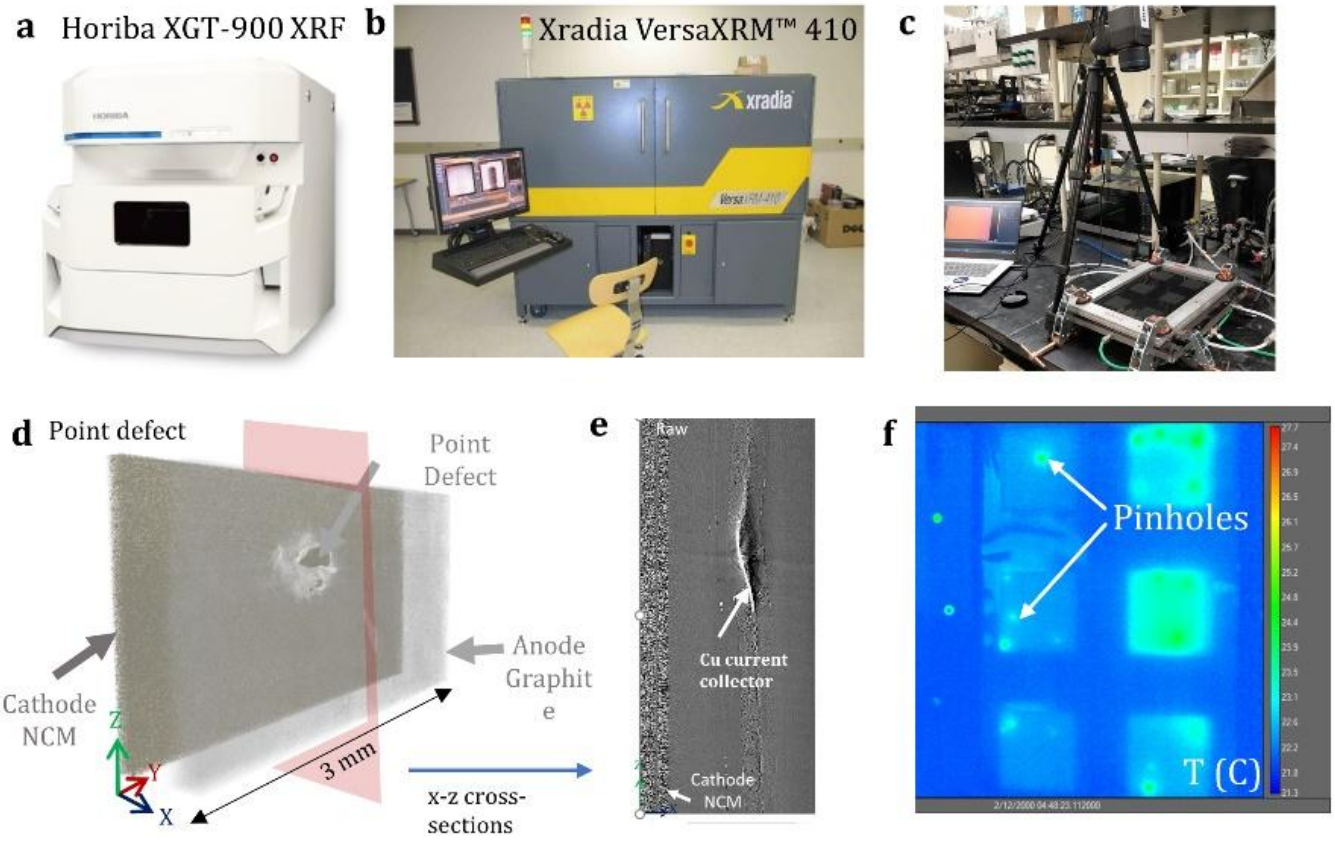
Source: Lookin, Inc.

Electrode Evaluation Results

Lookin performed an extensive evaluation campaign involving more than 100 anode and cathode electrode samples. These samples ranged in size from approximately 7 centimeters by 12 centimeters to 10 centimeters by 20 centimeters, with coating thicknesses between 50 micrometers and 200 micrometers. The sample set included commercially purchased electrodes, electrodes fabricated by UCI, and samples supplied by industrial collaborators.

The UCI group manufactured electrodes specifically for defect characterization. These electrodes contained imperfections that commonly arise during slurry coating, such as bare spots and agglomerates, as well as defects introduced after drying. Additional controlled defects were created under a microscope using a micromanipulator equipped with ultrafine probes. This process enabled the introduction of line defects, point defects, small bends, ripples, and agglomerations with feature sizes down to 10 micrometers. The defect sizes were validated using scanning electron microscopy. UCI's expertise in computer tomography-based metrology, infrared thermography, and x-ray fluorescence allowed them to document the morphology, thickness distribution, and uniformity of the electrodes before they were evaluated with the terahertz scanner. Example images of these defects from low-throughput quality-control tools appear in Figure 9.

Figure 9: Quality Control at UCI

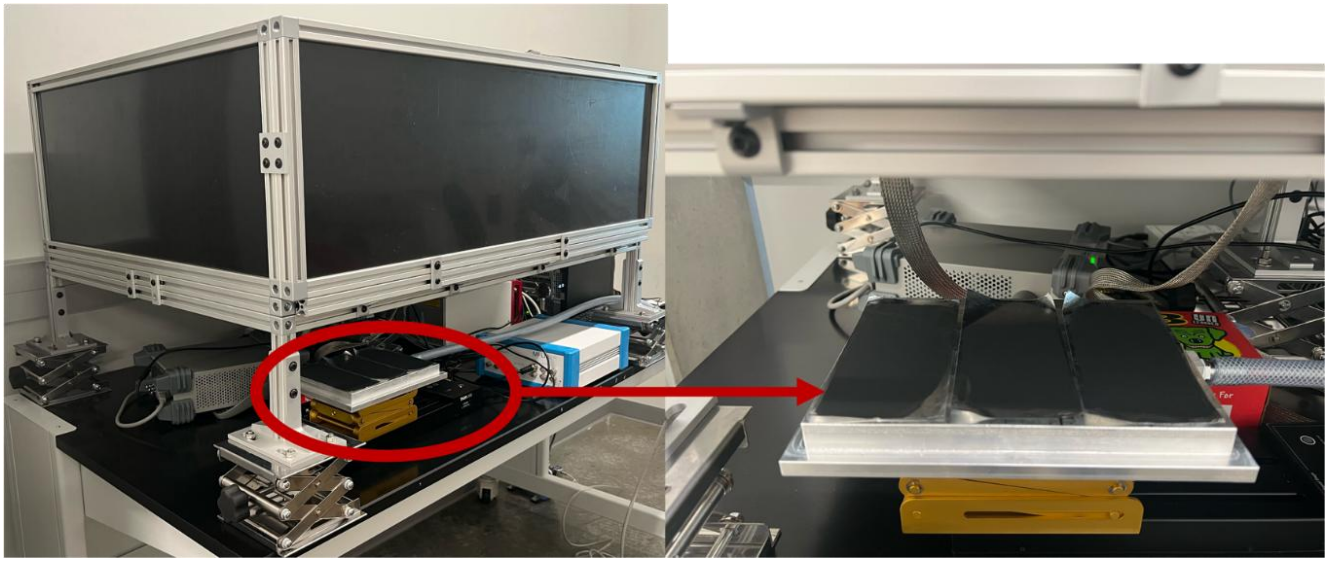


Facilities available at UCI for quality control (QC): (a) Horiba XGT-9000 XRF instrument, (b) Zeiss Xradia Versa XRM 410 x-ray computed tomography (CT), (c) custom-built infrared (IR) thermography setup for electrode imaging. Examples of defective batteries imaged with x-ray CT, where (d) shows the point defect on the anode current collector and (e) shows a cross section tomograph with a bent current collector. An example of IR thermography of electrodes with pinholes is shown in (f).

Source: University of California, Irvine

Lookin and UCI conducted electrode evaluation measurements at their laboratory facilities. During testing, the team shaped the terahertz beam into a line and operated the system as a terahertz line scanner. They placed each electrode sample on a motorized stage beneath the prototype, as shown in Figure 10. As the stage translated the sample in one direction, the scanner recorded sequential line scans and reconstructed two-dimensional terahertz images of the electrode.

Figure 10: Electrode Samples and the Prototype



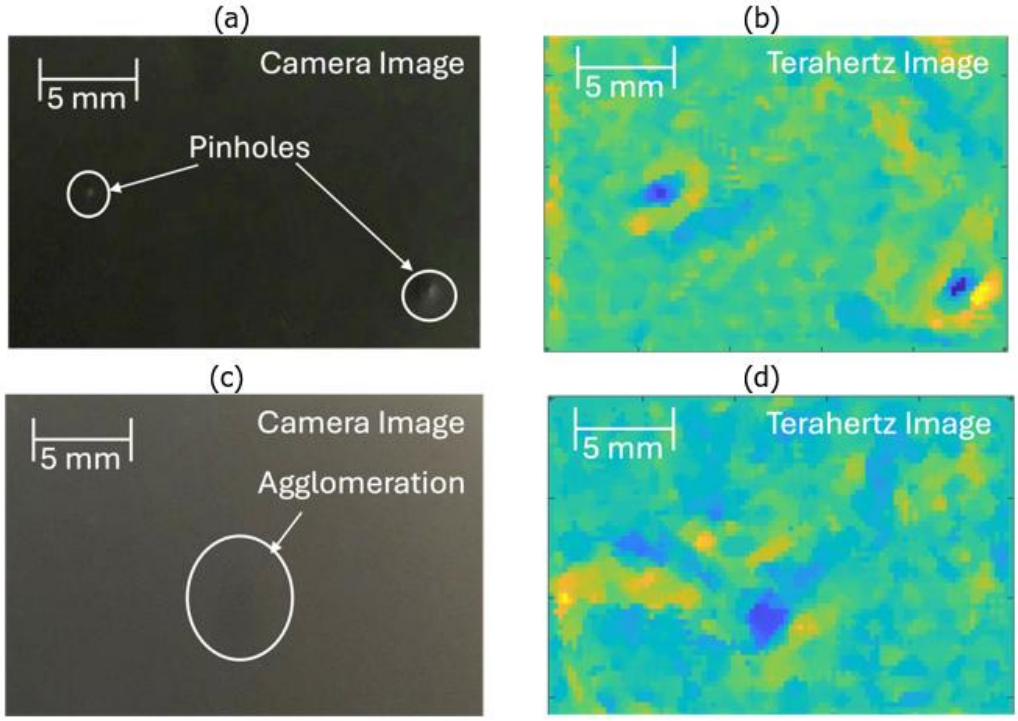
The scanner prototype at UCI for electrode evaluation tests. The electrode sample was placed on a motorized stage under the prototype.

Source: University of California, Irvine

Defect Detection

The project imaged a variety of samples containing typical manufacturing defects, including pinholes, agglomerates, and divots. In one example, a cathode sample contained two pinholes of approximately 20 micrometers in diameter. These defects were barely visible in charge-coupled device (CCD) images taken at visible wavelengths, as shown in Figure 11a. The corresponding terahertz amplitude image in Figure 11b revealed the pinholes with significantly higher contrast, demonstrating the sensitivity of the technique to small surface defects. A second defective sample contained an agglomerate (Figure 11c). Again, the terahertz amplitude image (Figure 11d) highlighted the defect more clearly than the optical camera image.

