Analysis and mitigation of an oscillating background on hybrid complementary metal-oxide semiconductor (hCMOS) imaging sensors at the National Ignition Facility

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ABSTRACT
Nanosecond-gated hybrid complementary metal-oxide semiconductor imaging sensors are a powerful tool for temporally gated and spatially resolved measurements in high energy density science, including inertial confinement fusion, and in laser diagnostics. However, a significant oscillating background excited by photocurrent has been observed in image sequences during testing and in experiments at the National Ignition Facility (NIF). Characterization measurements and simulation results are used to explain the oscillations as the convolution of the pixel-level sensor response with a sensor-wide RLC circuit ringing. Data correction techniques are discussed for NIF diagnostics, and for diagnostics where these techniques cannot be used, a proof-of-principle image correction algorithm is presented.

I. INTRODUCTION
Nanosecond-gated hybrid complementary metal-oxide semiconductor (hCMOS) imaging sensors were developed at Sandia National Laboratories as part of the Ultrafast X-ray Imager (UXI) program. Current-generation (“Icarus”) hCMOS sensors have demonstrated minimum gate times of 1–2 ns with a 2 ns minimum interframe time, and next-generation (“Daedalus”) hCMOS sensors have been completed with nominal 1 ns minimum gate and 1 ns minimum interframe times. The fast timing of these sensors is relevant for the ps-to-ns timescales of features of interest in high energy density experiments, including inertial confinement fusion, and for time-gated laser diagnostics. The speed of these sensors, along with their ability to collect multiple frames of data along a single line of sight (SLOS) and be tuned to different energies of electrons, light, and x rays, has led to their incorporation in a variety of advanced diagnostics at the National Ignition Facility (NIF), the Z Machine, the Omega Laser Facility, and elsewhere.

While these sensors have been deployed with great success and continue to be incorporated into new diagnostics, they are affected by an anomalous ringing signal when exposed to an incident excitation before or during the active gate time—a phenomenon that has been termed “background oscillations.” These oscillations must be taken into account for accurate sensor characterization and can affect sensor performance in diagnostics on the NIF and elsewhere by creating a spatially and temporally varying background. The oscillations are proportional to the rate of change of the total sensor-wide photocurrent \((\frac{di}{dt})\), and the sensor background becomes significant relative to signal levels when more than \(\sim 10\%\) of the total sensor area is illuminated. This has been linked to inductance in the bonding wires that connect the hCMOS readout integrated circuit (ROIC) to the package electronics. The rapid change in photocurrent (large \(\frac{di}{dt}\)) inherent to the fast operation of
the sensors makes this difficult to address directly through the sensor electronics, although some progress has been made with design changes for the Daedalus sensors (see Sec. II D).

Prior results have shown that the oscillations are consistent and reproducible for a given sensor and that oscillations characterized in one experiment can be scaled and subtracted to correct subsequent tests; however, direct study of the oscillations has been limited. This work includes a more thorough characterization of the background oscillations and discusses preliminary methods for predicting and correcting these oscillations in diagnostic applications.

II. CHARACTERIZATION
A. Methods

Around 100–2 cm, ∼0.5 megapixel hCMOS sensors have now been characterized at Lawrence Livermore National Laboratory using a 40 ps pulsed Nd:YAG laser, typically frequency-doubled to 532 nm. Repeated measurements are taken for each sensor with an incrementally increased delay between the laser and the sensor trigger time, “stepping” through the sensor response curve or gate profile, with a usual step size of 100–200 ps. Different sensor integration times and interframe times (timing modes) can be tested (a timing mode such as 4-2 represents a 4 ns integration time with a 2 ns interframe time).

These experiments measure both the sensor response and the background oscillation induced by the photocurrent in the sensor. However, the masking part of the sensor from the laser pulse blocks the signal and allows the background oscillation itself to be measured directly.

