# Scanning mmWave radar for inspection of thin Li-ion battery electrode films

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Abstract—The electrical properties of thin, conductive films are important for the overall performance of many engineered systems but are especially important for Li-ion battery electrodes. Electrical measurements of electrodes are challenging because the thin, conductive films are attached to conductive metal substrates. Estimating film electrical heterogeneity typically has been performed either by destructive or contact methods. In this work, 60 GHz mmWave imaging radar is used to spatially map the radar-reflection properties of films in a non-contact measurement. Theoretical radar returns for battery electrode films are reviewed and a sensitivity analysis to conductivity and thickness changes is performed. A scanning system was constructed to move a radar module and radar-absorbing conduit across a battery film. Radar returns were recorded and mapped, demonstrating how this method could be used to study evolution of film properties during manufacturing processes and for Liion battery film quality control. A paint analog and PVDFbased carbon black film were used to demonstrate significant radar return changes during drving processes. Scanning of a commercial-quality Li-ion battery electrode film is reported. Film irregularities and blemishes impact the quality of scanned reflection data from the electrode film. Scanning mmWave radar could be an inexpensive method to interrogate properties of thin films in manufacturing processes.

Index Terms-radar, imaging, mmWave, battery, thin film

# I. INTRODUCTION

Li-ion batteries are one of the world's most important technologies and are found in electronic devices and electric vehicles [1]. Their importance was recognized by the 2019 Nobel Prize for chemistry and their continued improvement is a major focus of academic and industrial research.

Generally, electrodes used in Li-ion batteries consist of thin metal current collectors with active materials and additives affixed to the current collectors with a polymer binder. A separator keeps the cathode and anode materials apart and electrolyte is added to allow for Li ions to pass through the separator during charging and discharging.

The electrical properties of the electrodes, primarily electronic and ionic conductivity, are controlled by their microstructure and determine the performance of the battery, particularly when the battery is subjected to fast charging or discharging conditions [2]. Spatially heterogenous conditions within the film, often due to inconsistencies in the manufacturing process, can lead to the formation of "hot spots" and nonuniform aging as the cell is used [3]. Thus, understanding the spatial heterogeneity of the electrical properties of thin

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Manuscript submitted December, 2024.

film electrodes is important to improve manufacturing and, ultimately, performance of Li-ion batteries.

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While there are lab-scale approaches to creating Li-ion batteries, industrial manufacturing of Li-ion batteries generally relies on continuous, roll-to-roll processes that create electrode films by coating electrode materials on long, thin strips of metal. A great deal of effort is placed on accurate metrology during the electrode coating process to measure coat weight and thickness, as well as film quality and absence of defects [4]. Some techniques require cutting a small piece of the roll and measuring its properties in a laboratory while other techniques can be employed in-line during the manufacturing process itself.

The great difficulty with direct electrical measurements of electrode films before incorporation into batteries is that measuring the properties of a thin ( $\sim 100 \ \mu m$ ) conductive material on a metal substrate is technically challenging because electrical current is not confined to the electrode film but easily passes into the attached metal substrate. Electrical measurements of the electrode films themselves can be obtained by separating or dissolving the metal substrate but those processes are destructive [5]. Nanoprobe techniques can also be used to measure electrical properties at the nanoscale but result in limited area coverage of the measurements and require specialized equipment to manipulate the probes [6]. The development of micro-four-line-probe techniques expanded the ability to measure multiple electrical parameters of electrode films in ambient conditions [7]. Hioki has since released their commercial RM2610 electrode resistance measurement system based on planar arrays of miniature probes. However, none of these electrical electrode measurement techniques can be used for in-line inspection.

Microwaves have historically been used in many methods to inspect materials but, traditionally, not Li-ion battery electrodes [8]. Scanning microwave probe microscope techniques are excellent for fine resolution and revealing nanoscale phenomena but are not easily expanded to large electrode films on the scale of meters [9]–[12]. Contactless microwave measurement methods for bulk materials could be advantageous if they could be adapted to measure films as they are being manufactured [13]. However, some microwave non-contact methods, even though they are sensitive, may not be suitable because of other restrictions based on cavity size or a need to have dielectric substrates [14]–[16].

There has been recent work done on characterization of battery films with THz radiation [17] but these studies are often concerned mostly with estimating thicknesses of film layers [18].

In thickness estimation, it is generally assumed that the



Fig. 1. Overview of the principle of interrogation of the battery electrode film using mmWave radar energy. Incident energy is directed towards a thin film. Some of the energy is transmitted and absorbed within the film due to the electromagnetic material properties of the film. Reflected energy from the film then contains information about the properties of the film.

material of interest does not have widely ranging electromagnetic property variations. If optical and/or heat transfer properties of the films are known, in-line coating thickness can be measured by laser scanning techniques or by using active thermal scanning [20]. Thickness measurements are most simply and inexpensively done by using mechanical calipers, but calipers can only be used after the electrode films are dry.