Figure 11: Camera Images of Electrodes

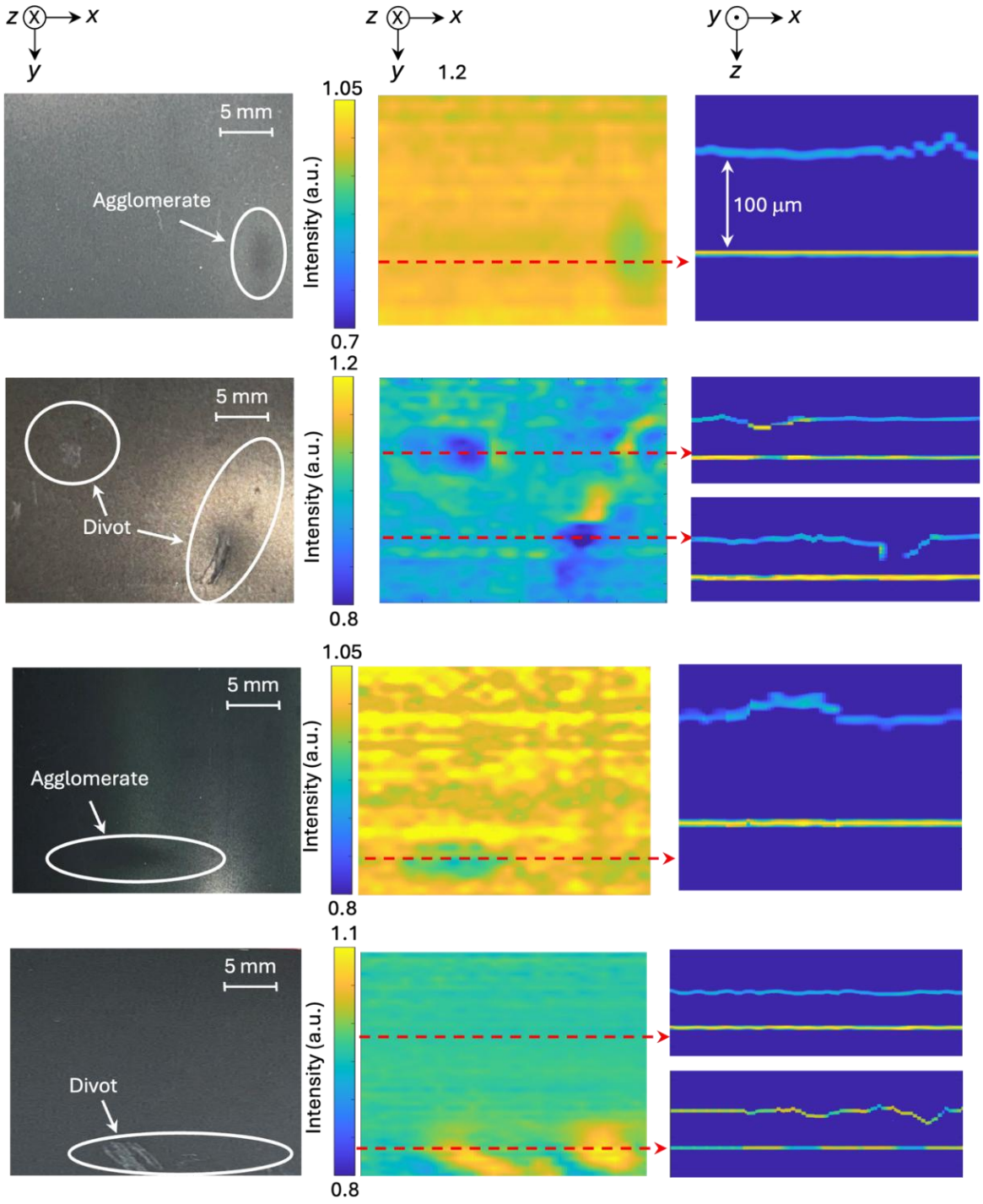


(a) CCD camera image of an electrode containing pinholes. (b) Terahertz image of the same electrode. (c) CCD camera image of an electrode containing agglomeration. (d) Terahertz image of the same electrode.

Source: Lookin, Inc

In addition to top-view images, the time-domain terahertz signals allowed reconstruction of cross-sectional views that illustrate how divots and agglomerates alter the internal structure of the coating. Examples of these cross-sectional results are shown in Figure 12.

Figure 12: Cross-Sectional Results



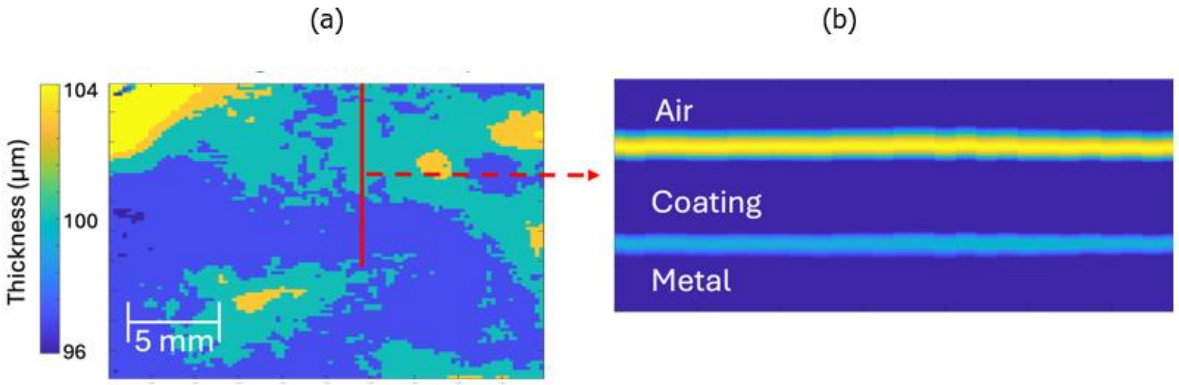
Source: Lookin, Inc

Thickness Mapping

The time delay between the terahertz reflections from the air-to-coating interface and the coating-to-electrode interface enabled precise extraction of coating thickness. Using this method, the scanner measured cathode coating thickness with approximately 1-micrometer

accuracy and anode coating thickness with approximately 3-micrometer accuracy. Figure 13 shows a representative thickness map of a nondestructive electrode.

Figure 13: Electrode Coating Thickness Map

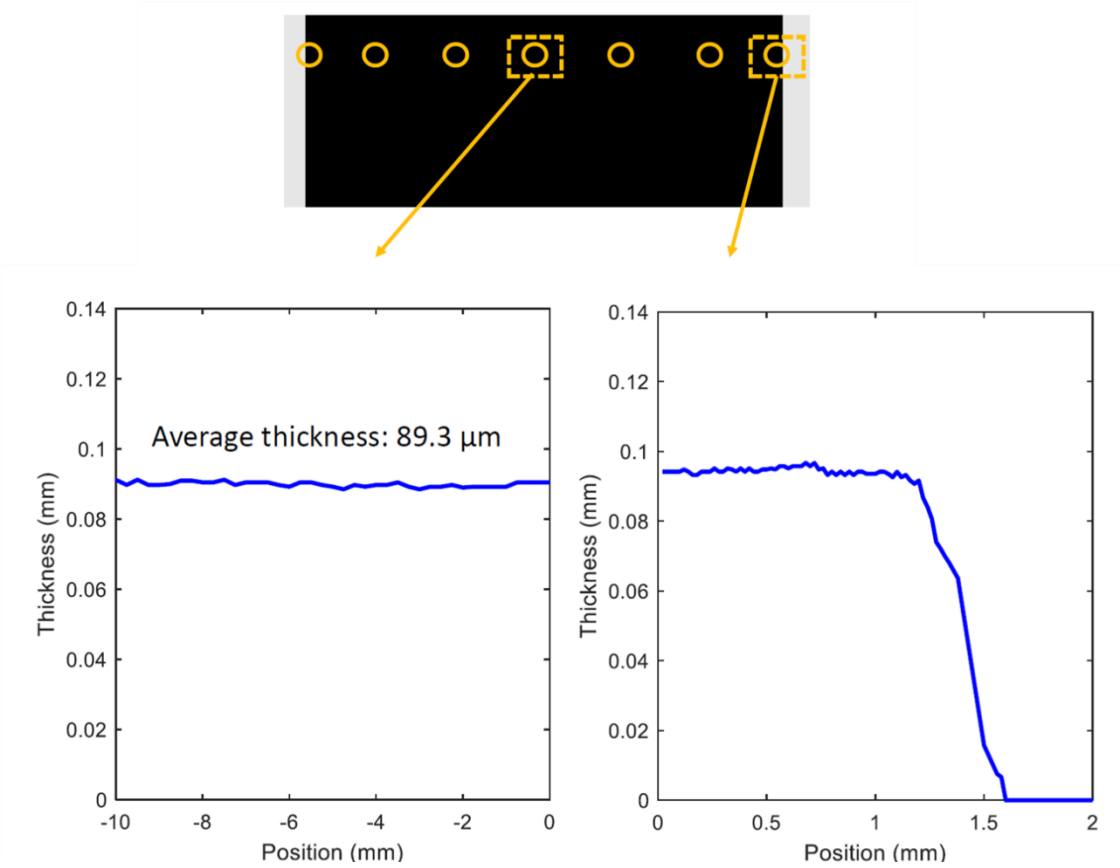


(a) Electrode coating thickness map obtained with the terahertz scanner.
(b) Cross-sectional view obtained with the terahertz scanner.

Source: Lookin, Inc

To validate the scanner's capability in areas exhibiting significant thickness variation, the team acquired measurements along two distinct regions of the coating: one at the center, where the thickness remains relatively uniform; and another near the edge, where the transition in thickness occurs abruptly. These profiles provide a rigorous test of the system's spatial resolution and sensitivity to rapid geometric changes. As illustrated in Figure 14, the extracted thickness profiles clearly demonstrate the scanner's ability to resolve sharp discontinuities and capture fine-scale variations in coating geometry. This performance underscores the robustness of the imaging approach for quality control in manufacturing environments where precise detection of edge effects and localized anomalies is critical.

Figure 14: Thickness Profile



The thickness profile of the electrode coating at the center and the edge of the electrode.

