Terahertz PHASR Scanner With 2 kHz, 100 ps Time-Domain Trace Acquisition Rate and an Extended Field-of-View Based on a Heliostat Design

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Abstract—Recently, we introduced a Portable Handheld Spectral Reflection (PHASR) Scanner to allow terahertz time-domain spectroscopic (THz-TDS) imaging in clinical and industrial settings using a fiber-coupled and alignment-free telecentric beam-steering design. The key limitations of the version 1.0 of the PHASR Scanner were its field-of-view (FOV) and speed of time-domain trace acquisition. In this article, we address these limitations by introducing a heliostat geometry for beam scanning to achieve an extended FOV, and by reconfiguring the asynchronous optical sampling system to perform Electronically Controlled Optical Sampling (ECOPS) measurements. The former change improved the deflection range of the beam, while also drastically reducing the coupling of the two scanning axes, the combination of which resulted in a larger than four-fold increase in the FOV area. The latter change significantly improves the acquisition speed and frequency-domain performance simultaneously by improving measurement efficiency. To accomplish this, we characterized the nonlinear time-axis sampling behavior of the electromechanical system in the ECOPS mode. We proposed methods to model and correct the nonlinear time-axis distortions and tested the performance of the high-speed ECOPS trace acquisition. Therefore, here, we introduce the PHASR Scanner version 2.0, which is capable of imaging a 40 × 19 mm² FOV with 2000 traces/s over a 100 ps TDS range. This new scanner represents a significant leap toward translating the THz-TDS technology from the lab bench to the bedside for real-time clinical imaging applications.

Index Terms—Terahertz (THz) imaging, terahertz time-domain spectroscopy (TDS).

I. INTRODUCTION

TERAHERTZ (THz) imaging has enjoyed many diverse potential applications, such as art preservation [1], [2], security screening [3], [4], nondestructive testing [5], [6], [7], and biomedical analysis [8], [9], [10], [11], [12]. However, many of the available imaging devices are not field deployable or rely on raster scanning of the sample or instrument for image formation. Current THz camera systems do not provide spectroscopic information from the sample [13], [14], [15], [16], [17], [18]. Therefore, images obtained from today’s THz cameras are not well suited for common techniques, such as spectral “fingerprinting” [5], material parameter extraction (e.g., measuring refractive index) [8], [19], and analysis of scattering behavior [20], [21], [22], [23]. In contrast, the time-domain spectroscopy (TDS) method can be used in these studies. Additionally, THz-TDS can provide structural information and subsurface imaging based on the time-of-flight analysis [24], [25]. Compressive sensing techniques allow for THz-TDS image formation using a stationary system, but its field-of-view (FOV) is limited to the collimated beam width [26], [27], [28], [29].

Portable THz spectroscopy has been demonstrated for single-point measurement using the battery-powered micro-Z [30] and mini-Z [31], [32] devices. Also, one-dimensional (1-D) line scanning has been demonstrated using beam steering along a single axis [33], [34]. However, in order to form an image, these devices would still need to be mechanically translated across the surface of a target. To address the need for portable full spectroscopic THz imaging devices, we developed the THz Portable Handheld Spectral Reflection (PHASR) Scanner [35], [36]. This instrument acquired THz-TDS images over a 12 × 19 mm² FOV using an f-θ lens and a mirror mounted in telecentric alignment on a motorized gimbal. An ASynchronous Optical Sampling (ASOPS) system was used to provide fast acquisition rates of 100 waveforms/s. Recently, this device has been demonstrated in the assessment and longitudinal monitoring of burn injuries in an in vivo porcine model [37]. However, the use of the scanner in our preclinical studies have highlighted two key limitations in the first version of the scanner: First, the FOV, limited by the distortions inherent to its scanning geometry and the mechanical limits of the gimbal, and second, scanning speed, limited by the acquisition rate of the ASOPS technique. Solutions to these two limitations are crucial in translation of our technology from bench to the bedside in the upcoming pilot human studies.

Here, we present the new THz PHASR Scanner 2.0, as shown in Fig. 1(a). To increase the FOV, we redesigned the beam-steering geometry based on a heliostat configuration, which additionally eliminated the distortions due to the intercoupling of the scanning axes in the gimbaled motors of the PHASR Scanner 1.0. To increase the speed of the TDS trace acquisitions, we have adapted our existing ASOPS electronic hardware to

Manuscript received 8 April 2022; revised 12 July 2022; accepted 1 August 2022. Date of publication 22 August 2022; date of current version 7 November 2022. This work was supported in part by the National Institute of General Medical Sciences of the National Institutes of Health under Award R01GM112693 and in part by US Army Medical Research Acquisition Activity under Award W81XWH-21-1-0258. (Corresponding author: M. Hassan Arbab.)

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This article has supplementary material provided by the authors and color versions of one or more figures available at https://doi.org/10.1109/TTHZ.2022.3200210. Digital Object Identifier 10.1109/TTHZ.2022.3200210

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perform Electronically Controlled Optical Sampling (ECOPS) instead. These changes produce a new scanner with a large $40 \times 27 \text{ mm}^2$ FOV and capable of recording 2000 waveforms/s, representing a 20-fold increase in acquisition speed.

II. DESIGN OF THE PHASR 2.0 SCANNER

The schematic of a general telecentric THz-TDS imager is shown in Fig. 1(b). The THz light is generated by a commercial fiber-coupled photoconductive antenna (PCA), collimated, and then directed through a beam splitter. The beam is steered across a custom high-density polyethylene (HDPE) $f$-$\theta$ lens by a gimbaled mirror located at the lens’ rear focal point, thus creating a telecentric configuration. In this design, the lens maintains a normal incidence angle on the target, a flat focal surface plane, a constant focal spot size, and constant optical path length for all positions within the FOV [38]. The normal incidence and flat focal plane mean that the reflected beam is collocated with the incident beam, returning by the same path to the beam splitter where it is directed toward the detector PCA. Optionally, an imaging window can be used at the focal plane to flatten soft targets and allow for self-calibration reference measurements using the air-window interface reflections [19].