The development of mmWave imaging radar has been driven by the desire for inexpensive, high-quality radar imaging for automotive and industrial applications. Unlike THz sources at this time, it is now possible to find inexpensive frequency modulated continuous wave (FMCW) imaging radars for a number of consumer applications [19]. Thus, while mmWave may not be the perfect frequency for evaluating all the properties of a thin electrode film, the fact that it is readily available means that it could be an attractive method of spatially imaging films in a manufacturing or inspection application.

In this work, the use of imaging radar based on mmWaves is used to interrogate the radar-reflective properties of an electrode film before the film is incorporated into a battery. This is illustrated in Fig. 1. In this illustration, mmWave energy is launched towards a film through a coupling medium with a real part of relative complex permittivity of  $\epsilon'_1$  and real part of relative complex permeability  $\mu'_1$ . This energy then penetrates a film of thickness d with real part of relative complex permittivity  $\epsilon'_2$ , real part of relative complex permeability  $\mu'_2$ , and conductivity  $\sigma$ . Some of this energy is reflected back towards the source - how much reveals information about the thickness and electromagnetic properties of the film.

This article first explores the theoretical possibility of using mmWave radar energy to interrogate relevant properties of drying films that are used to simulate parameters found in commercial Li-ion battery coating and drying processes [21]. Experiments using mmWave imaging radar are performed to test the performance of this mode of interrogation and to explore limitations of the approach. Observations and conclusions about the technique are then made.

### II. BACKGROUND

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# A. Electromagnetic propagation through lossy materials

While the concepts of transmission and reflection are common in the radar community, these concepts are not common in the Li-ion battery community. Three important quantities describe how mmWave electromagnetic energy interacts with a material. They are the attenuation constant,  $\alpha$ , the phase constant,  $\beta$ , and the intrinsic impedance,  $\eta$ , of the material. We will use the definitions found in [22] to describe these quantities for a transverse uniform plane wave in a lossy medium. These properties are dependent on the angular frequency of the electromagnetic radiation,  $\omega$ , as well as on the intrinsic conductivity,  $\sigma$ , the permittivity,  $\epsilon$ , and the permeability,  $\mu$ , of the constituent materials. The notation of  $\epsilon$  is a compact notation for  $\epsilon = \epsilon'_r \epsilon_0$  where  $\epsilon'_r$  is the real part of relative complex permittivity and  $\epsilon_0$  is the permittivity of free space. Likewise,  $\mu$  is a compact notation for  $\mu = \mu'_r \mu_0$  where  $\mu'_r$  is the real part of relative complex permeability and  $\mu_0$  is the magnetic permeability of free space.  $\mu'_r$  is 1 for electrodes which are non-magnetic.

In particular, it is the quantity  $\sigma$  that is of most importance to battery film manufacturers. In a complete battery,  $\sigma$  is a combination of electronic and ionic conductivity. Additives such as carbon black are often used to increase  $\sigma$  in electrodes to increase electronic conductivity during film formation [23]. Increasing  $\sigma$  generally increases overall battery performance, especially under high rate conditions.

We describe the attenuation constant,  $\alpha$ , by

$$\alpha = \omega \sqrt{\mu \epsilon} \left( \frac{1}{2} \left[ \sqrt{1 + \left( \frac{\sigma}{\omega \epsilon} \right)^2} - 1 \right] \right)^{\frac{1}{2}}, \qquad (1)$$

the phase constant,  $\beta$ , by

$$\beta = \omega \sqrt{\mu \epsilon} \left( \frac{1}{2} \left[ \sqrt{1 + \left(\frac{\sigma}{\omega \epsilon}\right)^2} + 1 \right] \right)^{\frac{1}{2}}, \qquad (2)$$

and the intrinsic complex impedance,  $\eta$ , by

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$$\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}}.$$
(3)

Much of the behavior of these quantities can be determined by the fraction  $\frac{\sigma}{\omega\epsilon}$  which determines if an approximation can be used to represent the material as either a good conductor or a good dielectric. For a cathode electrode conductivity of approximately 100 mS/cm [24] at a frequency of 60 GHz and  $\epsilon'_r = 3, \frac{\sigma}{\omega \epsilon} = 1$ . Thus, cathodes have conductivity between that of good conductors and dielectrics. Full calculations of  $\alpha$  and  $\beta$  using Eqs. 1 and 2 are required. These calculations are shown in Figs. 2 and 3 and show that these parameters are sensitive over conductivity ranges typical of Li-ion battery electrodes. Various solvents could also change the permittivity of the material during the drying process. An electrode saturated with water could have  $\epsilon'_r$  on the order of 10 in the tens of GHz [25]. The attenuation constant basically increases as conductivity of the battery electrode increases. The phase constant is frequency-dependent because of the changing wavelength of the radiation and thus is also quite dependent on

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Fig. 2. Attenuation constant,  $\alpha$ , plotted against the conductivity of a battery electrode for various mmWave frequencies. Solid lines correspond to  $\epsilon'_r = 1$  and lines with dots correspond to  $\epsilon'_r = 10$ .