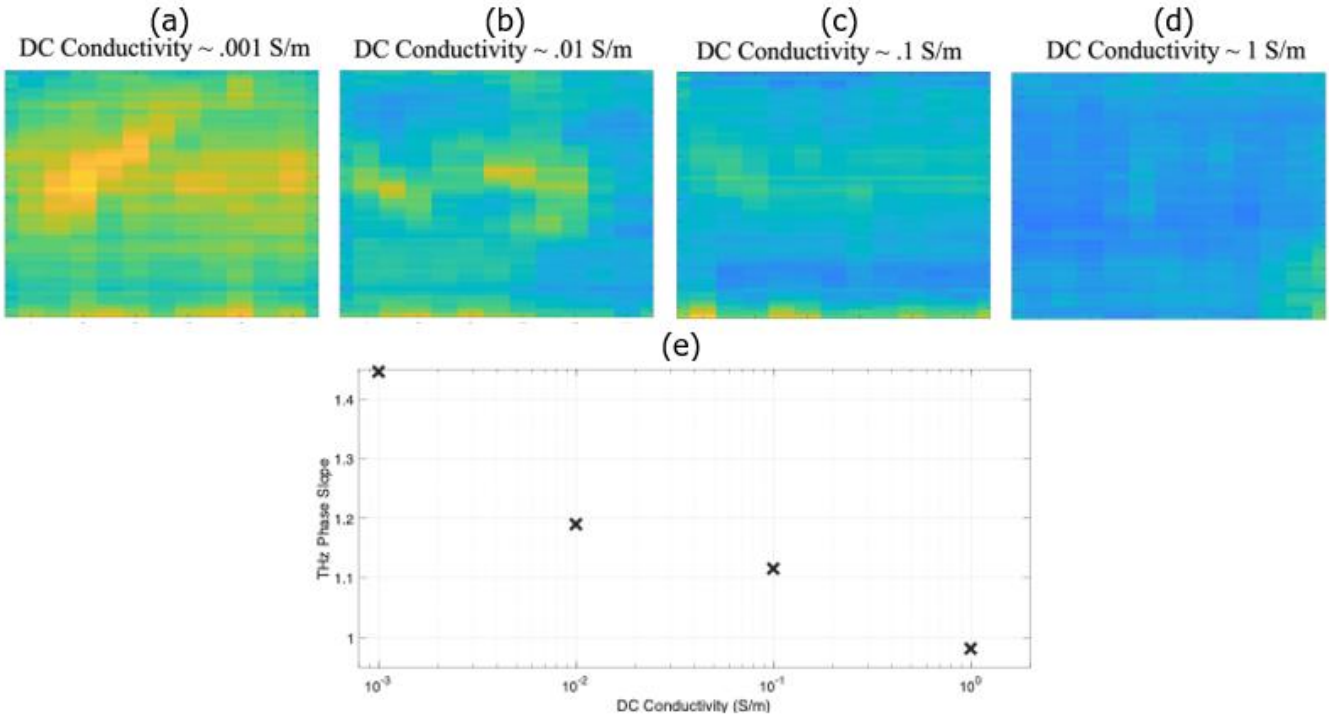
Source: Lookin, Inc

Conductivity Characterization

An additional objective of this study was to assess whether the electrical conductivity of the coating could be inferred from its refractive index as measured by the terahertz system. To enable this evaluation, project collaborators fabricated cathode samples with four distinct conductivity levels, spanning a range from approximately 0.001 siemens per meter to 1 siemens per meter. This controlled variation provided a robust basis for analyzing the sensitivity of terahertz signals to changes in electrical properties.

The experimental results revealed that the phase component of the terahertz waveform exhibits the highest sensitivity to conductivity differences among the tested parameters. This finding suggests that phase-based analysis may serve as a reliable indicator for estimating conductivity in noncontact, high-throughput inspection scenarios. Figure 15 shows the measured phase response as a function of conductivity.

Figure 15: Phase Images of Electrodes



(a-d) Phase images of electrodes with different DC conductivity levels from 0.001 to 1 S/m. (e) The correlation between the THz phase signal and the DC conductivity.

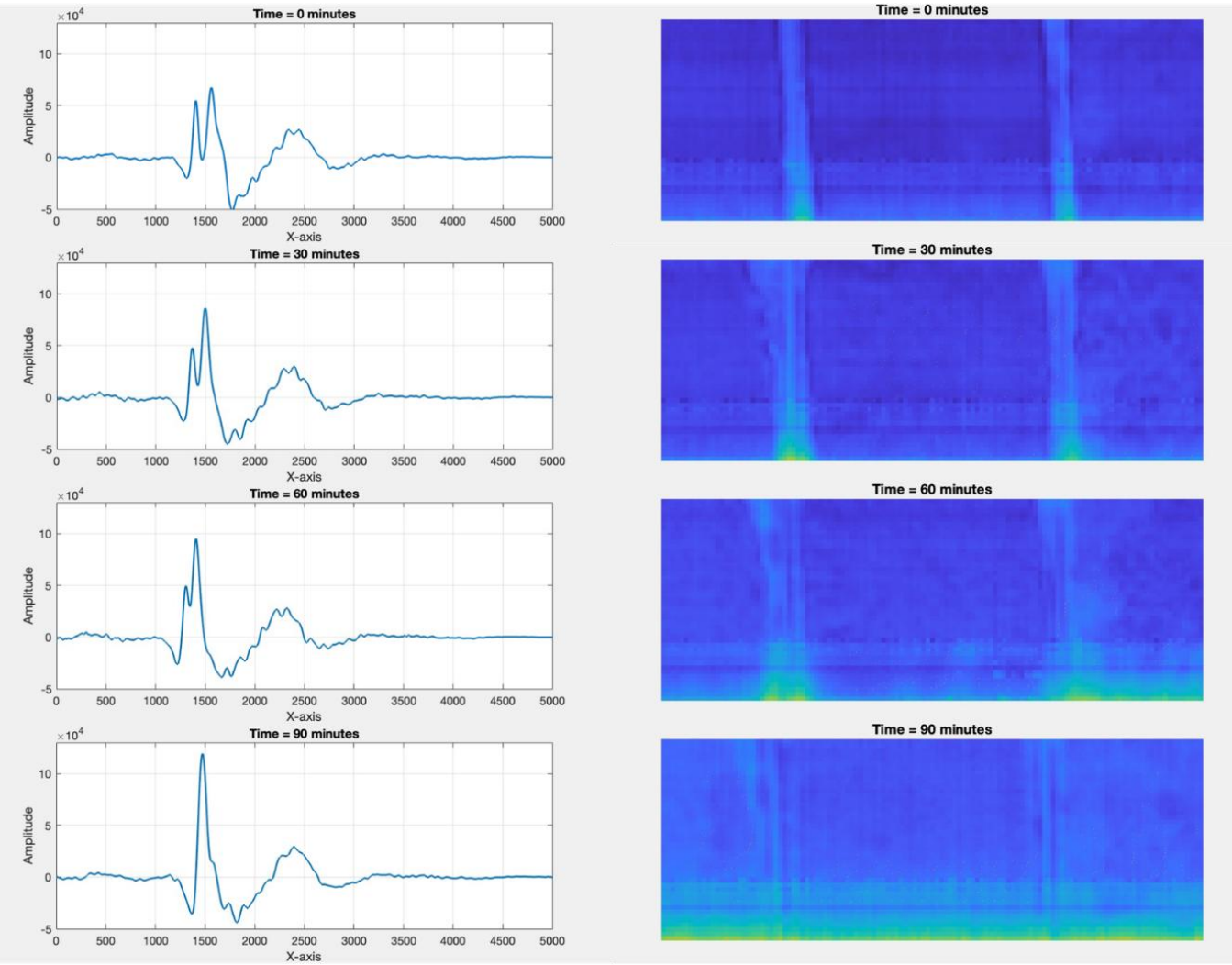
Source: Lookin, Inc

Drying Behavior

Given the strong sensitivity of terahertz wave propagation to water content, the team used the imaging system to monitor and characterize the drying behavior of coated electrodes. Collaborators at UCI prepared wet electrode samples and tested them under controlled laboratory conditions to capture changes in terahertz response during moisture removal. The team examined more than 20 samples under varying drying protocols. For one set of experiments, the team placed samples in a 158°F (70°C) oven between measurement intervals to accelerate drying. The team conducted terahertz scans every 15 minutes, enabling high-resolution tracking of moisture reduction over time. In a complementary set of tests, the team monitored additional samples under ambient conditions for approximately one day to evaluate natural drying dynamics.

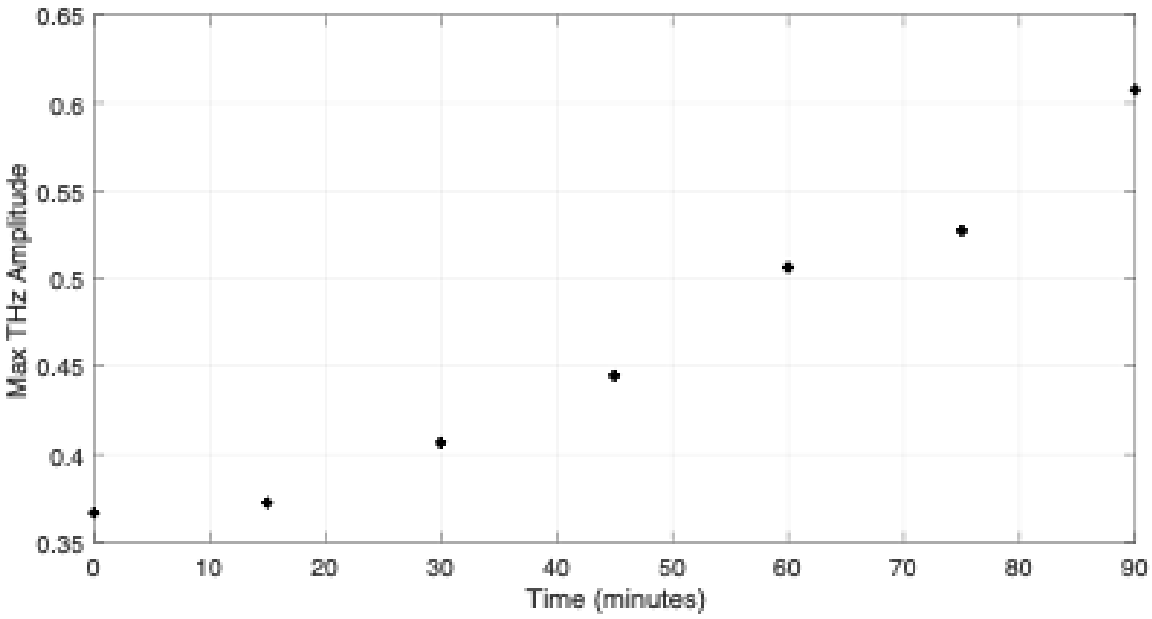
Figure 16 illustrates the progression of the terahertz waveform and corresponding amplitude images as the coatings transitioned from wet to dry states. As anticipated, the amplitude of the terahertz signal increased steadily with decreasing water content, reflecting the reduced absorption and scattering associated with drying. Figure 17 quantitatively summarizes this trend, plotting amplitude as a function of drying time and providing clear evidence of the system's capability to noninvasively monitor moisture removal in real time.

Figure 16: Terahertz Time-Domain and Amplitude Images of Wet Electrodes as They Dry



Source: Lookin, Inc.

Figure 17: Maximum Terahertz Signal Level as a Function of Drying Time of LIB Electrode Coating



Source: Lookin, Inc.