The simplified model of a generalized gimbal in Fig. 2(a) shows how rotations about the outer gimbal axis (blue, $\alpha$) change the orientation of the other axis (red, $\beta$). In our previous design, we used a commercial gimbal unit with $\pm 7^\circ$ deflection in each axis. Due to the specific gimbal architecture, the unit was mounted at a $45^\circ$ angle, as shown in Fig. 2(b). In this arrangement, the angle between the elevation axis and the incident beam, $b_{\text{in}}$, is dependent on the orientation of the azimuthal axis. Note that, at the default position of the azimuthal motor, $\alpha = 0^\circ$, as shown in Fig. 2, the elevation axis, $\beta$, is perpendicular to the incident beam, whereas if the azimuthal axis rotates to its maximum range, $7^\circ$, the angle between the elevation axis and the beam would be about $5^\circ$. As a result of this varying angle, movement directly along the horizontal, $x$, or vertical, $y$, scanning directions requires contribution from both motors. In other words, the two gimbal axes are intercoupled. Fig. 2(c) shows the coordinate mapping from the motor angles to the position of the focused beam for this design, derived in detail in [35], which only provided a $12 \times 19 \text{ mm}^2$ FOV.

To improve this range, we have redesigned the mirror gimbal layout, as shown in Fig. 3(a). Inspired by heliostats, instruments used in astronomy to reflect light from the sun as it moves through the sky to a fixed point, we have adapted the scanning mechanism’s orientation to reduce the axial coupling [39]. Instead of a single off-the-shelf gimbal, a pair of motors were stacked in a “daisy-chained” configuration. A rotation stage controlling the azimuthal axis is fastened directly to the scanner housing. The elevation angle is controlled by a motorized goniometer attached to the rotation stage. A 3D-printed mirror mount biased by $45^\circ$ about the elevation axis is used to properly locate the mirror for scanning. The model gimbal, as shown in Fig. 3(b), demonstrates this orientation. Note again the effect that rotating about the azimuthal axis has on the angle between the incident beam and the elevation axis. In this design, the outer azimuthal axis is collinear with the incident beam and as such, the elevation axis remains perpendicular to the incident beam at any azimuthal position. This provides the larger and significantly more rectilinear FOV, as shown in Fig. 3(c). For comparison, the outline of the PHASR Scanner 1.0 FOV is shown by the black dashed line. The vertical scan range, limited by the $\pm 10^\circ$ travel of the goniometer, is approximately $27 \text{ mm}$ at the center, expanding slightly at larger horizontal positions. The color within the scanning area in Fig. 3(c) shows the simulated normalized power at the target calculated via ray tracing. The circular profile shows how the primary limiting factor of the horizontal scan range is the diameter of the $f$-$\theta$ lens, which provides approximately a $40$-mm range.

A. Heliostat Beam Scanning Algorithm

To demonstrate the decoupling of the imaging axes of rotation in the heliostat design, we derive the scanning coordinate system from the axial deflections. We define the $z$-axis to be aligned antiparallel with the optic axis of the $f$-$\theta$ lens and the $x$ and $y$ axes, as shown in Fig. 3(a). A vector perpendicular to the face of the mirror then has the direction

$$\hat{m} = \begin{pmatrix} \cos(\beta - 45^\circ) \sin(\alpha) \\ \sin(\beta - 45^\circ) \\ -\cos(\beta - 45^\circ) \cos(\alpha) \end{pmatrix}$$

(1)

where $\alpha$ and $\beta$ are the angles rotated by the azimuthal and elevation motors, respectively, and defined in Fig. 3(b). That is, the mirror points in a direction corresponding to a simple spherical coordinate system with azimuthal angle about the $y$-axis and elevation measured in either direction from the $xz$-plane. The collimated THz beam is then described by the incident and reflected vectors, respectively

$$\hat{b}_{\text{in}} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \quad b_{\text{out}} = \begin{pmatrix} x \\ y \\ -f \end{pmatrix}$$

(2)

where $(x, y)$ is the location of the beam at the lens plane. Reflecting $-\hat{b}_{\text{in}}$ about $\hat{m}$ to get the direction of $b_{\text{out}}$ and scaling such that the $z$ coordinate is equal to $-f$ so that $x$ and $y$ coordinates represent the location at the lens plane, it can be...
Fig. 2. (a) Geometry of the beam steering in PHASR Scanner 1.0. (b) Simplified representation of the gimballed mirror in PHASR 1.0. (c) Resultant scanning pattern from this geometry. Blue and red grids represent the coordinates of angular deflection of the scanning mirror, \( \alpha \) and \( \beta \), about its azimuthal and elevation axes, respectively.

Fig. 3. (a) Geometry of the PHASR Scanner 2.0 beam steering. (b) Simplified representation of the gimballed mirror in PHASR 2.0 showing the azimuthal axis, in blue, aligned with the incident beam and elevation axis, in red, perpendicular to it. (c) Resultant scanning pattern from this geometry. Blue and red grids represent the coordinates of the angular deflection of the scanning mirror, \( \alpha \) and \( \beta \) about its azimuthal and elevation axes, respectively. The dashed black line shows the FOV accessible with the previous version of the scanner and the solid black line shows the typical scanning area of 25.4 \( \times \) 25.4 mm\(^2\) (1 \( \times \) 1 in). The color scale shows the normalized incident power at the target as determined by ray-tracing simulation.

seen that

\[
b_{\text{out}} = \begin{pmatrix} f \tan(\alpha) \\ f \sec(\alpha) \tan(2\beta) \end{pmatrix} = \begin{pmatrix} f \sin(\alpha) \\ \tan(2\beta) \end{pmatrix} = \begin{pmatrix} m_x \\ m_y \end{pmatrix}.
\]  

(3)

Equation (3) shows that, at the lens plane, the \( x \)-coordinate is only dependent on \( f \) and \( \alpha \), and the value \( h = f \sec \alpha = \sqrt{x^2 + z^2} \) is the distance to the lens plane at azimuthal angle \( \alpha \). Similarly, the \( y \)-coordinate is only dependent on \( h \) and \( \beta \). That is, the angle within the \( xz \)-plane is determined only by \( \alpha \) and the angle away from the \( xz \)-plane is determined only by \( \beta \).