Fig. 3. Phase constant,  $\beta$ , plotted against the conductivity of a battery electrode for various mmWave frequencies. Solid lines correspond to  $\epsilon'_r = 1$  and lines with dots correspond to  $\epsilon'_r = 10$ .

permittivity. Note that increases in permittivity have opposite effects on  $\alpha$  and  $\beta$ . At extremely high conductivities, the effect of permittivity is negligible.

Calculation of the attenuation constant when  $\epsilon'_r = 3$  results in a skin depth  $(1/\alpha)$  of approximately 1 mm, which is about an order of magnitude thicker than most battery electrode films so the wave will penetrate and interrogate through the complete depth of most electrode films. Even if the film becomes 100 times more conductive, the skin depth is still approximately 65  $\mu$ m. This suggests that mmWaves could also be used to interrogate anodes as well as cathodes.

The phase constant for the same battery film parameters used to calculate the attenuation constant above is approximately 2 rad/mm. Film thickness will impact the phase characteristics of the film but will not be so dependent on thickness that small variations in thickness will greatly affect the interference of reflected waves at the surface. As the conductivity of the film increases,  $\beta$  will also increase, resulting in increased sensitivity to thickness variations.

The intrinsic impedance of a battery film is dependent on



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Fig. 4. Magnitude of intrinsic impedance,  $\eta$ , plotted against the conductivity of a battery electrode for various mmWave frequencies. Solid lines correspond to  $\epsilon'_r = 1$ , dashed lines correspond to  $\epsilon'_r = 2$ , and lines with dots correspond to  $\epsilon'_r = 10$ . The intrinsic impedance of air is also plotted.

the interrogation frequency, conductivity, and permittivity of the film calculated through Eq. 3. Varying the conductivity, in particular, can significantly affect this intrinsic impedance. In Fig. 4 the magnitude of the intrinsic impedance is varied as a function of changing conductivity over a range that is typical of commercial-quality films. The roll-off in  $\eta$  indicates that there will be a large difference in the intrinsic conductivity between the film and the intrinsic impedance of air which is approximately 377  $\Omega$ . It is also noted that lower frequencies in the mmWave range have a greater intrinsic impedance sensitivity over the typical range of conductivities associated with cathodes. As the permittivity of the film increases, the intrinsic impedance also departs more strongly from the intrinsic impedance of air.

These calculations indicate that the  $\alpha$ ,  $\beta$ , and  $\eta$  constants are sensitive to changes that would be consistent with changes in Li-ion battery film quality relevant in commercial applications.

#### B. Theory of radar reflectance

Radar has a long history associated with the reflectance properties of thin films. Absorption of RF energy has been important in enhancing the stealth properties of aircraft and other military vehicles [26]. Thus, the theory of multilayer electrical properties of thin films on conductive materials is well-established.

The formulation found in Fig. 1 describes the mmWave reflection response of a film. While angle of incidence can be a factor, in this study it is assumed that incidence and reflection are perpendicular relative to the surface of the film.

Whenever there is an interface, the coefficient of reflection between the regions 1 and 2,  $\Gamma_{12}$ , is described by

$$\Gamma_{12} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \tag{4}$$

where the  $\eta$  values are computed from  $\epsilon$ ,  $\mu$ , and  $\sigma$  using Eq. 3. For battery films, this yields reflection curves that are found in Fig. 5. In this plot, the dB value of the squared absolute value

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Fig. 5. Power magnitude of the reflection coefficient,  $\Gamma_{12}$ , plotted in dB against the conductivity of a battery electrode for various mmWave frequencies. Solid lines correspond to  $\epsilon'_r = 1$ , dashed lines correspond to  $\epsilon'_r = 2$ , and lines with dots correspond to  $\epsilon'_r = 10$ .

of  $\Gamma_{12}$  is used because it represents the proportion of reflected power from the surface of the film in the way that radar return power is typically reported. It is important to note that as conductivity increases, the reflection coefficient increases. The upper limit of 0 dB would be a perfectly conducting film resulting in perfect reflection. When the conductivity is low and  $\eta_1$  and  $\eta_2$  are consequently less mismatched, more power penetrates into the film. If the film were perfectly matched ( $\eta_1 = \eta_2$ ), this would correspond to a value of  $-\infty$  dB.