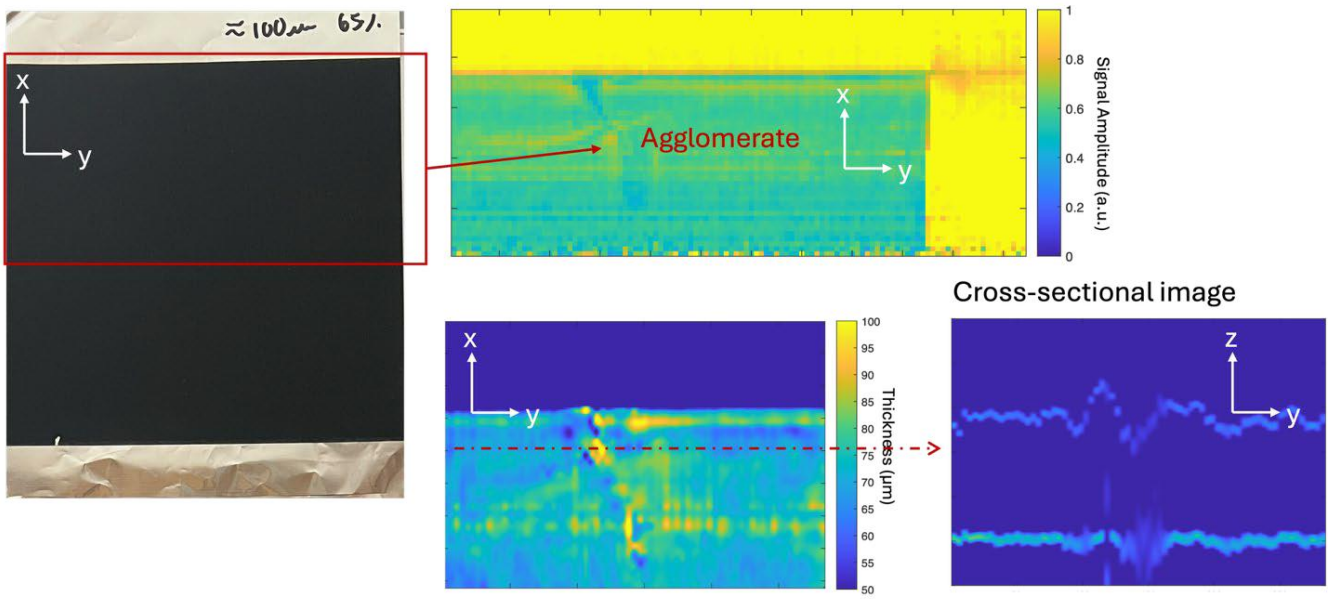
Field Testing

Lookin conducted extensive field testing of the terahertz scanner in collaboration with Navitas Systems to validate system performance under realistic manufacturing conditions. These tests covered defect detection, thickness measurement, porosity estimation, drying evolution, and both benchtop and in-line operation on production-relevant electrodes. The results demonstrate that the scanner has reached industrial readiness and can reliably operate in R2R environments.

The field-testing campaign began with benchtop evaluations using Navitas-supplied cathode and anode electrodes. These measurements confirmed the system's ability to identify common electrode defects, including agglomerates, divots, and pinholes. Terahertz amplitude images clearly revealed defects that could not be seen through standard CCD optical imaging, while cross-sectional time-domain data differentiated between surface-level anomalies and subsurface structural variations as seen in Figure 18. This capability is particularly important for preventing defective material from moving downstream into calendering or battery cell assembly, where scrap costs and safety risks escalate.

The field testing also verified the system's thickness measurement capabilities. Full-field thickness maps were obtained with approximately 1 micrometer accuracy for cathode electrodes and around 3 micrometers for anode electrodes. The scanner successfully measured both central coating regions and coating edges, resolving tapering, thickness gradients, and abrupt thickness changes. These measurements support tuning of slurry coating, drying, and calendering parameters in production environments.

Figure 18: Effect of Agglomerate on Coating Thickness



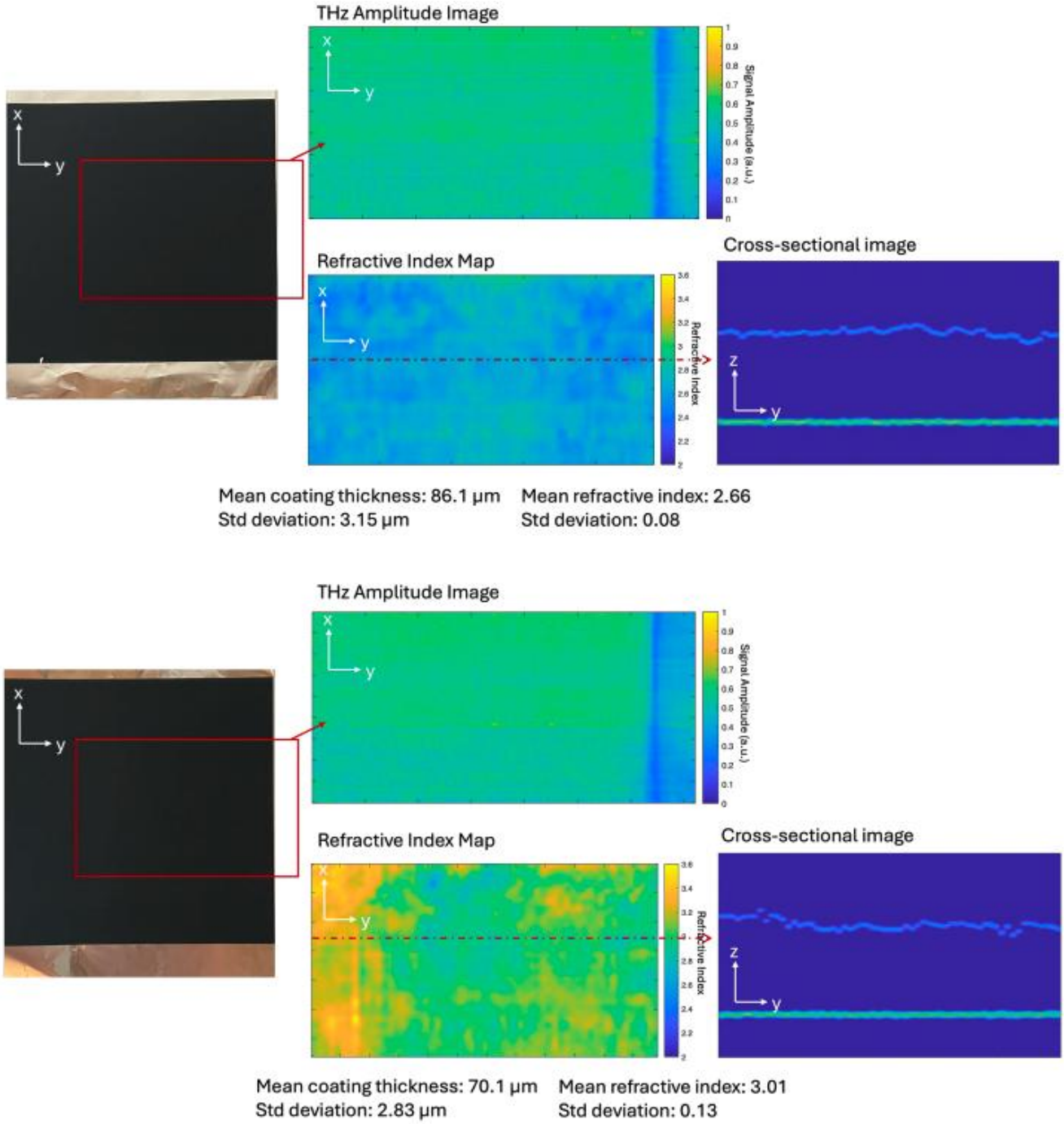
An example of an agglomerate that cannot be seen with a CCD camera but can be revealed with THz imaging. The thickness map and cross-sectional image also reveal the effect of agglomerates on the coating thickness.

Source: Lookin, Inc.

Porosity Estimation

The team evaluated porosity estimation through by mapping refractive index mapping derived from phase-resolved terahertz signals. The tests showed clear differentiation between calendered and uncalendered electrodes. After calendering, electrodes exhibited higher refractive-index values, indicating increased density and lower porosity, while uncalendered and less compacted coatings showed lower refractive-index values (Figure 19). Monitoring porosity is essential for assessing electrode quality, predicting electrochemical performance, and optimizing process parameters such as calendering pressure.

Figure 19: Samples Before and After Calendering, Analyzed and Characterized with the Terahertz Scanner



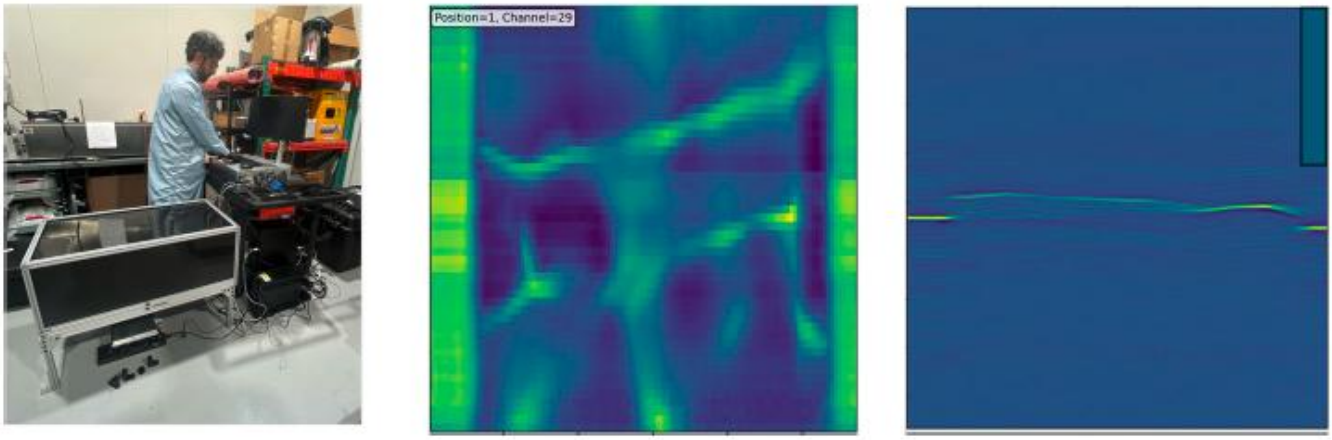
Source: Lookin, Inc.

Dry Electrode Defect Detection

Next, in the benchtop configuration, terahertz imaging was used to characterize dry-coated cathode and anode samples. Dry coating introduces unique challenges, such as binder inhomogeneity (uneven distribution of the binder material throughout the coating), density

variations, and microcracks that are difficult to detect with existing techniques. The terahertz scanner successfully visualized microcracks and binder nonuniformities down to tens of micrometers, which were invisible to optical inspection (Figure 20). Cross-sectional terahertz images revealed delamination and density gradients through the coating thickness. Thickness measurements on dry-coated samples were repeatable within ±3 micrometers, confirming quantitative stability. Lookin's scanner is integrated into a coater web line for in-line characterization of the battery electrode during manufacturing. Figure 21 shows top-view terahertz images while Lookin's scanner captures defective areas on the rolling electrode.