By characterizing both the illuminated sensor response (gate profile and background oscillation) and the masked sensor response (oscillation only), the oscillation-corrected gate profile can be obtained. This has previously been performed using two separate

FIG. 1. Temporal illustration of the measured background oscillations for a 16-pixel region on the IV1-13-2AG04 Icarus hCMOS sensor. One analog-to-digital converter (ADC) count is ∼61 photodiode electron–hole pairs. (a)–(c) Test images at different times are shown (flat background subtracted). Nearly the full sensor was illuminated, leading to a large oscillation amplitude relative to signal levels. The region of interest (ROI) for the line plots is boxed. (d) Measurements for the pixel region show the gate profile response and an extraneous oscillation. The red crosses indicate the times for (a)–(c). (e) The measurement from the masked region illustrates the background oscillations alone. (f) After accounting for the relative sensor time skew between the two regions, the measurement in the region of interest can be corrected for the oscillations, leaving only the gate profile (dotted red line). (g) The inferred oscillation for the ROI varies from the top row oscillation by the relative shutter time skew (here, 260 ps) between the two regions.
sensor measurements, one with a region of interest masked and another with the region illuminated; the masked oscillation was scaled in amplitude and shifted in time to match the illuminated gate profile and could then be subtracted.\cite{13} We have additionally found that background oscillations are similar enough across the sensor that the oscillation from a small masked region can be similarly scaled and shifted to infer the oscillation for each pixel in the illuminated area on the same sensor, thus characterizing essentially the entire sensor in a single experiment (Fig. 1; see Sec. II B below).

These corrected gate profiles can be used to more accurately characterize pixel-level variations for each sensor, especially the variations in shutter timing known as time skew\cite{2,13} (Fig. 2), than is possible through the use of the raw gate profiles alone.

To measure the quantitative importance of the background oscillation for a given sensor, we use the following metric $\epsilon$:

$$
\epsilon = \frac{\int \langle |M(t)| \rangle \, dt}{\int \langle G(t) \rangle \, dt},
$$

where $M$ is the measured characterization oscillation for a fully illuminated sensor, $G$ is the corresponding measured gate profile, and the brackets represent averages over all sensor pixels. A typical value of $\epsilon$ for Icarus is about 1.5, but this varies somewhat from sensor to sensor.

### B. Oscillations are a sensor-wide phenomenon

Despite the spatial component of the background oscillations, we have observed that the oscillations are themselves a sensor-wide phenomenon. A transmission line model of the sensor supports this claim. To first order, the 2–3 $\mu$m wide aluminum grid sitting atop the silicon sensor substrate (typically either 8 or 25 $\mu$m thick) can be modeled as a microstrip transmission line, for which we calculated an effective relative permittivity $\epsilon_r$ of about 7, based on the materials and geometry of the device. The characteristic wavelength $\lambda$ of an electrical signal in this transmission line is given by

$$
\lambda = \frac{c}{f} = \frac{c}{v/\sqrt{\epsilon_r}},
$$

where $c$ is the speed of light, $v = c/\sqrt{\epsilon}$ is the speed of signal propagation, and $f$ is the signal frequency. Since typical oscillation frequencies are $\sim$150–250 MHz (see Sec. II C), this gives a characteristic wavelength on the order of 1/2 m (far greater than the $\sim$2 cm sensor dimensions), indicating that an oscillating electrical signal across the sensor should be mostly in phase spatially.

Experimentally, this observation is strengthened by noting the similarity of oscillations across the sensor. As discussed earlier and in Fig. 1, oscillations from one region of the sensor can be used to correct gate profiles elsewhere after accounting for the temporal skew between their locations. Additionally, a sensor-wide analysis illustrates that the spatial variation in the oscillations closely follows the contours of the time skew (Fig. 2).

Noting that the spatial variations in the oscillations are correlated with the pixel-level variations in the sensor response implies...
that the measured oscillation can be described as the convolution of the sensor gate response with a sensor-wide oscillatory electrical signal,

\[ M(t,x,y) = R(t,x,y) \ast \text{osc}(t), \]

where \( M \) is the measured sensor oscillation for these short-pulse characterization experiments, \( R \) is the sensor response at each pixel (measured with the corrected gate profile for a given frame and timing mode), and \( \text{osc} \) is the oscillation signal caused by the photocurrent-driven RLC ringing; \( x \) and \( y \) are the pixel spatial dimensions, and \( t \) is the time.