Electromagnetic energy that penetrates into the film is attenuated by the conductivity of the film material. Then, the wave strikes the current collector and is perfectly reflected back through the film again. Because of the mismatch between  $\eta_1$  and  $\eta_2$ , the wave will be partially reflected from the interface and energy will reflect back and forth within the film until it is completely dissipated.

The reflection coefficient at the interface is  $\Gamma_{21} = -\Gamma_{12}$  and the transmission coefficient is  $T_{21} = 1 - \Gamma_{21} = 1 + \Gamma_{12}$ . The attenuation and phase constants affect signals every time the signal passes through the film by the factor  $e^{j2\theta}$  where  $\theta = (\beta - j\alpha)d$  in which d is the thickness of the film. The current collector is considered to be a perfect electrical conductor with  $\Gamma_{23} = -1$ . The overall reflection coefficient,  $\Gamma_{\text{total}}$ , can be written as an infinite series:

$$\Gamma_{\text{total}} = \Gamma_{12} + T_{21}e^{-j\theta}\Gamma_{23}e^{-j\theta}T_{12} + T_{21}e^{-j\theta}\Gamma_{23}e^{-j\theta}\Gamma_{21}e^{-j\theta}\Gamma_{23}e^{-j\theta}T_{12} + T_{21}e^{-j\theta}\Gamma_{23}e^{-j\theta}\Gamma_{23}e^{-j\theta}T_{12} + \cdots$$
(5)

This equation considers the initial reflection and then multiple passes through the thin film. Each time there is a transmission and reflection, the signal is changed by a factor of  $e^{-j2\theta}$ . This equation can be further reduced to the following:

$$\Gamma_{\text{total}} = \Gamma_{12} + T_{21}\Gamma_{23}T_{12}e^{-j2\theta} \cdot \left[1 + \Gamma_{21}\Gamma_{23}e^{-j2\theta} + \cdots\right]$$
(6)



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Fig. 6. Power magnitude of the total reflection coefficient plotted against the conductivity of a battery electrode for various mmWave frequencies when  $\epsilon'_r = 2$ . The solid lines are a thickness of 100  $\mu$ m and the (+) lines are a thickness of 500  $\mu$ m.

Because the right multiplication is a geometric series, the entire expression can then be written as:

$$\Gamma_{\text{total}} = \Gamma_{12} + \frac{T_{21}\Gamma_{23}T_{12}e^{-j2\theta}}{1 - \Gamma_{21}\Gamma_{23}e^{-j2\theta}}$$
(7)

By algebra and appropriate substitutions, the following simple expression can be used to calculate the total reflection coefficient for the thin film:

$$\Gamma_{\text{total}} = \frac{\Gamma_{12} - e^{-j2\theta}}{1 - \Gamma_{12}e^{-j2\theta}} \tag{8}$$

This equation is a convenient and compact representation for the total reflection response to a plane wave striking the thin film (similar expressions found in [17], [22]). The dependence on the thickness of the film, d, is captured in the  $\theta$  parameter in the exponent. One would also expect that the reflection from the intrinsic impedance mismatch,  $\Gamma_{12}$ , would greatly influence the total reflection, especially when the conductivity is large.

The power magnitude of the total reflection coefficient,  $\Gamma_{total}$ , is plotted in Fig. 6 for two different thicknesses of film, 100  $\mu$ m and 500  $\mu$ m. These thicknesses were chosen to emphasize the interplay of thickness variation and conductivity. When the conductivity is low, then the radiation passes through the interface into the material but is reflected off of the metal backplane and so most energy is reflected back through the film into the air again. When the conductivity is high, and  $\Gamma_{12}$ is large, then the radiation is reflected off the air-film interface. Significant absorption only occurs when the conductivity of the film is such that significant air-film interface reflection does not occur but also film thickness is sufficient to dissipate energy within the film.

For thin films  $\leq 100 \ \mu$ m, only relatively large changes in high conductivity will result in large reflection differences. For example, for  $d = 100 \ \mu$ m, a 10% increase in conductivity from  $10^3 \text{ mS/cm}$  results in a change of -0.03 dB in  $|\Gamma_{\text{total}}|$  at 60 GHz.

A sensitivity analysis to thickness changes is shown in Fig. 7. In this analysis, the power of  $|\Gamma_{total}|$  is plotted as



Fig. 7. Power magnitude of the total reflection coefficient plotted against the thickness of a battery electrode for various conductivities of the film when  $\epsilon'_r = 2$ . The solid lines represent 60 GHz mmWave interrogation and the dashed lines represent 80 GHz mmWave interrogation.