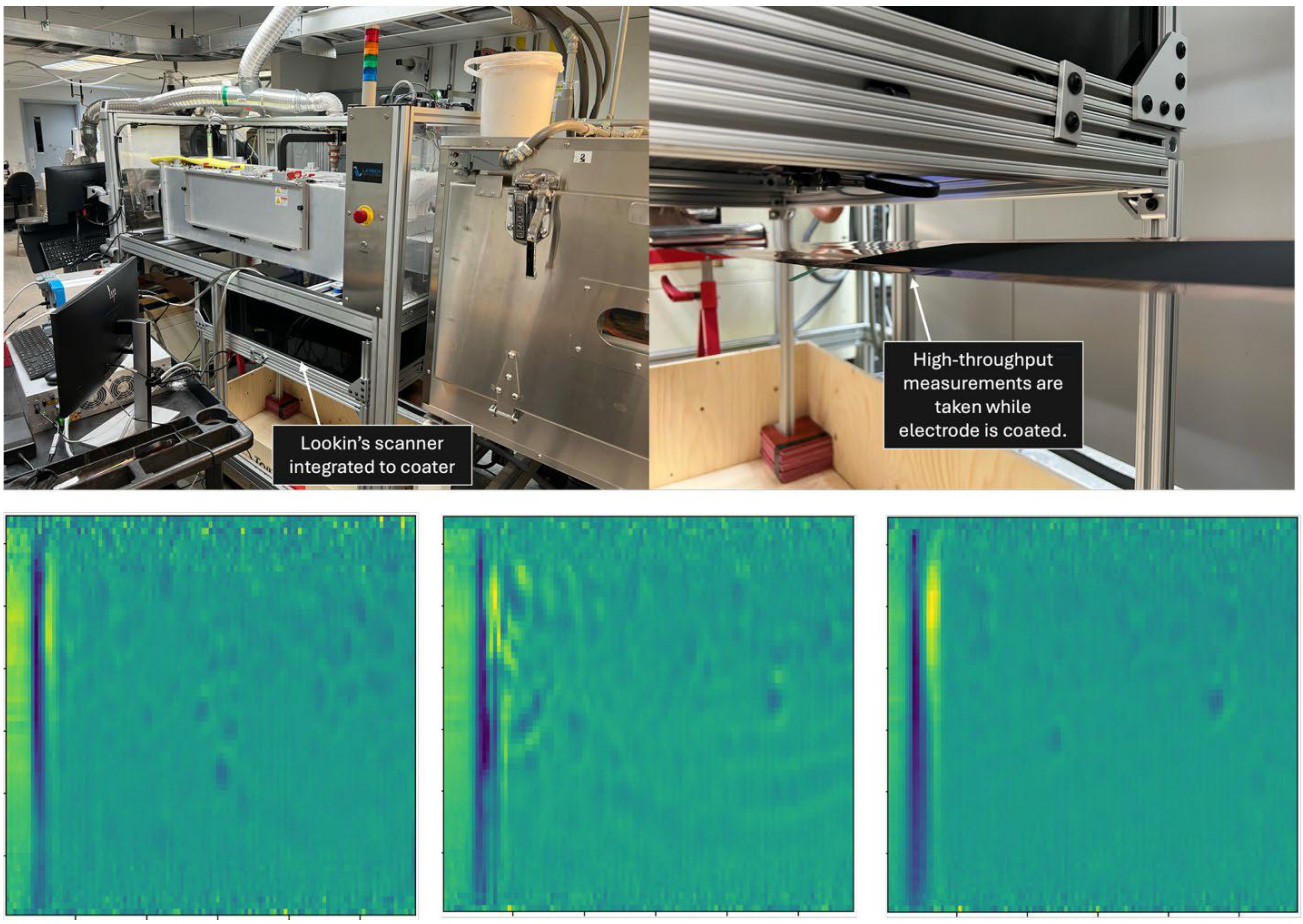
Figure 20: Optical Inspection



Lookin's terahertz scanner prototype works as a tabletop system to characterize electrodes manufactured through dry electrode processing in the battery lab. Top-view terahertz image reveals microcracks in electrodes. Cross section terahertz image reveals delamination on electrodes.

Source: Lookin, Inc.

Figure 21: Coater Web Line for In-line Characterization



Lookin's scanner integrated into a coater web line for in-line characterization of battery electrode during manufacturing. Images show top-view terahertz images while Lookin's scanner captures defective areas on the rolling electrode.

Source: Lookin, Inc.

R2R Operation

The in-line demonstration represented the most significant field validation milestone. The team mounted the scanner onto a pilot-scale R2R coater using a custom alignment frame and synchronized with the web motion controller. At a line speed of 40 meters per minute and a 5-centimeter field width, the system continuously captured amplitude and phase images, producing real-time maps of coating thickness, uniformity, and defect patterns. This exceeded the project's original target of 36 meters per minute. The scanner identified tapering at electrode edges, coating voids caused by slurry flow irregularities, and other localized nonuniformities. The team performed these measurements under vibration, environmental fluctuations, and normal production variations, demonstrating the system's robustness.

Software Development

The team also developed comprehensive software tools to support data acquisition, instrument coordination, signal processing, and visualization for the terahertz imaging platform. The

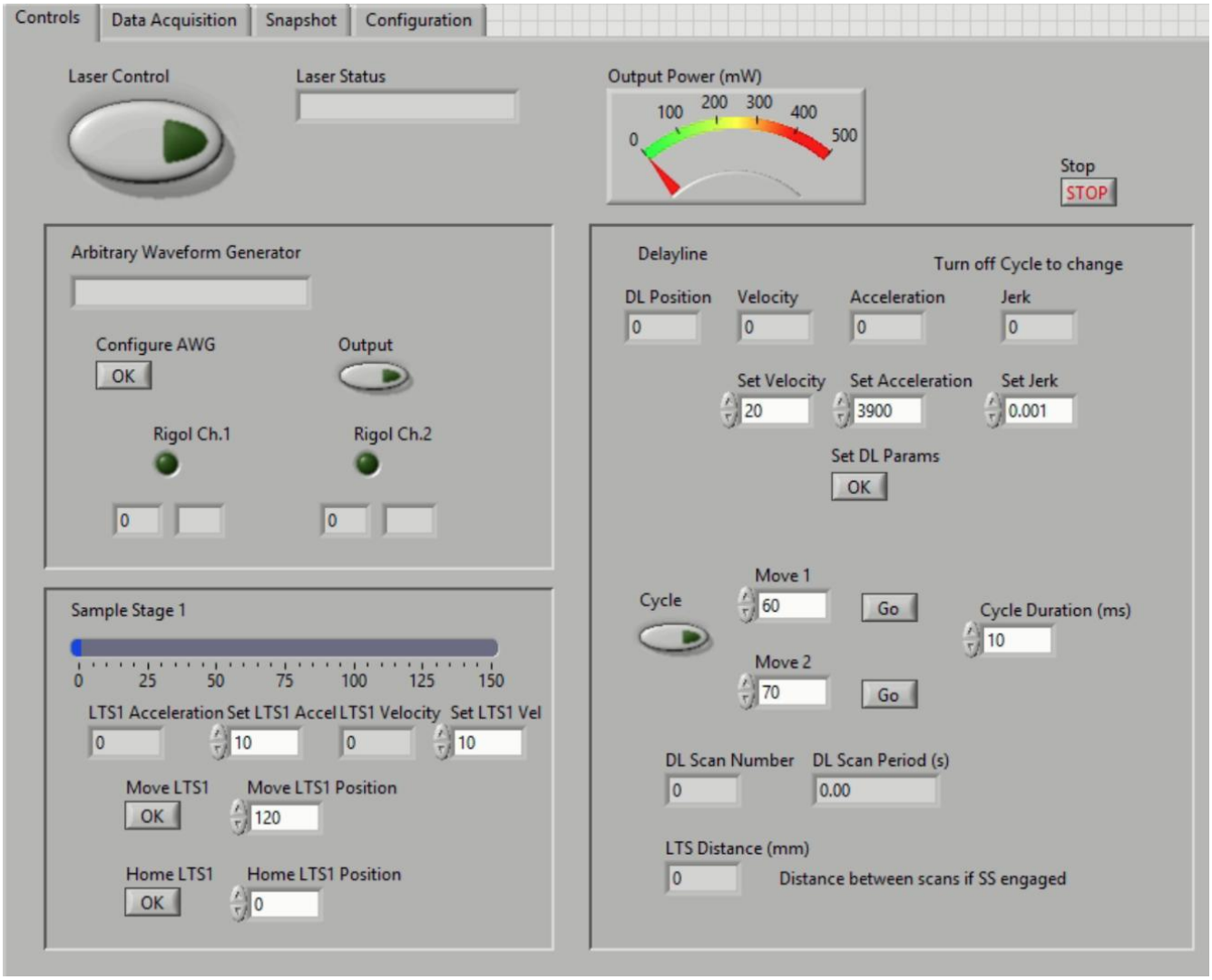
software effort consisted of two complementary components: a LabVIEW-based control and acquisition application and a Python-based post-processing and visualization suite. Together, these tools enabled fully automated operation of the prototype scanner and streamlined analysis of the large volume of data produced during laboratory and field measurements.

The team created the LabVIEW application software shown in Figure 22 to unify control of the laser source, delay line, waveform generator, and motorized sample stages within a single interface. This replaced a workflow that previously required several independent software packages and extensive manual setup. The application automated the timing and synchronization of the system, controlled scan parameters such as stage velocity and scan range, and monitored key laser and hardware status indicators. By consolidating all hardware commands, the application reduced operator workload, minimized setup errors, and improved the repeatability of data acquisition. The interface was designed for ease of use, allowing operators to define scan routines, perform calibration actions, and begin data collection with minimal training.

The LabVIEW system collected raw waveform data, and the Python-based analysis and visualization tool shown in Figure 23 processed and visualized the results. This tool implemented a modular data cleaning pipeline that performed essential preprocessing, including signal conditioning, background normalization, and waveform alignment across the array of detector channels. Parallelized processing steps were used internally to accommodate the high data rates produced by the scanner. Following preprocessing, the software extracted key features from the waveforms, enabling computation of amplitude maps, thickness profiles, phase-based contrast, and other parameters relevant to electrode quality assessment.