As a consequence of this, we expect to measure different background oscillations for different timing modes of the sensor, which effectively change the duration of the sensor response \( R \). Analysis of the background oscillations shows this to be the case, as shown in Fig. 3: different waveforms are measured for different timing modes, with distinct oscillatory features aligning oppositely in sign with the rising and falling edges of the gate, consistent with Eq. (3). The pseudo-sinusoidal oscillations for shorter timing modes, as highlighted in Fig. 1, can be understood as the interference of the rising and falling edge responses for gate profiles on the same timescale as those features.

C. Frequency analysis

Although oscillations are different for each sensor, the frequency content is usually similar: two main peaks are present, with a primary peak between about 150 and 250 MHz and a secondary peak between about 50 and 100 MHz (Fig. 4). The wire model simulation discussed in Sec. III highlights the ~200 MHz frequency as likely related to the RLC response of the photocurrent and sensor bond wires.

Equation (3) predicts that the RLC frequencies of the sensor should have a sinc-shaped envelope due to being convolved with a boxlike gate profile, with zeros at frequency intervals equal to 1000 MHz divided by the effective gate width in ns. These envelopes can be observed in Fig. 4, especially in plot (b).

D. Background oscillations on Daedalus sensors

The next generation of hCMOS sensors, Daedalus, has been completed and is undergoing preparatory testing for its planned
deployment in several diagnostics. As part of the Daedalus design process, packaging changes were made with the intent of mitigating the background oscillations, most notably a significant reduction of bond wire inductance. Preliminary data indicates that the Daedalus sensors have an oscillatory response reduced by about two-thirds compared with the Icarus sensors (Fig. 5), with an $\epsilon$ of about 0.5 [Eq. (1)]. Despite this considerable improvement, the oscillations are still non-negligible and will need to be accounted for in diagnostics using Daedalus sensors.

One feature of interest regarding oscillations on Daedalus is that the preliminary oscillation frequencies are noticeably higher due to this reduction in inductance: ~100 and ~330 MHz instead of ~50 and ~200 MHz. Additional electronics adjustments may be able to tune the oscillations further to even higher frequencies. If so, this suggests a potential technique for mitigating the background oscillations: if the background signal is described by Eq. (3) as the convolution of the circuit ringing response and the sensor response, oscillations tuned to have a shorter period than the gate integration time would be greatly reduced, as the gate profile would integrate over multiple oscillation periods. This technique may be explored in future hCMOS designs.

### III. OSCILLATION SIMULATION

The hCMOS sensor connects its ROIC to the outside circuit board by means of bonding wires. One side effect of these bond wires is a significant inductance which, in combination with the large photocurrent rate of change inherent in a fast photodiode sensor, results in a large induced voltage across the sensor and causes a ringing effect. As discussed earlier, this appears to be the primary cause of the background oscillations.

To further investigate this hypothesis, a wire model simulation was performed for the Icarus sensor. The simulation predicted a sensor-wide photocurrent-induced voltage oscillation in the capacitors used for measuring signals, which would be sampled by convolving the oscillation with the gate profile response. This simulated prediction agrees well with the experimental data, indicating that this is a reasonable physical explanation for the experimental results discussed earlier.

#### A. Wire model

The significance of wires and associated parasitic elements (resistance, capacitance, and inductance) increases for large die sensors. Therefore, it is crucial to consider them when trying to capture the sensor’s behavior at high speeds. To achieve this, we employed wire modeling, which encompassed the metal planes within the active area ($25.6 \times 12.8 \text{ mm}^2$) and the bond wire connections between the die and printed circuit board (PCB) substrate.

Each pixel was represented as a $25 \times 25 \mu m^2$ unit cell connected to its neighboring pixels through the ground and photodiode bias planes. The parasitic capacitance and resistances for each pixel were extracted using the Caliber and Cadence software design tools, which were then modeled as discrete components. Additionally, a single $25-\mu m$ thick photodiode was modeled with a 2.3 fF capacitor and a parallel current source, which represented the simulated junction capacitance and photocurrent. The bond wire inductances were calculated by counting and visually measuring each bond wire based on its physical properties. The junction capacitance, 1 k$\Omega$...
shutter resistance, and bond wire inductance dominated the RLC response for the Icarus model.