The basic scanning algorithm for this design is then as follows. The face of the mirror must point in the direction bisecting the incident and reflected beams

\[
m = \begin{pmatrix} m_x \\ m_y \end{pmatrix} = \begin{pmatrix} \tan(\alpha) \\ \tan(2\beta) \end{pmatrix} = \begin{pmatrix} \frac{m_x}{m_z} \\ \frac{m_y}{m_z} \end{pmatrix}.
\]  

(4)

The axes of the gimbal must rotate to

\[
\alpha = \arctan \left( \frac{m_x}{-m_z} \right), \quad \beta = \arctan \left( \frac{m_y}{\sqrt{m_z^2 + m_x^2}} \right) + 45^\circ.
\]  

(5)

Our previously demonstrated linear correction can be applied to account for slight deviations due to the \( f-\theta \) lens [35]. This method is general for heliostat scanning over \( f-\theta \) lenses. Variations on this design using different lenses might provide
better performance for different applications, albeit with some tradeoffs. For instance, a lens with a larger focal length provides a greater FOV for the same angular range of travel at the gimbal but at the cost of a larger spot size at the focus, reducing the spatial resolution of the device. The particular $f$–$\theta$ lens used here has been developed to suit the needs of a compact scanner. Thus, the vertical scan range of the PHASR Scanner 2.0, limited by the $\pm 10^\circ$ travel of the goniometer, is approximately 27 mm at the center, whereas the horizontal scan range is limited only by the lens area (e.g., here to approximately 40 mm).

### III. ECOPS Measurements Using ASOPS Hardware

The imaging rate of our previous scanner was limited by the measurement speed of the commercial ASOPS system used for generation and detection of THz pulses. Although faster than using a mechanical delay line, the THz-TDS acquisition rate was slower than speeds provided by the ECOPS technique. ECOPS trace acquisition rates of 2.5 kHz [40], 8 kHz [41], and even as high as 60 kHz [42] have been demonstrated, although with THz time-axis ranges limited to less than about 20 ps at those speeds. Imaging systems using ECOPS technique have been reported with the operating speeds of 1000 trace/s [43], [44]. Also, the point measurements of sample layer thickness have been acquired at 1600 Hz rates with 200 ps of range [45]. Both ASOPS and ECOPS use 2 fs lasers to, respectively, generate and sample the temporal waveform of the THz electric fields. These two techniques are described in detail elsewhere [46], [47]; however, an overview is provided here and illustrated conceptually in Fig. 4.

In both techniques, the difference in repetition rate of the two lasers causes the sampling laser to progressively record sequential THz pulses in time, building a representative time-domain acquisition. Here, we call the laser generating the THz pulses “Laser A,” which has a constant repetition frequency $f_{rep}$ and will, thus, produce THz pulses separated by a period of $T_{rep} = 1/f_{rep}$. The laser sampling the THz pulses is called “Laser B” and has its repetition rate set to $f_{rep} - \Delta f$, where $\Delta f$ is small compared to $f_{rep}$. In general, the difference frequency $\Delta f$ can be set by the user and is dependent on time $t$. As a result, the THz pulse samples occur at a frequency of $1/(f_{rep} - \Delta f)$. Assuming no variation in the beam path, each of these THz pulses is essentially identical at the detector, so the different repetition periods of the two lasers mean that, in comparison to the previous sampling location of the THz pulse, each subsequent sample will be delayed by [46], [47]

$$\Delta \tau (t) = \frac{1}{f_{rep} - \Delta f (t)} - \frac{1}{f_{rep}} \approx \frac{\Delta f (t)}{f_{rep}^2} \quad (6)$$

where the values of $\tau$ refer to the effective time-axis intervals of the THz pulse and are usually in picoseconds. The actual sampling interval in lab time, $t$, is $T_{rep} = 1/f_{rep}$ and is equal to the period of the femtosecond laser pulses. Each successive pulse from Laser B will sample the corresponding THz pulse generated by Laser A at a point time shift by $\Delta \tau$. Starting at an arbitrary sampling time $\tau(0) = \Delta \tau_0$ at time $t = 0$, the effective sample time at $t$ is given by

$$\tau (t) = \tau_0 + \sum_{n = 0}^{n \times f_{rep} \Delta f} \frac{\Delta f (n/f_{rep})}{f_{rep}} \times \frac{1}{f_{rep}} \quad (7)$$

where $n = t \times f_{rep}$ is the integer number of laser pulses that have occurred since $t = 0$. The separated factor of $1/f_{rep}$ in (7) emphasizes the fact that this is, in essence, a Riemann sum with its step size defined by the repetition interval of the laser. Thus, the transform between time and the sampling location can be approximated by the integral of the difference frequency over time.