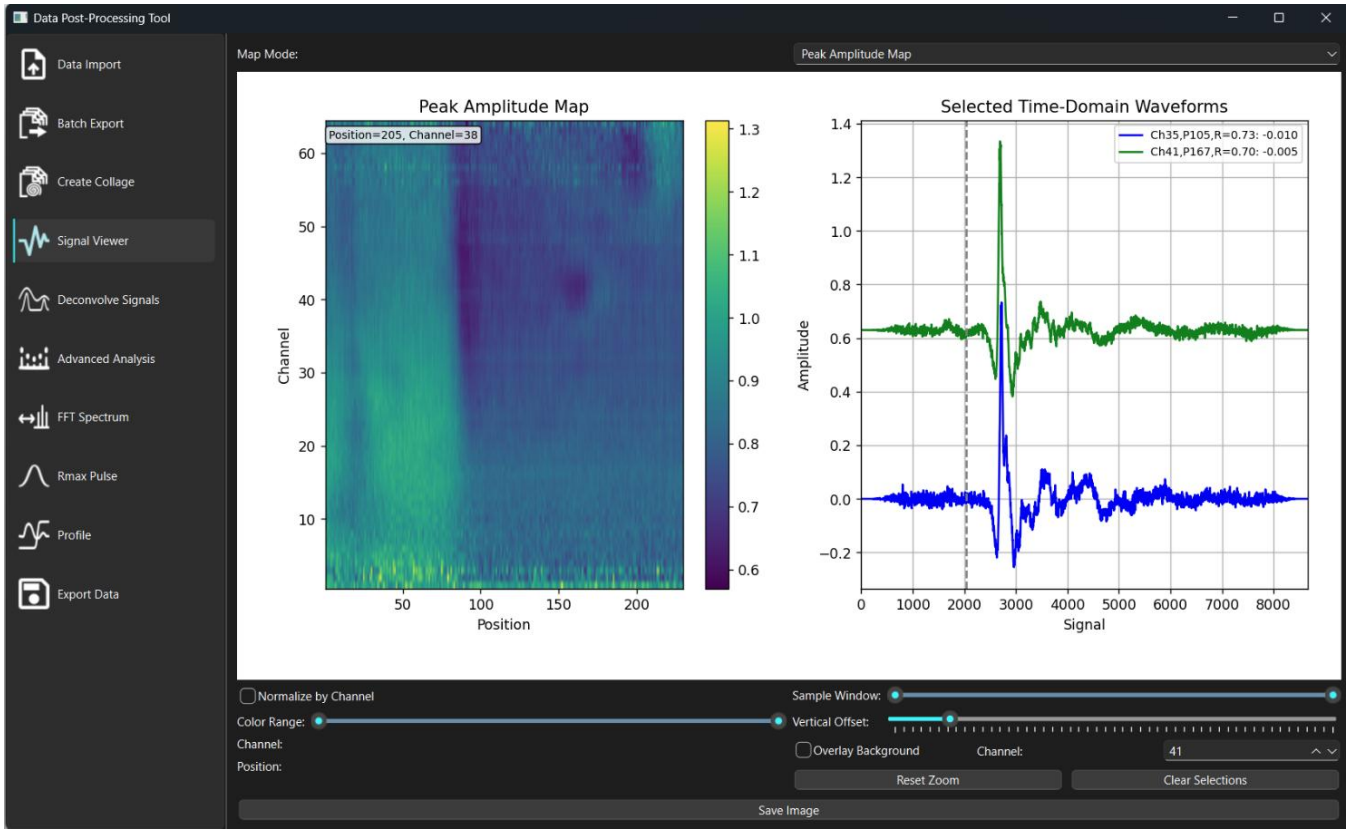
To support efficient analysis, the team integrated the processing routines into a graphical user interface designed for general users who do not have programming experience. The interface provided tools for browsing and inspecting two-dimensional maps, viewing time-domain waveforms, exporting images, and performing batch operations on multiple datasets. Features such as channel selection, color scale adjustment, configurable analysis modes, and automated export functionalities were added to enhance user friendliness. Together, the LabVIEW and Python applications provided a complete software environment for data acquisition, processing, and interpretation, enabling reliable use of the terahertz scanner during both laboratory testing and field demonstrations.

Figure 22: LabVIEW Application



Source: LabVIEW

Figure 23: Screenshot from LabVIEW and Python



Source: Lookin, Inc.

CHAPTER 4:
Key Takeaways

Prototype Development and Laboratory Validation

This project successfully transformed an early laboratory prototype into a compact, reliable terahertz imaging system capable of inspecting battery electrodes without causing any physical damage. Through comprehensive improvements to the optical, electronic, and mechanical subsystems, the scanner was engineered for stability, ease of alignment, and robust performance under real-world manufacturing conditions. These enhancements enabled the collection of high-quality data even in environments subject to vibration and operational variability.

The system demonstrated exceptional precision in measuring coating thickness and exhibited the ability to detect minute defects that conventional optical cameras cannot identify. Beyond thickness measurement, the scanner proved sensitive to variations in moisture content, material density, and internal structural features — parameters that are critical for ensuring battery performance, longevity, and safety.

Extensive testing across a diverse set of electrode samples confirmed the system's consistency and reliability, establishing its readiness for integration into motion-based inspection and factory-scale trials. These results represent a significant step toward deploying terahertz imaging as a high-throughput, noncontact quality-control solution for next-generation battery manufacturing.

Electrode Evaluation Results

Over the course of this project, the team evaluated more than 100 electrode samples, including university-fabricated specimens with intentionally introduced defects and commercially produced electrodes representative of industry standards. This diverse sample set ensured rigorous validation of the scanner's performance under realistic conditions.

The terahertz imaging system consistently identified a wide range of imperfections — such as pinholes, scratches, agglomerated material, and other subtle anomalies — that are nearly invisible to the naked eye and difficult to detect using conventional inspection tools. In addition to defect detection, the system generated highly accurate thickness maps and successfully resolved sharp transitions near coating edges, providing manufacturers with actionable insights to optimize coating uniformity and process control.

Beyond geometric characterization, terahertz measurements revealed variations in electrical conductivity and water content within the coatings. These indicators serve as early warnings of potential drying issues or material inconsistencies, both of which can impact battery performance and reliability. Furthermore, the scanner delivered both surface-level images and cross-sectional, slice-like views, offering a unique perspective on internal coating structure — capabilities that traditional optical or x-ray tools cannot easily achieve.

Field Testing

The terahertz imaging system demonstrated reliable performance under real factory conditions at Navitas Systems, operating effectively despite environmental challenges such as vibration, temperature fluctuations, and extended run times. During these trials, the scanner successfully detected genuine manufacturing defects and thickness variations in electrodes produced on full-scale production equipment, confirming its robustness and practical utility.

For dry-coated electrodes, the system revealed fine cracks and subtle density variations — features that are extremely difficult to identify using conventional optical inspection methods. In R2R testing, the scanner achieved a processing speed of 36 meters per minute while generating real-time maps of coating thickness and defect distribution. This performance exceeded the project's targeted throughput, underscoring the technology's readiness for high-volume manufacturing.

These results confirm that the terahertz imaging system is prepared for industrial deployment, offering manufacturers a powerful tool to prevent defective material from advancing to later, more costly stages of battery production. By enabling early detection of critical anomalies, the technology supports improved quality control, reduced waste, and enhanced process efficiency.

Software Development

To streamline operation and enhance usability, the team developed a single, unified control program using LabVIEW, which replaced multiple independent tools and significantly simplified system management. This centralized platform enables full control of the scanner's hardware components, ensuring seamless coordination during data acquisition.

Complementing the control software, a Python-based processing suite cleaned data, analyzed waveforms, and converted raw measurements into actionable outputs such as thickness maps and defect indicators. Advanced parallel processing techniques enabled the suite to manage the large data volumes generated during high-speed scanning while maintaining real-time performance without compromising accuracy.

The team also designed a user-friendly interface to make the system accessible to nonexperts, allowing operators to visualize images, inspect waveforms, and save results without requiring programming knowledge. Together, these software tools transformed the scanner into a practical, efficient solution for both laboratory testing and field demonstrations, supporting everyday use in research and industrial environments.

Summary of Key Findings

The project successfully demonstrated the feasibility and value of a terahertz imaging platform for nondestructive quality control of lithium-ion battery electrodes.

- The team designed and assembled a compact terahertz scanner based on a multipixel focal plane array, developed integrated control and analysis software, and validated system performance through extensive laboratory testing and field measurements.

- The system captured high-quality time-domain terahertz signals across 64 channels and produced two-dimensional images, thickness profiles, conductivity maps, and drying curves of anode and cathode electrode coatings.
- Laboratory work conducted at Lookin and at the UCI showed that the scanner can detect common defects such as pinholes, agglomerates, divots, and thickness variations with micrometer-level sensitivity.
- Field tests conducted with Navitas Systems confirmed stable operation outside the laboratory, validated sample-handling procedures, and generated practical insights for system refinement.

These results collectively show that terahertz imaging can provide information not readily available from camera-based or low-throughput analytical tools, and that the prototype developed under this project has the core capabilities needed for further scaling and industrial integration.

Lessons Learned

Throughout the project, the team gained important technical and operational insights that will guide future development.

1. Stable in-line scanning requires careful coordination of mechanical motion, optical alignment, and data acquisition, and even small variations in environmental conditions can influence signal quality. Close collaboration with manufacturing partners helped clarify practical constraints such as sample handling, scan speeds, and integration with existing workflows.
2. High-volume terahertz data require robust software infrastructure for data management and visualization. The development of unified control and analysis tools significantly improved usability and demonstrated the importance of making the system accessible to nonexpert operators.
3. Early field testing revealed configuration details and operational steps that need refinement before integration into a production environment. Addressing these practical considerations is as important as advancing the core terahertz technology.

The project also encountered several challenges that shaped the technical and commercial direction of the work.

1. Operating sensitive terahertz hardware in manufacturing environments required significant attention to mechanical stability and thermal control.
2. Vibrations from coating and drying equipment introduced noise that had to be mitigated through mechanical damping and software compensation.
3. Variability in electrode samples from different sources revealed the need for adaptive algorithms that can handle a wide range of material properties, defect types, and coating conditions.

4. Integrating the scanner with fast-moving R2R lines also required modifications to the data acquisition architecture and synchronization methods.
5. On the market side, manufacturers expressed concern about adding new inspection tools to production lines without evidence of long-term robustness, which emphasized the importance of extended field demonstrations and clearly defined value metrics.

These challenges informed the system upgrades and development priorities described in the commercialization roadmap.

Pathways for Commercialization and Future Work

The terahertz inspection technology developed under this project is now positioned to transition from prototype to early commercial deployment. Laboratory validation and factory demonstrations have confirmed the terahertz scanner's ability to deliver real-time, high-resolution measurements critical for R2R electrode production. The next phase will focus on integrating the scanner into partner manufacturing lines, refining mechanical and software interfaces for continuous operation, and advancing analytics for automated process control. Commercialization efforts will center on scaling, ruggedization, and customer adoption. The expected post-grant development roadmap is as follows.

Phase 1 (0–6 months):

- Incorporate field feedback from Navitas Systems into hardware and software.
- Upgrade terahertz camera electronics for higher line speeds and improved signal-to-noise ratio.
- Conduct pilot-line demonstrations with multiple partners under varied production conditions.

Phase 2 (6–18 months):

- Develop application-specific software modules for coating uniformity scoring, defect classification, drying-rate estimation, and conductivity-based health metrics.
- Integrate with manufacturing execution systems for automated feedback control.
- Complete environmental and reliability testing for customer qualification.
- Prepare for low-volume beta unit production.