Fig. 8. Top-down view of the system hardware and the overall software flow used to scan electrodes.

a function of thickness for various conductivities and at two different interrogation frequencies, 60 GHz and 80 GHz. A helpful way to read this plot is to imagine the film shrinking from the right-side to the left-side during a consolidation or drying process. As the film gets thinner, the total reflected power decreases dramatically. It is important to note, however, for thick films, the reflected power decrease may not be strictly monotonic because of the interplay of thickness and wave propagation within the film. Additionally, if a drying process resulted in evaporation of a non-conductive solvent, the conductivity might also vary as the film consolidates. This analysis does indicate that only large thickness changes of thick films, such as those conditions found during a drying process, would be strongly observable when interrogating with perpendicularly-directed mmWave radiation in a reflection measurement.

This section has indicated that properties of thin battery electrode films should be electromagnetically responsive to mmWave radiation but that sensitivity may be limited to larger changes in conductivity and/or thickness. In general, as demonstrated in calculations of  $|\Gamma_{total}|$ , higher frequencies (60 GHz versus 40 GHz, for example) are often preferred for larger signal response to film property changes.

### III. EXPERIMENT

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#### A. Apparatus

A general system diagram for the apparatus used in the experimental portion of this work is found in Fig. 8. The basic hardware configuration is a radar module that can move in 3 dimensions over an electrode on a scanner bed. The laser unit measures distance to the electrode surface. Radar return and electrode height data are collected in MATLAB through screen capture and interface toolboxes. A script in MATLAB controls gantry movement and logs data.

A Texas Instruments IWR6843 Antenna-on-Package Plugin module (IWR6843AOPEVM) was acquired and connected through a USB cord to a controlling computer running the Radar Toolbox Support Package for Texas Instruments mmWave Radar Sensors in MATLAB 2024a. The IWR6843 has 3 transmit antennas and 4 receive antennas. Radar parameters were configured in the Texas Instruments mmWave Demo Visualizer, saved, and then uploaded to the module on startup as part of the scanning script in MATLAB. The start frequency was 60 GHz with a slope of 100 MHz/ $\mu$ s. The sampling rate was 9.5 Msps. 304 samples were taken per chirp and there were 48 chirps per frame. The sweep bandwidth was 3.2 GHz and the frame periodicity was 200 ms.

It is important to note that the TI FMCW radar uses a transmitted frequency chirp starting at 60 GHz and so the notion of a single frequency being used in the theoretical analysis for  $|\Gamma_{total}|$  is only correct insofar as reflection across the entire sweep bandwidth of frequencies (60 to 63.2 GHz in this case) is considered. Additional useful details about FMCW radar are given in [19]. However, since the reflections are expected to be broadband, in the sense that there are no sharp peaks for specific resonant frequencies, the overall computed reflected energy across 60-64 GHz is comparable to averaged theoretical returns between 60 and 64 GHz.

To report the important parameters of most relevance to this study, the TI radar range depth and width were both limited to 0.5 m and reflection peaks were not grouped automatically. The Constant False Alarm Rate (CFAR) range threshold was set to its lowest level (approximately 0 dB) and no static removal of clutter was performed. The returns from a set distance were filtered so that only data from directly in front of the radar was reported (within 5 cm of center). Range returns between 7 and 9 cm were accepted as true measurements to compute the radar return. The Noise and Signal-to-Noise measurements were summed to create a Total Return metric (dB). The Total Return metric is the average of returns from the surface over the swept bandwidth from 60 GHz to approximately 63.2 GHz.

The radar was mounted to a Carbide 3D XYZ stage to control the movement of the radar. Movement commands were sent by MATLAB to collect measurements in a raster pattern. Additionally, a Keyence LK-H052 was mounted next to the radar, about 2 cm in the Y direction, to create a topographic height map of the interrogated electrode surface. Data from the laser probe (as displayed in LK-Navigator 2) were also collected using the same MATLAB script controlling the radar data acquisition.

This article has been accepted for publication in IEEE Transactions on Instrumentation and Measurement. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TIM.2025.3554868

IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. XX, NO. X, XX 202X



Fig. 9. Labeled photograph of movable radar and laser measurement head used to measure reflective properties of thin films.

During preliminary experiments, spurious reflections were obtained as the electrodes were scanned. To minimize these reflections, the radar measurement head was placed within a rectangular arrangement of radar-absorbing foam to minimize these spurious reflections. To keep the film relatively flat, in early experiments a vacuum table made of a consumer-grade air hockey table with the fan in reverse provided gentle suction to the films. Later, a large sheet of aluminum was used as a platform for subsequent experiments.