In ASOPS measurements, as illustrated in blue in Fig. 4, $\Delta f$ is kept constant and $\tau$ will increase by the same amount per pulse. The direction in which the sampling progresses depends on which laser has a higher repetition rate, i.e., it depends on the sign of $\Delta f$. If Laser B has a lower repetition frequency, as depicted in blue in Fig. 4(a), the sampling can be said to be in the “forward” direction as each subsequent sample is associated with a later time in the THz signal, as shown in Fig. 4(b). If the frequency of Laser B is higher, the sampling will occur in the opposite, “backward,” direction. For ASOPS measurement in either direction, after one full period of the difference frequencies, $1/|\Delta f|$, the accumulated sample time will equal to that of a full period of the laser repetition, that is, $\tau(1/|\Delta f|) - \tau_0 = T_{rep}$, and thus samples covering the full THz
pulse will have been acquired. To improve the signal-to-noise ratio (SNR), multiple sequential acquisitions are then typically averaged to build a single THz-TDS trace, so the total time per trace is the number of averages multiplied by $1/|\Delta f|$.

However, ASOPS measurements are not time efficient because, in every acquisition event, the entire $T_{\text{rep}}$ on the order of 10 ns is recorded but only the relevant THz-TDS measurements range, typically on the order of 100 s of ps, is retained. This effect is illustrated in Fig. 4(b) by the range between the dashed lines. Thus, the majority of the period of ASOPS is spent sampling timepoints outside of the range of interest. ECOPS improves the measurement speed by only sampling a small range of interest.

The ECOPS technique can be understood as ASOPS measurement with an alternating $\Delta f$, such as the illustrations shown in Fig. 4(a). As a result of the modulated $\Delta f$ value, instead of sampling the entire $1/|\Delta f|$ period, Laser B repetitively samples in both forward and backward directions over only a small section of the available period, as shown in red in Fig. 4(b). If the frequency of the modulation is $f_M$, single-shot THz-TDS traces can be acquired at $2f_M$ since the data can be recorded in both directions. However, unlike ASOPS, which can sample any-sized section of the entire $T_{\text{rep}}$ period of the THz waveform, ECOPS’s measurement range, $T_{\text{THz}}$, is linked to the speed through both $\Delta f$ and $f_M$. Thus, while the THz acquisition window and its smaller than the $T = \Delta f$ value, instead of $\Delta f$ should be understood as a nominal modulation of the form $\Delta f = (32 \text{ Hz}) \sin(2\pi(1000 \text{ Hz}))$. In contrast, ASOPS measurements, which have a constant difference frequency, will be indicated just by that value, e.g., $\Delta f = 100 \text{ Hz}$.

### A. Timing Drift

Drift occurs if the system responds differently to the two forward and backward directions of time-domain scanning, e.g., through a hysteresis in the piezo. In that case, the two directions will cover different amounts of $\tau$, leading to an apparent drift of the THz signal due to the drift of the ECOPS sampling range. Left unchecked, this drift will quickly cause the region of interest to shift out of the scanning window. To counteract this effect, a small offset (typically on the order of tens of mHz) to the base repetition rate of laser B, $f_B$, is required to bias the modulation by the same amount opposite to the drift. However, in our system, using a constant offset value is insufficient as the drift varies over time, as much as 5 ps/s within minutes. To address this issue, we have implemented a state control model for real-time drift compensation, as described by the flowchart in Fig. 5. In order to properly track the drift, we must find and lock on to a feature (such as the peak of a THz pulse) known to be stationary.

For rough surface or malleable targets, such as liquid or skin, the flat imaging window, as shown in Fig. 1, provides an ideal reflection reference from the air-window interface. Since the $\text{f-}\theta$ lens provides a constant phase at its focus over the entire planar FOV [38], there is no additional compensation for scanning location needed. The difference of the current apparent time location of this feature, $\tau_{\text{curr}}$, from the location measured some amount of time, $\tau_{\text{prev}}$, provides the drift, $d$, of the ECOPS time window. A small adjustment to the frequency offset is made to compensate, any time, the window drift that is above a certain threshold, $d_{\text{max}}$, in either direction. Once engaged, this compensation actively counters the majority of the drift in real time. In this article, we classify any remaining variation as jitter, which contributes to the measurement noise, and will be discussed in Section IV-A.

### B. Nonlinear Time-Domain Sampling and Its Correction

In addition to the drift described Section III-A, the other time-axis distortions are present as a result of the electronic and mechanical systems response to the frequency modulation. For example, any inaccuracy of the modulation electronics, mechanical responses of the piezos to the electronic waveform, or drift correction will modify the modulation from the nominal sinusoid and, thus, deviate the sampling from the expected points. The extent of this distortion is illustrated by measurements from a multilayer reference target, as shown in Fig. 6(a). TDS point measurements of a thin wafer of silicon, sandwiched between the imaging window and metallic back layer, provides many distinct pulses due to the Fabry–Perot reflections. The relative timing of these “landmark” features allows for simple comparison between ECOPS signals and an ASOPS reference...
Fig. 5. Flowchart of state model drift compensation algorithm. Drift, \( d \), is calculated as the change in measured feature location \( (\tau_{\text{Curr}} - \tau_{\text{Prev}}) \) over some amount of time, \( \Delta t \). If the magnitude of \( d \) is greater than a threshold, \( d_{\text{Max}} \), then a small corresponding correction is made to the base repetition rate of Laser B, \( f_B \).