Phase 3 (18–40 months):

- Deploy first commercial systems on full-scale R2R lines.
- Expand to complementary inspection tasks such as multilayer stacks and separator characterization.
- Scale manufacturing capacity to meet demand from domestic gigafactories.
- Explore international markets in Europe and Asia.

Several market barriers are anticipated as the technology moves toward commercial adoption.

- One is integration risk, as manufacturers may hesitate to introduce new sensing tools into high-throughput lines without evidence of long-term stability. This challenge will be addressed through extended trials with early partners and offering a modular design that can be installed without disrupting existing workflows.
- Another barrier is cost sensitivity, as battery manufacturers operate on narrow margins and require clear demonstrations of yield improvement before investing in new tools. To mitigate this, quantitative pilot line studies will be conducted to measure scrap reduction and process optimization enabled by the scanner.
- Data interpretation provides another market barrier, as operators need actionable insights rather than raw measurements. This will be resolved by developing intuitive dashboards, automated quality metrics, and optional cloud-based analytics services.
- Competing with established inspection technologies, such as x-ray systems and optical cameras that are already widely deployed in battery manufacturing facilities is yet another key commercialization challenge. The terahertz system addresses this challenge by offering capabilities that conventional tools cannot provide in a single platform, including subsurface imaging, water-content tracking, and micrometer-scale thickness measurement at industrial line speeds. Continued demonstration of these advantages and effective communication of their economic and operational benefits will be essential for market adoption.

CHAPTER 5:
Knowledge Transfer

The BRIDGE project enabled a coordinated set of technology development, knowledge dissemination, and market engagement activities designed to transition terahertz-based quality control from a laboratory research tool to an industrially viable solution. These efforts established critical connections among Lookin and battery manufacturers, academic collaborators, national laboratory stakeholders, and market analysts. Collectively, this provided the foundation for understanding customer requirements, validating system specifications, and shaping early commercialization pathways. Public presentations, outreach initiatives, and follow-on funding activities are detailed in subsequent sections of this report.

Direct Engagement with Battery Manufacturers

A central component of technology transfer involved close collaboration with LIB manufacturers. Lookin partnered with industry leaders through sample exchanges, performance demonstrations, and technical discussions. These interactions provided essential insights into defect modes, coating uniformity requirements, calendering effects, and environmental conditions encountered on R2R production lines. This feedback directly influenced key system specifications, including working distance, enclosure design, field of view, and data-rate targets.

Navitas Systems served as the primary industrial host for field demonstrations, where their engineering team provided critical input that guided several design revisions. In total, the project engaged more than 120 stakeholders through laboratory collaborations, factory trials, technical exchanges, and market discovery interviews. More than 150 electrode samples were evaluated across Lookin and UCI facilities, and more than 20,000 terahertz line scans were collected during R2R demonstrations at Navitas Systems.

Technical Advisory Committee and Stakeholder Feedback

Thirteen participants attended the Technical Advisory Committee meetings, representing battery manufacturers, academic researchers, and California Energy Commission staff. Committee members emphasized the importance of subsurface defect detection, the need for increased scan speed, and the potential value of integrating machine learning while ensuring robustness under real industrial variability. This early feedback helped refine system requirements for throughput, environmental stability, and industrial enclosure design.

Academic Collaborations and Knowledge Transfer

Knowledge transfer was further strengthened through collaborations with UCLA and UCI. UCLA contributed fabrication expertise for plasmonic terahertz emitters and detectors, along with guidance on device packaging and signal optimization. UCI provided independent validation of scanner performance during dynamic-motion tests that simulated R2R electrode production.

These partnerships ensured scientific rigor, reproducibility, and alignment across institutions throughout the project.

Market Discovery and Commercialization Pathway

Market transfer activities expanded significantly through Lookin's participation in the National Science Foundation (NSF) I-Corps National Teams program. During this effort, the team conducted approximately 100 structured interviews across the battery-manufacturing ecosystem, including electrode material suppliers, gigafactory operators, equipment manufacturers, quality assurance engineers, automation specialists, and research groups. These interviews revealed critical pain points such as coating defects, scrap rates, drying variability, calendering-induced damage, porosity nonuniformity, and the lack of effective subsurface in-line inspection tools. A consistent theme emerged: Existing quality-control solutions do not provide real-time, noncontact, subsurface detection capability at industrial web speeds.

The I-Corps program also enabled the development of a comprehensive, evidence-based business model for terahertz quality control. Key components included identification of primary customer segments, characterization of early adopters, definition of buying processes, assessment of integration barriers, and quantification of economic value based on scrap reduction and throughput improvements. Interviews with automation and process-control specialists clarified system requirements for factory integration, including mechanical footprint, data formats, communication protocols, and alarm or feedback mechanisms. These insights directly informed system design and commercialization strategy.

Additional Market Engagement and Intellectual Property Development

Further commercialization support was provided through structured programs such as U.S. DOE Technical and Business Assistance, Larta Institute, and consultations with national laboratories and federal agencies. These efforts delivered competitive landscape analysis, market sizing, economic impact modeling, and identification of long-term opportunities in adjacent sectors such as fuel cells, separation membranes, composite materials, and semiconductor structures. The BRIDGE-enabled prototype and early validation data served as a key asset in these discussions, helping stakeholders recognize the transformative role of terahertz imaging in modern manufacturing.

The project also advanced intellectual property development in collaboration with the UCLA Technology Development Group. Progress achieved under BRIDGE strengthened Lookin's position in negotiating rights for plasmonic terahertz devices and opened new opportunities for intellectual property extensions covering device packaging, signal-processing algorithms, calibration strategies, and industrial integration methods.

Public Presentations

Public dissemination of project-related findings occurred through a series of invited talks, conference presentations, and peer-reviewed publications. These presentations helped

communicate advances in terahertz focal plane array technology, high-throughput imaging, and battery electrode quality control to the scientific, engineering, and manufacturing communities. Many of these presentations showcased results that were directly enabled by the BRIDGE project, including system design, imaging performance, and application-specific demonstrations.

The project team delivered multiple invited talks at the Society for Optics and Photonics (SPIE) conferences, which are among the leading international venues for terahertz science and imaging instrumentation. These invited presentations highlighted both the fundamental device advancements and the system-level integration work associated with this project. Presentations included:

- Yardimci, N.T., A. Charkhesht, M. Jarrahi. "*Advancing Terahertz Pulsed Imaging: A MultiPixel Approach Using Plasmonic Nanoantennas*." SPIE Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications XVIII. 2025.
- Yardimci, N.T., A. Charkhesht, G. Pawin, S. Recinos, M. Jarrahi. "*Plasmonic Nanoantenna-Based Terahertz Focal Plane Arrays for High-Speed Multipixel Imaging*." Proc. SPIE Terahertz Emitters, Receivers, and Applications XVI. September 2025. Paper PC1360909. Invited talk.
- Yardimci, N.T., Charkhesht, M. Jarrahi. "*High-Throughput Terahertz Scanning for Quality Assessment of Battery Electrode Manufacturing*." SPIE Health Monitoring of Structural and Biological Systems XVIII. May 2024, Vol. 12951. Paper 129510P.
- Yardimci, N.T., Charkhesht, D. Turan, M. Jarrahi. "*Rapid Scanning Through Wide Field-of-View Terahertz Focal Plane Arrays*." SPIE Terahertz Emitters, Receivers, and Applications XV. 2024. Paper PC1314105.
- Yardimci, N.T., D. Turan, A. Charkhesht, M. Jarrahi. "*High-Speed and Large Field-of-View Imaging through Terahertz Focal Plane Arrays*." SPIE Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications XVII. March 2024. Paper PC1288509.
- Yardimci, N.T., D. Turan, A. Charkhesht, M. Jarrahi. "*Terahertz Focal Plane Arrays for High-Speed and Large Field-of-View Terahertz Imaging*." SPIE Terahertz Emitters, Receivers, and Applications XIV. October 2023. Paper PC126830D.

The team also disseminated results from precursor-device research during the project period. These included:

- Yardimci, N.T., D. Turan, A. Charkhesht, M. Jarrahi. "*One-Dimensional Terahertz Focal Plane Arrays Based on Plasmonic Nanocavities for Terahertz Line Scanning*." SPIE Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications XVI. March 2023. Paper PC124200B.
- Yardimci, N.T., Yardimci, D. Turan, A. Charkhesht, M. Jarrahi. "*One-Dimensional Terahertz Focal Plane Arrays Based on Plasmonic Nanocavities for Terahertz Line Scanning*." SPIE Photonics West. San Francisco, Calif. January 28 to February 2, 2023.

In addition to conference presentations, the team published results in a peer-reviewed journal. The following paper, published during the project period, includes scientific advances relevant to the device architecture that underlies the scanner used in this project:

- Li, X., D. Mengu, N.T. Yardimci, D. Turan, A. Charkhesht, A. Ozcan, M. Jarrahi. "Plasmonic Photoconductive Terahertz Focal-Plane Array with Pixel Super-Resolution." *Nature Photonics* 18, 139 to 148, 2024.

While not all content in these works was produced directly under this project, the progress supported by the BRIDGE award substantially contributed to system-level demonstrations, field-readiness improvements, and broader dissemination of terahertz imaging capabilities to the international research community. These public presentations helped raise awareness of advances in high-speed terahertz imaging and established visibility for the technology within both academic and industrial audiences.

Outreach

Outreach activities during the BRIDGE project focused on raising awareness of terahertz-based quality control among battery manufacturers, research institutions, government agencies, and the broader clean-energy community. These efforts ensured that project outcomes reached stakeholders who influence manufacturing standards, quality assurance practices, and adoption of advanced inspection technologies.

Lookin engaged with more than 100 engineers, production managers, automation specialists, and materials scientists through structured discussions and demonstration sessions. Feedback consistently highlighted the lack of effective subsurface in-line inspection tools, the high cost of scrap from coating defects, and the need for actionable metrics rather than raw data. Interest in drying-process monitoring and conductivity tracking reinforced the relevance of terahertz imaging for industrial environments.

Outreach extended beyond primary partners to include companies, academic groups, and technical experts in battery materials, coating processes, and manufacturing systems. These interactions broadened the collaboration network and provided valuable external feedback on system capabilities and limitations. Academic engagement with UCLA and UCI facilitated technical exchanges, validation studies, and exposure of students and researchers to terahertz imaging as an emerging metrology tool.

Additional outreach included briefings to national laboratories and federal research centers — such as National Renewable Energy Laboratory, National Aeronautics and Space Administration Langley Research Center, and the Office of Naval Research — highlighting the broader applicability of terahertz imaging for clean-energy technologies. Lookin also participated in California-based innovation events hosted by the California Energy Commission and university-affiliated programs, ensuring visibility within the state's advanced manufacturing ecosystem.

The NSF I-Corps program significantly expanded outreach through approximately 100 structured interviews across the battery-manufacturing value chain. While focused on customer discovery, these interactions introduced terahertz quality control to a wide audience and refined communication strategies for future deployment.