The arrangement of the IWR5843 radar package and Keyence LK-H052 in a movable measurement head with the radar-absorbing foam is depicted in Fig. 9.

# B. Materials

The paint in the film drying experiment was Extreme Sheen Metallic Paint in the color Amethyst (DecoArt DPM18). The copper substrate was a standard copper on FR4 substrate used in PCB manufacturing. This substrate was chosen because it provided a relatively flat, semi-rigid metal surface which could then be coated and moved without disturbing the film.

For the electrode drying experiments, the materials were carbon black (CB) (Alfa Aesar 39723), poly(vinylidene fluoride) (PVDF) (Aldrich 182702), and 1-Methyl-2-pyrrolidinone (NMP) (Sigma-Aldrich 328634).

A commercial-grade,  $LiCoO_2$  double-sided positive electrode film was obtained from SAFT America in 2009 and used for measurements in this study. This film was representative of a finished film before being incorporated into a full battery (with separator, electrolyte, etc.). The film was 20.8 cm wide, coated edge-to-edge, and had been formed in a continuous process. The film had been calendered to 40% porosity.

#### C. Procedure

Three experiments were performed in this work. In the first two, slowly drying films were created so that radar return data could be obtained on thin films with time-varying properties under ambient laboratory conditions. No heat or forced air was used to accelerate the drying process. In the third experiment, a scan of the commercial quality Li-ion electrode film was obtained to examine spatial heterogeneity of the electrode film.



Fig. 10. Labeled photograph of movable radar and laser head approaching the drying paint on copper surface soon after the paint was applied.

1) Paint Drying Experiment: A 1:2 v/v mixture of acrylic paint and water was prepared in a 2 mL micro-centrifuge tube and then vortex mixed at 3,000 rpm for 1 minute (Velp Scientifica). The water was added to decrease the viscosity of the paint and to increase the drying time. Measurements were repeatedly taken in a linear scan in the Y direction over a distance of 80 mm at 5 mm steps. Approximately 1 mL of the solution was then pipetted onto the copper electrode surface once baseline scans were obtained of the copper surface without the paint mixture. Measurements were continuously obtained over a 4 hour period as the film dried. Days after the film dried, the scanning apparatus was used to take thickness scans of the substrate and dried film at a resolution of 2 mm.

2) Electrode Drying Experiment: A mixture of 1 g PVDF, 12.5 g NMP, and 0.1 g CB was prepared by mixing with a magnetic stir bar. This mixture was then coated and spread using a doctor blade across the copper electrode surface. Then repeated measurements were obtained as the film dried over a 60-hour period, similar to the paint drying experiment. Days after the film dried, the scanning apparatus was used to take thickness scans of the substrate and dried film at a resolution of 2 mm.

3) Li-ion Electrode Film Scanning: Measurements were taken in a raster pattern with a 2 mm step in the X and Y electrode plane directions. After data were obtained, the radar data were shifted by 3 cm (to also compensate for the center of the antennas) to reflect the Y offset between the LK-H052 data and the radar data.

# IV. RESULTS

# A. Paint and Electrode Drying Experiments

A photograph of the paint drying experiment is shown in Fig. 10. It is noticeable that the paint does not perfectly extend across the entire measurement region and that there are departures from a perfectly circular drop. The path of the radar and laser measurement goes approximately through the middle of the paint film.

Height measurement data during drying are displayed in Fig. 11. For each position (5 mm increments from 0 mm to 80 mm), the difference between the original distance at the starting time and the current distance is shown. Additionally, the height data were processed such that the data at 80 mm were used as a global trend baseline for the other data. It is

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Fig. 11. Height measurement data over the course of the thin paint film drying. Positions from 0 to 80 mm are indicated in the legend.



Fig. 12. Total return data over the course of the thin paint film drying. Positions from 0 to 80 mm are indicated in the legend.

clear that the drying time is approximately three hours and the final thickness of the film is approximately 200  $\mu$ m. As the photograph of the experiment in Fig. 10 also indicates, the Y direction length of the thin film is approximately 2.5 cm.

Total return data are displayed in Fig. 12. At each position, the original total return at the starting time was subtracted from the current total return. The average total return magnitude



Fig. 13. Horizontal laser scan across the dried paint on the FR4 substrate. Left and right correspond to the left and right edges of the FR4 substrate while the middle corresponds to the middle of the substrate. The arrows indicate approximately where the start and stop of the paint dried on the substrate.



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Fig. 14. Labeled photograph of measurement head during a scan of the drying CB electrode on the copper surface soon after the electrode slurry was applied.