Fig. 6. (a) Illustration of the multilayer reference target used for providing constant sampling points in the time domain. (b) Representative time-domain signals when using the ECOPS time axis \( (f_M = 1000 \text{ Hz}, \Delta f = \pm 32 \text{ Hz}, 50 \text{ avg.}) \) in the forward (blue) and backward (red) directions compared to the reference ASOPS signal (black) of the same target \( (\Delta f = 100 \text{ Hz}, 100 \text{ avg.}) \). (c) Distribution of the measured delay between the two pulses marked in (b) over 30 traces from each of the ECOPS directions with black dotted line showing the ASOPS value. (d) Comparison of the difference between the measured ASOPS and ECOPS location \( s \) (adjusted for different \( \tau_0 \) values) of the time-domain reflection peaks in the forward (blue, lower axis) and backward (red, upper axis) for all 30 ECOPS datasets.

measurement of the same location on the multilayer sample. Fig. 6(b) illustrates the ECOPS time axes generated by (7), \( \tau_{\text{ECOPS}}(t) \), using the expected modulation function. This basic model does not result in the correct time axes and notably the timing error is not the same for both directions of the ECOPS sampling. For instance, note the interval labeled by \( \Delta \tau_{\text{pks}} \) in Fig. 6(b). As measured by the ASOPS reference, the later peak arrives 42.62 ps after the first. As shown in Fig. 6(c), this difference is consistently underestimated by the ECOPS signals. Fig. 6(d) shows the time-dependent difference in the ECOPS location of the landmark peaks from the same observed ASOPS locations, \( \tau_{\text{ASOPS}} \), offset by the different \( \tau_0 \) values for each trace. If the ECOPS measurement perfectly reproduced the ASOPS signal, these points would fall at 0 for each \( t \). Instead, the nonzero slopes of the two sets indicate that the scaling provided by (7) did not capture the dynamic response of the electrical and mechanical hardware. The differences in the response to each direction of modulation is also made clear by plotting the forward and backward ECOPS measurement using red and blue data points and corresponding time axes.

The full extent of the timing error can be seen in Fig. 7(a) and (b), which compares the expected time-axis function calculated...
an ASOPS acquisition provides time-axis calibration. We can approximate this transform for an individual acquisition using a polynomial equation of order \( N \) given by

\[
\tau(t) - \tau_0 = \sum_{P=1}^{N} C_P t^P
\]  

(8)

where \( C_P \) are the coefficients of the \( P \)th polynomial term. If we label the landmark features \( a, b, c, \ldots \) and associate their ECOPS locations in lab time: \( t_a, t_b, t_c, \ldots \) with their ASOPS time locations: \( \tau_a, \tau_b, \tau_c, \ldots \), then the set of \( C_P \) values and \( \tau_0 \) can be found using a least squares fitting algorithm produced by numerically solving the matrix equation, given by

\[
\begin{bmatrix}
(t_a)^N & (t_a)^{N-1} & \cdots & t_a & 1 \\
(t_b)^N & (t_b)^{N-1} & \cdots & t_b & 1 \\
(t_c)^N & (t_c)^{N-1} & \cdots & t_c & 1 \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
\end{bmatrix}
\begin{bmatrix}
C_N \\
C_{N-1} \\
\vdots \\
C_1 \\
\tau_0 \\
\end{bmatrix} =
\begin{bmatrix}
\tau_a \\
\tau_b \\
\tau_c \\
\vdots \\
\end{bmatrix}.
\]  

(9)

The initial sampling point, \( \tau_0 \), depends on the starting point of the window, thus, in general, will be different for each acquisition. The polynomial coefficient terms, \( C_P \), model the shape of the ECOPS time sampling and, excluding jitter, are expected to be the same for each acquisition.

The accuracy of this approximation will be limited by the number and distribution of sampling points used to generate the fit. We further increase the number of reference points by using multiple acquisitions with different \( \tau_0 \) values, and thus different time-window locations. In order to find the correct coefficients for all acquisitions, we fit a system of equations in which the constant terms (zeroth order) are unique to acquisitions of the different time windows but nonconstant (first and greater order) polynomial terms remain the same. That is, for \( M \) different ECOPS acquisitions, we extract the time locations, \( t_{i,m} \) and \( \tau_{i,m} \), where \( i = a, b, c, \ldots \) and \( m = 1, 2, \ldots, M \), for all “landmarks” time sampling locations. The system of equations can
be represented by the matrix equation given by

\[
\begin{bmatrix}
(t_a,1)^N & (t_a,1)^{N-1} & \cdots & t_a,1 & 1 & 0 & 0 & \cdots & 0 \\
(t_b,1)^N & (t_b,1)^{N-1} & \cdots & t_b,1 & 1 & 0 & 0 & \cdots & 0 \\
(t_c,1)^N & (t_c,1)^{N-1} & \cdots & t_c,1 & 1 & 0 & 0 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
(t_a,2)^N & (t_a,2)^{N-1} & \cdots & t_a,2 & 0 & 1 & 0 & \cdots & 0 \\
(t_b,2)^N & (t_b,2)^{N-1} & \cdots & t_b,2 & 0 & 1 & 0 & \cdots & 0 \\
(t_c,2)^N & (t_c,2)^{N-1} & \cdots & t_c,2 & 0 & 1 & 0 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
(t_a,M)^N & (t_a,M)^{N-1} & \cdots & t_a,M & 0 & 0 & 0 & \cdots & 1 \\
(t_b,M)^N & (t_b,M)^{N-1} & \cdots & t_b,M & 0 & 0 & 0 & \cdots & 1 \\
(t_c,M)^N & (t_c,M)^{N-1} & \cdots & t_c,M & 0 & 0 & 0 & \cdots & 1 \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots 
\end{bmatrix}
\begin{bmatrix}
C_N \\
C_{N-1} \\
\vdots \\
C_1 \\
\tau_{01} \\
\tau_{02} \\
\tau_{03} \\
\vdots \\
\tau_{0M} 
\end{bmatrix} = 
\begin{bmatrix}
\tau_{a,1} \\
\tau_{b,1} \\
\tau_{c,1} \\
\vdots \\
\tau_{a,2} \\
\tau_{b,2} \\
\tau_{c,2} \\
\vdots \\
\tau_{a,M} \\
\tau_{b,M} \\
\tau_{c,M} \\
\vdots 
\end{bmatrix}.
\]

(10)

Solving this equation gives the single set of coefficients for the mapping, \(C_N, C_{N-1}, \ldots, C_1\) as well as the \(\tau_0\)'s. Furthermore, simultaneous fitting to multiple \(M\) acquisitions reduces the impact of jitter on the calculated value of the coefficients.