Finally, the team supported the outreach through digital resources, educational materials, and website updates that explained system operation and performance in accessible terms. These efforts created entry points for potential collaborators and customers.

Overall, outreach under the BRIDGE project played a critical role in disseminating knowledge, engaging stakeholders, and preparing the market for the adoption of terahertz quality-control systems. These activities established the foundation for public presentations and follow-on commercialization efforts described in subsequent sections.

Follow-on Activities

The progress achieved under this BRIDGE project created a strong foundation for multiple follow-on activities that extend the technical, commercial, and strategic impact of the work. These activities involve continued development of terahertz imaging hardware and software, expanded field testing with industrial partners, submission and award of federal research grants, and preparation for commercial pilot deployments. Together, they demonstrate the effectiveness of EPC-21-035 in enabling long-term technology transition beyond the original project scope.

A major follow-on outcome of the project was the selection of Navitas Systems as the host site for the first in-line pilot deployment of the terahertz quality-control system. The technical readiness achieved during the BRIDGE effort enabled Lookin to progress from laboratory prototypes to field-installed configurations. The system packaging, enclosure design, alignment procedures, and data-handling framework developed under EPC-21-035 are now being used to prepare for extended pilot operation at Navitas. This deployment will focus on measuring coating uniformity, detecting embedded defects, monitoring moisture content after drying, and observing thickness variations introduced during calendering. The successful field demonstration supported by BRIDGE was a key prerequisite for this next step.

The project also enabled successful acquisition of multiple federal research awards that build directly on the terahertz imaging capabilities supported by the CEC. Following the BRIDGE project, Lookin secured several SBIR Phase II awards from the U.S. DOE, the Office of Naval Research, and the National Aeronautics and Space Administration. These awards collectively exceed $6 million in follow-on funding and support continued development of high-throughput terahertz imaging for battery electrodes, composite materials, catalyst-coated membranes, and other advanced manufacturing applications. Federal reviewers repeatedly cited the technical maturity, prototype readiness, and field validation achieved under EPC-21-035 as strong evidence that the technology was capable of transitioning from early research to real-world industrial use.

In addition to federal funding, the project enabled deeper collaboration with major battery manufacturers. General Motors, Gotion, Mercedes-Benz, Coulomb Technologies, and other manufacturers have requested updated demonstrations and data reviews based on progress achieved during the project. These engagements support the development of a multisite pilot pipeline that extends beyond the initial Navitas Systems deployment.

Participation in the NSF I-Corps National Teams program created additional follow-on activities that reinforce the commercialization trajectory of the technology. Insights gained from approximately 100 stakeholder interviews helped finalize the initial version of Lookin's business model, validate customer segments, and define early adopters in the battery-manufacturing ecosystem. These findings now guide ongoing product development, pricing strategy, and pilot planning. Several interview contacts initiated new technical discussions, follow-up sample evaluations, and requests for additional performance information, further expanding the network of potential deployment partners.

Lookin also continued to advance intellectual property positions based on technical findings from the BRIDGE project. New concepts in device packaging, optical alignment, waveform processing, and calibration routines were identified as candidates for future patent applications. These innovations extend the original UCLA intellectual property portfolio underlying the terahertz focal plane array technology and help solidify the company's ability to commercialize industrial terahertz imaging systems.

Finally, the project's technical and demonstration outcomes have prepared the system for transition into more mature manufacturing environments. The improved mechanical stability, environmental robustness, and multipixel throughput achieved under this project support future integration with R2R equipment manufacturers and factory automation systems. Lookin has initiated discussions with equipment vendors to explore mechanical and software integration pathways and to evaluate opportunities for embedding terahertz imaging into commercial coating, drying, and calendering tools.

Together, these follow-on activities demonstrate that the BRIDGE project created long-lasting impact by enabling technical readiness, expanding industrial interest, securing federal investment, and preparing the technology for commercial pilot deployments. The work supported by EPC-21-035 continues to drive advances in terahertz imaging and expands its role in high-volume, clean-energy manufacturing.

CHAPTER 6: Conclusion

Technical Approach

The primary goal of this project was to transition terahertz imaging from a laboratory-based technique to a practical solution for real-world lithium-ion battery production lines. Traditional terahertz systems were limited by slow acquisition speeds and high sensitivity to vibration, making them unsuitable for industrial environments.

To overcome these challenges, researchers at UCLA developed advanced terahertz devices that significantly enhanced signal strength and enabled simultaneous multipixel measurements. These innovations allow the scanner to accurately assess coating thickness, density, and moisture content and detect hidden defects, all without physical contact with the material.

The system was further engineered with a compact, rugged design and integrated into a mobile mounting platform, ensuring compatibility with R2R manufacturing processes. This advancement represents a critical step toward implementing high-speed, nondestructive quality control in battery production.

Terahertz Scanner Design and Specifications

The imaging system employs a specialized laser in combination with advanced terahertz emitters and detectors to capture fine structural details within battery coatings. A 64-pixel terahertz camera enables simultaneous multipoint measurements, delivering high-speed scanning that aligns with the pace of continuous web-based production lines.

To ensure reliability in industrial environments, the scanner is housed within a robust enclosure designed to withstand vibration, dust, and ambient light. This configuration supports precise, noncontact measurements of coating thickness and moisture content with micrometer-level accuracy, even under high-throughput conditions.

The system's compact, modular architecture provides flexibility for integration across diverse production platforms, making it suitable for deployment on various R2R manufacturing tools.

Experimental Methods and Test Plan

The development team conducted a phased testing approach, beginning with controlled laboratory evaluations and progressing to full-scale trials in manufacturing environments. Initial lab tests demonstrated the scanner's ability to accurately measure coating thickness, moisture content, and porosity and detect small defects.

Subsequent motion tests at Lookin and UCI confirmed that the system could maintain performance while tracking moving electrode webs, simulating real production conditions. Field trials at Navitas Systems further validated the scanner's operation near critical process equipment, including coating, drying, and calendering stations.

These trials confirmed stable, real-time performance under factory conditions, including exposure to vibration and temperature fluctuations, establishing the system's readiness for industrial deployment.

Data-Analysis Framework

The team developed a unified software platform to provide centralized control of all scanner hardware components. During experimental phases, a LabVIEW application managed real-time data acquisition and system operations, ensuring seamless integration with hardware.

For data analysis, the team implemented a dedicated Python-based pipeline to generate detailed thickness maps, moisture profiles, and defect indicators. This processing framework is optimized for speed and supports GPU acceleration, enabling real-time performance essential for factory environments.

To facilitate deployment on production lines, the system includes an intuitive user interface that allows nonexperts to visualize results and export comprehensive reports with minimal training.

Benefits to California Ratepayers

California is rapidly scaling investments in battery manufacturing, energy-storage systems, and electrified transportation. High-quality, consistent battery electrodes are critical for achieving long cycle life, improving safety, reducing waste, and lowering costs in these sectors. The terahertz imaging platform developed under this project provides a nondestructive, real-time method for monitoring electrode properties that directly impact battery performance, including:

- Coating uniformity.
- Thickness.
- Moisture content.
- Material defects.

By enabling early detection of quality issues and reducing reliance on destructive sampling and slow analytical techniques, this technology can:

- Lower manufacturing losses.
- Improve product reliability.
- Accelerate deployment of advanced energy-storage solutions.

These improvements ultimately benefit California ratepayers by supporting the development of safer, more efficient, and cost-effective energy-storage technologies, which enhance grid resilience and advance the state's clean-energy goals. To maximize the impact of this innovation and enable broader adoption, the following actions are recommended:

- **Future Research and Development**
    - Explore integration of terahertz imaging into automated battery-manufacturing lines.
    - Investigate scalability for high-throughput quality control in large-format batteries.
- **Policy and Regulatory Considerations**
    - Develop industry guidelines for nondestructive electrode inspection methods.
    - Consider updates to codes and standards to incorporate advanced quality assurance technologies.
- **Market Adoption Strategies**
    - Support pilot programs with California-based battery manufacturers.
    - Encourage partnerships between technology developers and utilities to validate performance benefits.

List of Terms/Glossary

Term	Definition
BRIDGE	Bringing Rapid Innovation and Development to Green Energy
CCD	charge-coupled device
CEC	California Energy Commission
EPIC	Electric Program Investment Charge
GPU	graphics processing unit
Hz	Hertz
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LIB	lithium-ion batteries
NSF	National Science Foundation
R2R	roll-to-roll
UCI	University of California, Irvine
UCLA	University of California, Los Angeles
U.S. DOE	U.S. Department of Energy

Project Deliverables

Project deliverables, including interim project reports, are available upon request by submitting an email to pubs@energy.ca.gov.

- Terahertz Scanner Prototype Technical Memorandum
- Electrode Evaluation Report
- Battery Cell Performance Report
- Draft and Final Verification Report
- Test Plan and Review
- Technology Transfer Report

California ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

APPENDIX A: Project Performance Metrics

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Appendix A:
Project Performance Metrics

This section summarizes the key performance metrics proposed at the beginning of the CEC EPIC BRIDGE Agreement (EPC-21-035) and compares them with the actual results achieved during the project. All measurements were verified through laboratory tests and field trials performed at Navitas Systems, including both benchtop dry electrode characterization and in-line operation on a production R2R coater. The results demonstrate that the system not only met but, in several cases, exceeded its target specifications.

Scrap Rate Reduction: Industry scrap rates typically range from 5–10 percent. While the THz scanner demonstrated full defect-detection capability, actual scrap rate reduction could not be directly measured by THz alone and depends on corrective actions implemented by the manufacturer. Comparison of THz-flagged defects with production scrap data confirmed the potential for significant waste reduction through improved process control.

Defect–Electrical Correlation: A new metric was introduced to assess predictive accuracy. The project achieved 100 percent correlation between THz-detected defects and electrical performance degradation in cells fabricated from inspected electrodes at Navitas. Post-inspection electrical testing confirmed that every THz-detected anomaly corresponded to measurable electrical failure or performance loss, validating the predictive power of the technology.

Scanning Speed During R2R Operation: Initial capability was limited to stationary scanning (0 m/min). The project achieved a scanning speed of 40 m/min during field tests on Navitas' production coater, exceeding the original design target of 10 m/min and demonstrating stable imaging and data acquisition under real production conditions.

Scanned Electrode Width: The system progressed from single-spot scanning (≤1 mm) to a demonstrated width of 5 cm, with scalability to 1.5 m through cascading scanners. Hardware and software verification during R2R integration confirmed a modular architecture suitable for full-width electrode inspection.

Thickness Measurement Accuracy: The THz system achieved micrometer-level precision, with an accuracy of 1–3 μm compared to mechanical profilometry and manufacturer data. This capability enables precise coating control across the entire electrode surface.

Porosity Estimation Capability: The technology advanced from qualitative assessment to quantitative measurement with ≤3 percent variation, using THz phase-based refractive index mapping correlated with density data. This provides real-time insight into coating density and calendering effectiveness.

Technology Readiness Level (TRL): The system advanced from TRL 4 (bench prototype) to TRL 6, verified through field tests on an operating R2R line. This demonstrates readiness for pilot-scale deployment in industrial settings.