Fig. 15. Height measurement data over the course of the CB electrode film drying. Positions from 0 to 50 mm are indicated in the legend.

over all the positions at the start of the experiment was 99.5 dB. As can be seen throughout the course of the experiment, total return data are reported in 0.1 dB increments and this magnitude of variation is found throughout the paint drying experiment for those positions that do not have paint added. Where the total return is affected by the application of the paint there is clearly a reflection difference which results in more radar energy being absorbed by the paint film initially. This reflection difference notably becomes negligible as the paint dries. Because the "spot" size of the radar is larger than that of the laser measurement, the return difference is noted over approximately 3 cm. It should be indicated that the spatial translation difference is about 2 cm.

Fig. 13 displays the results of the post-drying laser scan of the electrode using the scanning system and the Keyence sensor. It is clear that the FR4 substrate is bowed. The total amount of curve is only about 500  $\mu$ m, so it is not visibly significant over the ~16 cm substrate, but the laser scanning does indicate the presence of curvature clearly. The wet paint that was seen in Fig. 10 has clearly dried significantly to a thickness between 150-200  $\mu$ m.

A photograph of the CB electrode drying experiment is shown in Fig. 14. It is noticeable that the electrode coating is not uniform along the coating direction. The path of the radar and laser measurement goes approximately through the middle of the electrode film.



Fig. 16. Total return data over the course of the CB electrode film drying. Positions from 20 to 70 mm are indicated in the legend.



Fig. 17. Horizontal laser scan across the dried CB on the FR4 substrate. Left and right correspond to the left and right edges of the FR4 substrate while the middle corresponds to the middle of the substrate. The arrow indicates approximately where the dried CB was thickest on the substrate.

Height measurement data are displayed in Fig. 15. For each position (5 mm increments from 0 mm to 50 mm), the difference between the original distance at the starting time and the distance at the end of approximately 60 hours is shown.

Total return data are displayed in Fig. 16. At each position, the original total return at the starting time was subtracted from the total return at the end of approximately 60 hours. There is clearly a reflection difference which results in more radar energy being absorbed by the electrode film initially. This reflection difference notably becomes negligible as the electrode dries. It should be indicated that the spatial translation difference is about 2 cm, which is why Fig. 16 begins at 20 mm.

Fig. 17 displays the results of the post-drying laser scan of the electrode using the scanning system and the Keyence sensor. It is clear that this FR4 substrate is also bowed. The total amount of curve is only about 500  $\mu$ m, so it is not visibly significant over the ~23 cm substrate, but the laser scanning does indicate the presence of curvature clearly. The wet CB that was seen in Fig. 14 has clearly dried significantly to a maximum of thickness of about 50  $\mu$ m and is much thinner than 50  $\mu$ m for the rest of the coating. Maps from the scanning experiment on the commercial film are shown in Fig. 18. The edge of the film was approximately 40 mm from the start of the X direction of the film and approximately 10 mm from the start of Y direction of the film. A coating gap in the middle of the film is evident in the photograph, height, and total return maps obtained for the electrode.

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While the electrode film was substantially flat, there were some ripples along the edges that are evident in the height maps. Additional ripples in the film that are not easily visible to the eye show up in the height maps and are associated with similar geometries in the radar return maps.

## V. DISCUSSION

The paint drying experiment clearly indicates that ~60 GHz mmWave radar return measurements are affected by the drying state of a thin film and are most likely affected by significant thickness changes, as the thickness decreased from approximately a millimeter to about 200  $\mu$ m. This was confirmed by the subsequent laser scan. The paint mixture was diluted with water, which is a high-absorption electromagnetic material. When the film dried, presumably due to evaporation of water, the film was nonconductive (as tested with a multimeter) and thus did not significantly provide attenuation to an incoming electromagnetic wave. For this reason, after the film dried, the effect of the film on the total return measurements was negligible as evidenced in Fig. 12. This also corresponds to a conductivity below 1000 mS/cm for this thickness as theoretically shown in Fig. 7.

It is notable that the total return data is not monotonic during the drying process. Fig. 7 certainly indicates that the return does not need to necessarily be monotonic during thickness reduction but this also may suggest that the drying process also produced geometric changes when the thickness of the film was large that may have reflected the radar energy in non-perpendicular directions, thus contributing to apparent attenuation. The paint spot was also not uniform across the entire radar field of view, which could also have contributed to non-uniform radar returns as the film dried.