While this transformation could be applied independently for each direction of ECOPS scan, in practice, we have found that this is best done using ECOPS measurements, which have been “unwrapped,” as shown in Fig. 7, to contain both the forward and backward sampled signals as they were recorded. That is, the fitting method is applied to both the blue and red points at once, starting with the forward signal and followed by the reverse signal. The small delay between the two directions is the “rearm” time of the recording instruments in which no data are collected. This “full-cycle” approach more accurately fits the time in between the same landmark features’ location in the forward and backward directions. In other words, the full-cycle fitting would correct time-axis locations between 0 and 1 ms in Fig. 7. The true function should then be expected to be periodic with a period equal to that of the frequency modulation. Fig. 8 shows the mean-square-error (MSE) of the peak locations in the corrected time-axis results as a function of the fitting polynomial order. These results demonstrate that increasing the order of the fitting polynomial has diminishing returns beyond the eighth order. Therefore, in the subsequent sections, we will use an eighth-order polynomial function in (10).

Fig. 9 shows the application of the eighth-order polynomial time-axis correction to Fabry–Perot reflections in Fig. 6. Fig. 9(a) shows that this polynomial function, shown by the green dashed line, agrees with the experimental measurements much better in comparison to the theoretical model shown by the black dashed line. In particular, Fig. 9(b) shows that the time-axis error between the theoretical model and the ECOPS measurements can reach several picoseconds in a full-cycle measurement. In Fig. 9(c), however, this error, i.e., \(\Delta \tau_{\text{ECOPS}}(t)\), the difference between the measured locations and the polynomial model, is approximately uniform and smaller than 1 ps. As a result, there is a better match between the ASOPS and ECOPS signals in both directions, as shown in Fig. 9(d). Specifically, in Fig. 9(e), the delay between the pulses labeled by \(\Delta \tau_{\text{pks}}\) in Figs. 6(b) and 9(d) is reduced from 2 and 4 ps in the forward and backward direction, respectively, to less than 0.3 ps in the forward direction (blue) and less than 0.6 ps in the backward direction (red).

When using different ECOPS frequency modulation parameters, i.e., \(f_M\) and \(\Delta f\) values, following the method described in this section resulted in different eighth-order polynomial time-axis corrections, however with a similar accuracy in modeling the nonlinear time-domain sampling (data not shown). Although results shown in Fig. 9 indicate that the error of time-axis sampling can be markedly reduced, the effect of the residual difference in spectroscopic measurements must be investigated. In Section IV, we have used the eighth-order polynomial time-axis corrections to model and correct for the nonlinear time-axis behavior in evaluating the performance of the new PHASR 2.0 Scanner.

IV. INVESTIGATION OF PRACTICAL LIMITS

In order to validate the imaging capabilities of the PHASR Scanner 2.0 and the accuracy of our THz-TDS measurements in the ECOPS mode, we compare measurements against ASOPS data of the same type. In particular, four aspects of the THz-TDS measurements were examined: jitter, dynamic range, usable bandwidth, and spectroscopic accuracy. The first three values were calculated from measurements of a flat mirror, while the spectroscopic accuracy was calculated based on the well-studied resonance of lactose at 0.53 THz [23], [48], [49], [50]. In each case, the performance metric was estimated from 100 independent acquisitions obtained as single-point spectroscopy measurements on the sample and without the optional imaging window. These measurements were repeated using different setting values, which affect the acquisition rate, i.e., \(f_M\) for ECOPS, as well as the number of time-domain traces averaged per acquisition and \(\Delta f\) for both ASOPS and ECOPS. As per the manufacturer’s users’ manual, the \(\Delta f\) values of the ASOPS system can be selected between 1 and 1000 Hz. Since our aim for employing ECOPS measurements is primarily to provide faster acquisition rate than the capabilities of the existing ASOPS system, the examined modulation frequencies were limited to 800 and 1000 Hz. After time-axis correction, a gaussian high-pass filter (\(\mu = 0\) THz, \(\sigma = 0.05\) THz) was applied to all signals to remove low-frequency noise typical of internal reflections within our PHASR Scanner. Table I presents single-shot acquisition
Fig. 9. (a) Comparison between the model calculated from (7) (black dashed line) and polynomial fit (green dashed line) to the actual peak locations (blue and red points). (b) Difference from the calculated model and (c) difference from the polynomial fit highlighting the improved correspondence to ASOPS peak locations. (d) Corrected time-domain signal and (e) measurement of $\Delta\tau_{\text{pk}}$ demonstrating that, after nonlinear time-axis correction, the ECOPS traces much more closely match each other and the ASOPS reference. The histogram data are obtained from 30 ECOPS measurements of the sample in Fig. 6.