The bond wires are connected at the four corners of the hybridized photodiode array and ROIC. These bond wire lengths were estimated based on microscope images and distance measurements, multiplying the diameter distance by 1.5× to account for the wire’s loop height. The total bond wire inductance connecting the photodiode bias voltage and ground voltage to the photodiode array was 575 and 14 pH, respectively. For the Icarus model, we assumed that the equivalent serial inductance (ESL) in the decoupling capacitors and the PCB traces was negligible compared to the bond wires. However, in other PCB designs, additional sources of inductance should be considered in the modeling efforts. Conversely, newer PCB designs such as those for Daedalus need to minimize PCB inductance and account for the ESL performance of the decoupling at frequencies above 100 MHz.

A standard software package was used to perform the transient simulations; due to the model’s complexity, the simulation times were too long to feasibly tune the model values to match the experimental results. The raw simulation output provided voltage and current data for each pixel, which was parsed into a two-dimensional TIFF image file for analysis. This image file offers graphical and spatial insights into the potential appearance of an actual image read-off and can be easily analyzed using an image-viewing application.

The modeled electrical circuit represents the pixel in the integration state, effectively opening the electronic shutter and leaving it open indefinitely. This approach allowed us to extract the instantaneous current through each pixel’s sense capacitor at any given time. The signal was then convolved with different integration windows to synthesize various timing modes, enabling comparison with real-world data. However, it is important to note that the model did not simulate the reset voltage or when the electronic shutter was effectively closed. While the results closely align with observations, the simulations do not disprove alternative hypotheses.

To emulate the photodiode’s impulse response, the photocurrent was modeled as a triangle pulse, simplifying the representation of a Gaussian pulse. This simplification helped maintain a reasonable level of complexity and simulation time. The pulse has a Full-Width at Half-Maximum (FWHM) of 500 ps and a peak photocurrent of 10 mA, as shown in Fig. 6. The FWHM value is consistent with previous photodiode work documented elsewhere.\textsuperscript{14,15} The photocurrent source was connected to the center pixel, allowing us to observe the behavior of oscillations in the unilluminated pixels more clearly. Figure 6 shows the mean voltage oscillations on the high side of the storage capacitor for a collection of unilluminated pixels.

During the active photocurrent phase, the capacitor sense voltage goes negative due to inductance, as shown in the transient waveform in Fig. 6. This negative feature provides insight into the magnitude of the total inductance and the temporal response of the photodiode in real-world signals. The photocdiode response is faster than the oscillation frequency, with the photocurrent exciting the slower oscillations. (An 8-μm thick photodiode would have had a faster diode response than the 25-μm photodiode simulated, but the photocurrent-driven ringing behavior modeled would remain, as demonstrated in Fig. 3.) The higher oscillation frequency (here, 208 MHz) is determined by the total bond wire inductance and the pixel junction capacitances. These results are intuitively explained by considering the simplest LC circuit, composed of the junction capacitance for each pixel in parallel and the bond wire inductance in series. An expected frequency of ~190 MHz is then calculated. (The difference between this expected value and the 208 MHz result is primarily due to parasitic capacitance.)

Because the simulation time was not long enough to resolve the lower frequency adequately, the modeling effort was not able...
to explain the source of the \sim 50 \text{ MHz} frequency components seen in practice. This Icarus model explains why the reduced bond wire inductance of the Daedalus sensor package yielded an improvement in background oscillation amplitude (Sec. II D); a similar model based on the Daedalus package could highlight further areas of improvement.

IV. APPLICATION TO NIF DIAGNOSTICS

hCMOS sensors are particularly useful as part of the suite of diagnostics at the NIF and elsewhere, where they are used for high-speed gated imaging of x rays, laser beam profiles, and other sources of radiation. Background oscillations can significantly affect diagnostic data collected on these sensors when not corrected, so accounting for the oscillations in these settings is especially important.

A. Data analysis methods

Many hCMOS-based diagnostics naturally include a large unilluminated area where oscillations are incidentally measured on shot. Figure 7 illustrates this on a radiograph from the SLOS-CBI diagnostic at the NIF. Frame-by-frame oscillations are apparent, and the pixel-level variation due to the time skew can be seen.