The CB film drying experiment shared similarities with the paint drying experiment, but, because of use of a doctor blade, the thickness of the thickest region was substantially less than in the paint drying experiment. The thickest part of the dried CB indeed was estimated at approximately 50  $\mu$ m. Substantial warpage of the substrate (as evidenced between the differences in height between the left and right sides which did not have coating) is also evident. The initial  $\sim 100 \ \mu m$  difference in the first 20 mm for the right side is due to a label affixed at that location. The resulting CB film was conductive (as tested with a multimeter). The drying process was clearly observed in the normalized total return data. While the observed returns were not always monotonic, the returns over the thick areas behaved more similarly to each other. One of the features that was noted in both the thickness and radar data was the presence of two drying rate domains (two different drying rates appear to be observed before and after approximately 20 hours) reflecting two different coating consolidation phases [27].

# B. Li-ion Electrode Film Scanning



Fig. 18. Photograph (left), height scan (middle), and total radar return (right) of commercial-quality positive electrode.

As demonstrated in Fig. 7, battery films coated on metal substrates will have almost perfect reflection of 60 GHz radiation because the film thickness is small and the films are not significantly absorptive. The calculated magnitude of reflection for the largest conductivity changes is comparable to bare metal and should only modify reflection coefficients slightly (<1 dB change for 50  $\mu$ m thickness even at high conductivity). For the CB films in this study, when they are dry, that apparently was the case.

The mapping shown in Fig. 18 of the commercial-quality film demonstrated electromagnetic interrogation of a large area of battery film is possible using a scanning mmWave radar setup. However, as demonstrated in the paint and CB film drying experiments, variations in dried film properties are not easily resolved because the sensitivity of the mmWave to changes is low and relative material heterogeneity of the commercial-quality film is also presumably low.

One of the biggest lessons learned from these experiments is the necessity of having flat and uniform surfaces when taking measurements. Small ripples which may not even be easily visible to the eye cause large deviations in the radar pattern. Edges of the films also serve as sources of abnormal reflections. This is evidenced by the presence of banding about 10 mm from either edge of the film in the radar plots when compared to the height measurement plots. While it is clear that the radar evaluates a larger area than the nominal <1 mm spot size of the LK-H052, artifacts from edges are prominent in all of the radar return maps from the film. Slight changes in distance from the film can also result in different reflection. The measurement is quite sensitive to any physical changes to the apparatus configuration.

Because of the sensitivity of the method to roughness and other small deviations in the film, it is possible that mmWave radar in this configuration may be able to measure important aspects of film quality, especially the presence of inclusions or other small defects that may not be apparent using visible photography. Future work will be needed to explore these potential inspection possibilities.

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The map over the clear break in the film also clearly shows that physical disruptions to the film result in banding that is visible whenever coating stops and starts, even when absorptive foam is in place to mitigate contributing reflections. Without absorptive foam in place, all reflections from the films are exaggerated and even metal supports that are not part of the film produce visible artifacts.

These experiments show that there is potential to quantify the drying process during electrode manufacturing and some potential to quantify heterogeneity in completed films. Unfortunately, access to full roll-to-roll manufacturing facilities of battery electrodes was not available for this study.

## VI. CONCLUSION

Theoretical calculations of radar returns indicate that  $\sim 60$  GHz mmWave radar measurements have ability to reveal large changes in battery film electrode composition and conductivity for typical thicknesses and ranges of Li-ion battery electrode conductivity. This result could be useful because radar measurements can interrogate large areas of battery film electrodes in a fast, nondestructive, non-contact manner.

In practice, there are many difficulties with taking radar measurements of battery films. A critical one, that could be addressed in future work, is to ensure the uniformity and smoothness of the electrode surface. This should be more possible in a manufacturing operation in which the surface roughness of the films would be much more tightly controlled This article has been accepted for publication in IEEE Transactions on Instrumentation and Measurement. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TIM.2025.3554868

than in a laboratory setting with films that have been manufactured elsewhere and extensively handled. Small blemishes that disrupt the surface produce large changes in reflection coefficients of the films which could lead to anomaly detection. Tight control of spurious reflections, through radar-absorptive materials, is also important to obtain accurate measurements of surfaces without introduction of artifacts from reflections from other parts of the apparatus. There is also more information available in the total computed 3D radar return than the reflected energy at a particular distance that may be of use to further characterize battery films or other thin film materials and could be explored in future work.

This technique could also be used with other metrology such as infrared measurements and surface roughness measurements to provide an additional stream of information about films as they are being manufactured. The availability of compact, inexpensive mmWave radar modules will open up additional applications to study advanced materials as they are being processed.

#### VII. ACKNOWLEDGMENTS

B.A.M. thanks Karl Warnick at Brigham Young University for providing radar absorbing foam, Lizbeth Zurita Garcia at Brigham Young University for preparing the PVDF-CB electrode film, and Dean Wheeler at Brigham Young University for helpful discussions.

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