| Method | $f_M$ [Hz] | $\Delta f$ [Hz] | Single-Shot Time [ms] | Maximum THz-TDS Sampling Range [ps] | 20-Avg. Dynamic Range [dB] | 100-Avg. Dynamic Range [dB] |
|--------|------------|-----------------|-----------------------|-------------------------------------|-----------------------------|-----------------------------|
| ASOPS  | 0          | 50              | 20                    | 10,000                              | 35.4                        | 43.2                        |
|        | 0          | 100             | 10                    | 10,000                              | 30.5                        | 36.0                        |
|        | 0          | 200             | 5                     | 10,000                              | 21.9                        | 28.7                        |
|        | 0          | 400             | 2.5                   | 10,000                              | 14.3                        | 21.5                        |
|        | 0          | 500             | 2                     | 10,000                              | 8.7                         | 18.7                        |
|        | 0          | 1000            | 1                     | 10,000                              | 4.5                         | 9.1                         |
| ECOPS  | 800        | ±32             | 0.625                 | 140                                 | 34.2                        | 42.6                        |
|        | 800        | ±42             | 0.625                 | 181                                 | 34.4                        | 40.1                        |
|        | 1000       | ±15             | 0.5                   | 55                                  | 38.8                        | 44.5                        |
|        | 1000       | ±25             | 0.5                   | 94                                  | 36.2                        | 43.6                        |
|        | 1000       | ±32             | 0.5                   | 114                                 | 35.8                        | 43.2                        |
|        | 1000       | ±35             | 0.5                   | 123                                 | 34.6                        | 42.1                        |

### Table I

Measurement Capabilities at Different ASOPS and ECOPS Settings

Consistent timing is vital to time-of-flight and phase-based measurements common to THz-TDS techniques, such as material parameter extraction and thickness determination. A representative comparison between the ASOPS and ECOPS time-domain measurements obtained at the center of a flat mirror placed at the focal point is shown in Fig. 10(a). We define the jitter by the standard deviation of the time-of-arrival (ToA) of the reflected pulse as measured by the location of the maximum amplitude in the time domain. Fig. 10(b) shows the performance of both techniques at different settings. Notably, single-shot ASOPS measurements at $\Delta f \geq 400$ Hz suffered from poor SNR such that a typical THz-TDS pulse could not be identified in the recorded trace. For example, single-shot ASOPS acquisitions...
of $\Delta f = 500$ and 1000 Hz were nearly indistinguishable from noise, requiring special effort to manually locate the correct time window for measurement. Increasing the number of traces averaged per ASOPS acquisition typically decreases the noise, improving precision in calculations involving time of flight or phase measurements. However, this trend reverses for acquisitions that take more than about a second. In contrast, our implementation of ECOPS only improves up to around 20 traces/acquisition. In both cases, this indicates that arbitrarily large averaging is inadvisable due to the limits on the stability of the difference frequency, although for ECOPS, this is also in part due to the limits of the simple drift compensation model in Section III-A. More advanced techniques or implementation of additional hardware, such as presented in [43] and [46], can improve the large-average performance to better match that of the existing ASOPS system.

B. Dynamic Range and Usable Bandwidth

In addition to time-resolved measurements, much of the strength of the THz-TDS imaging is due to the ability to measure broadband spectra. Representative frequency-domain reference measurements for both ASOPS and ECOPS are shown in Fig. 10(c) along with comparable measurements without the presence of the reference mirror to establish the noise floor. The peak dynamic range, calculated as the maximum ratio of the signal to the noise floor in the frequency domain, is shown in Fig. 10(d). Usable bandwidth is then calculated as the frequency at which the dynamic range first falls to below 3 dB and is plotted in Fig. 10(e). Some ASOPS measurements with high difference frequency and low averaging did not exceed this threshold at any point, resulting in a bandwidth of 0 THz. Since the magnitude of the frequency spectra is not affected by the timing of the pulse, the drift does not affect broadband frequency performance, determined using the magnitude of the Fourier transformation of the TDS pulses, in the same way that it affected the ToA measurements. Thus, as expected, increasing the averaging lowers the noise floor, improving both the dynamic range and usable bandwidth of the measurements. The effect of increasing averaging suppresses the noise floor for all settings, resulting in the parallel trends in dynamic range plot. Most notably, ECOPS measurements offer approximately 10–20 dB higher dynamic range.
range as compared with the ASOPS measurements. Furthermore, decreasing the ASOPS difference frequency improves the performance in both measures. ECOPS, which operates with even lower difference frequencies, shows a similar capability to that of the best ASOPS setting (Δf = 50 Hz) when comparing measurements with a similar averaging despite the significantly shorter ECOPS measurement times.

The effect of measurement speed on bandwidth is not as easily defined. Two series of water absorption lines beginning at approximately 1.1 and 1.7 THz [51], visible in Fig. 10(c), naturally limit dynamic range in their vicinity and create artificial striation in the measured bandwidth values. We have used a centered moving average filter, with 0.2 THz width applied to the signal spectra, as a simple method to remove the water absorption lines and other spectral fluctuations. Following this step, Fig. 10(e) shows that, similar to the dynamic range, the bandwidth of the ASOPS measurements show a marked improvement with decreasing difference frequency. The bandwidth of the ECOPS measurements is higher than all ASOPS settings with similar numbers of averaging. However, the improvement in ECOPS bandwidth with increasing averaging is modest. This behavior is the result of the differing shapes of the spectral density of the noise floor in each technique, as illustrated for instance above 1.7 THz in Fig. 10(c). In general, higher difference frequencies result in a steeper negative slope in the noise floor, while lower difference frequency values produce a flat noise floor.

C. Spectroscopic Accuracy

To characterize the ability of our modified system to accurately measure frequency spectra, we calculated the measured location of the resonance of lactose, theoretically expected at 0.53 THz. The sample consisted of an approximately 4 mm thick pellet consisting of equal parts by mass of α-lactose monohydrate and HDPE (for binding). The two components were mixed as powders with mortar and pestle and then compressed for 3 h. The sample was placed on a mirror and the reflection from the back surface (that is, the signal which has passed through twice the sample thickness) was captured. The location of the resonance was then determined by finding the location of the minimum spectral amplitude in the area between 0.45 and 0.65 THz. This test provides additional insight into how well the nonlinear time-axis sampling correction performs over large sections of the signal, as incorrect scaling will lead to frequency shifts. Fig. 11(a) and (b) shows the distribution of the resonance locations using a selection of ASOPS and ECOPS.

Fig. 11. Distribution of the measured lactose resonance. (a) ASOPS measurements and (b) ECOPS measurements, including values calculated from forward (blue) and backward (red) directions using (7) as well as time-axis corrected (black). (c) Frequency-domain plot of select ASOPS (Δf = 100 Hz, 20 avg., light blue box in (a)) and ECOPS (f_M = 1000 Hz, Δf = ±32 Hz, 20 avg, blue and red for ECOPS forward and backward directions before time-axis correction, respectively, and orange for after correction). Area demonstrates the mean ± standard deviation among 100 acquisitions (50 each of forward and backward for ECOPS signals). Light blue- and orange-colored boxes in (a) and (b) indicate the corresponding boxplots. The resonance of lactose at 0.53 THz in time-axis corrected ECOPS measurements (orange) overlap closely with ASOPS results (light blue). (d) Standard deviation of the measured resonance location for each set of acquisitions. ECOPS measurements shown only after time-axis correction.

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settings after averaging 20 independent traces. For ECOPS measurements, the distribution of the resonances calculated for each direction using (7) (i.e., without time-axis correction) is also shown in red and blue. It can be seen that the precision of ASOPS measurements improves as the difference frequency is lowered; however, the accuracy of ECOPS measurements remains higher than ASOPS and independent of ECOPS settings after our proposed time-axis correction method. Fig. 11(c), for example, compares the spectral location of lactose’s resonance for ASOPS measurements marked with the light blue box in Fig. 11(a) ($\Delta f = 100$ Hz) with ECOPS measurements selected by the orange box in Fig. 11(b) ($f_M = 1000$ Hz, $\Delta f = \pm 32$ Hz) before and after the nonlinear time-axis correction. Overall, the time-axis corrected ECOPS results perform better than even the $\Delta f = 50$ Hz ASOPS measurement, consistent with the trend according to difference frequency described previously. As shown in Fig. 11(d), the precision of this measurement improves as increasing averaging reduces the noise. This precision, as measured by standard deviation of the absorption peak location, is plotted for all measurement settings. While the variation decreases with increasing averaging as expected for both techniques, the standard deviation of the ASOPS results is nearly an order of magnitude higher than the corresponding ECOPS measurements, which have the same acquisition time. Caution should be taken not to interpret these values as the frequency resolution of the signals—which is determined by the signal length upon which the Fourier transform is applied—but rather as a measure of the repeatability of measurements. For example, if the extracted values of the resonance location are split between a relatively few numbers of close frequency bins, the calculated standard deviation can be smaller than the frequency resolution for that measurement setting.

V. FAST ACQUISITION DEMONSTRATION

Finally, we show the overall improvement of our PHASR Scanner 2.0 by demonstrating its scanning capabilities in situ. A video demonstrating a scanning time of approximately 8 s over a $27 \times 27$ mm$^2$ FOV with 1 mm pixel sizes, (i.e., a 729-pixel image) is presented in the supplemental materials. The scan was acquired at $f_M = 1000$ Hz, $\Delta f = \pm 32$ Hz, for a 2000 THz-TDS trace/s acquisition rate. The acrylic target with letters SBU (Stony Brook University) and peak-to-peak amplitude image of the scan is shown in Fig. 12(a) and (b), respectively. Each pixel represented the average of ten time-domain traces. To ensure that the pixels conform to a grid, each line of the scan consisted of an acceleration period, a constant speed section covering the FOV, and then a deceleration period and movement to the next line. The data were acquired during the constant speed section without pausing the beam steering for each pixel. The acceleration, deceleration, and line step periods added an additional overhead time of 154 ms/line or 4.0 s for an entire image, during which THz traces were not used.

A 1951 USAF resolution test target provides a demonstration case for the full FOV of the scanner. The area containing elements 4–6 of group-2 (line widths ranging from 1.41 to 1.12 mm) and the resulting THz peak-to-peak image are shown in Fig. 12(c) and (d), respectively. The circular area of the ECOPS image clearly shows the boundaries of the lens area.

VI. CONCLUSION

Our first effort at a portable handheld scanner, the PHASR Scanner 1.0, addressed many of the problems present in current applications of THz-TDS imaging but it also had clear limitations in FOV and scanning speed. Implementing a heliostat gimbal geometry drastically reduced the inherent distortion from the scanning system and improved the scanning range from $12 \times 19$ to $40 \times 27$ mm$^2$. This is combined with small modifications to the commercial ASOPS system, which allowed ECOPS operation of up to 2000 trace/s measurement rate. To implement this change, we used the existing ASOPS hardware, although specific attention is required to reduce signal drift and nonlinear time-axis sampling inherent to this upgrade. In particular, we used a state model to make real-time corrections.
to the time window and a polynomial time-axis calibration to an ASOPS measurement based on Fabry–Perot reflections for accurate time-axis scaling. The resulting polynomial fit can then be used for further measurements within that session or until the ECOPS modulation parameters are changed. We demonstrated the performance metric of the new ECOPS-based PHASR 2.0 Scanner. We show that we can use the ECOPS mode to take measurements with similar or better frequency-domain performance in significantly less time. These improvements make the PHASR Scanner 2.0 much more practical to use in scenarios, such as biomedical imaging, where scanning FOV and scanning speed significantly affect the patient experience. Our future work with the PHASR 2.0 scanner is intended to demonstrate its ability “in the field” for clinical and industrial applications. Results of these studies have already been implemented to extend the FOV and speed of our PHASR 1.0 Scanner for imaging large burns with 1” diameter in several preclinical in vivo studies [52], [53], [54]. Furthermore, recent results have demonstrated the value of polarization-sensitive THz measurement of biological samples [55], including skin [56]. This motivates successive designs that will develop our work on THz polarimetry [57] with the goal of providing fast, portable THz ellipsometry.

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