While the total oscillation variation in these data is substantial (thousands of counts, comparable to the signal levels), this can be straightforwardly corrected from the oscillation sampled in the unilluminated regions. This is demonstrated in Fig. 7 by averaging rows above and below the data since the time skew (and thus the spatial oscillation variation) is primarily vertical. An interpolation along time skew contours could have further reduced the oscillation residuals. A similar procedure can be followed for pinhole cameras such as the GLEH diagnostic.

B. Characterization-based image correction algorithm

Some hCMOS-based diagnostics—especially those designed for gated x-ray diffraction—require the full sensor area for data collection. For these diagnostics, such as the Gated Diffraction Development Diagnostic and its successor, the Flexible Imaging Diffraction Diagnostic for Laser Experiments (FIDDLE), currently under development at the NIF, correcting for the background oscillations is a significant data processing issue since the method described earlier cannot be applied.

A characterization-based image correction algorithm may allow the oscillations to be predicted in this case. Equation (3) describes the measured oscillations from the characterization experiments as composed of a photocurrent-induced waveform convolved with the sensor response. The characterized waveform is the response to a short (~40 ps) laser pulse, effectively an impulse compared with the photodiode response (>500 ps). The photocurrent-induced background oscillation for a NIF experiment can thus be predicted by convolving the illumination source (x rays or electrons) incident on the sensor with the impulse oscillation and sensor response, both of which are sampled in the characterization test for the sensor and timing mode used.

In this way, if the illumination source profile is known or can be well estimated, the corresponding oscillation can be predicted. By accounting for the time skew between pixels, this prediction can be extended to the full pixel array. Mathematically, the modeled response $f$ for a given diagnostic on a given NIF shot is given by

$$ f(t, x, y) = \Phi(t) \ast (R(t, x, y) \ast osc(t)) $$

$$ = \Phi(t) \ast M(t, x, y), $$

where the convolution is understood. Figure 7 shows the radiographic data and background oscillations recorded on SLOS, the Single Line-of-Sight camera, on the N200712 NIF shot. Background counts varied frame-to-frame by several thousand counts, comparable to the signal levels. Lineouts of the background taken at row 200 and row 600 (20-row averages), illustrating the spatial variation. The mean of those two lineouts is also shown, estimating the oscillation at row 400, where data were collected. (c) Lineouts of the data at row 400 with a constant value subtracted (black) and with the oscillation prediction from (b) subtracted (red). Accounting for the oscillations is essential for quantitative measurements.

FIG. 7. (a) Radiographic data and background oscillations recorded on SLOS, the Single Line-of-Sight camera, on the N200712 NIF shot. Background counts varied frame-to-frame by several thousand counts, comparable to the signal levels. (b) Lineouts of the background taken at row 200 and row 600 (20-row averages), illustrating the spatial variation. The mean of those two lineouts is also shown, estimating the oscillation at row 400, where data were collected. (c) Lineouts of the data at row 400 with a constant value subtracted (black) and with the oscillation prediction from (b) subtracted (red). Accounting for the oscillations is essential for quantitative measurements.
where $\Phi$ is the flux received by the sensor through the filter setup of the diagnostic, and $M, R,$ and osc are the measured impulse responses described in Eq. (3).

Figure 8 illustrates a proof-of-principle test of this algorithm applied to the GLEH diagnostic, where it can be compared with measurements in the unilluminated regions. This is performed for three NIF shots. Data points of the oscillation through time are collected by mapping unilluminated pixel measurements in accordance with their local time skew and the camera trigger times, effectively measuring $f(t, x, y)$ for those pixels. The source illumination profile $[\phi(t)]$ for the GLEH camera was estimated using the time-resolved x-ray spectra from the Dante diagnostic\(^{17}\) and accounting for the imaging setup (pinhole sizes and filters) used in GLEH. $M(t, x, y)$ was measured using the setup from Sec. II A for the sensor used in the GLEH imager. In general, this technique gives reasonable agreement with measurements, although some discrepancies remain. In practice, the 2D oscillation predictions for times when the camera was triggered would be generated using the 1D prediction shown in Fig. 8 and accounting for the trigger times and sensor time skew, and could potentially be used to correct for the oscillations seen on NIF shot images.

The prediction, as shown in Fig. 8, includes several limitations. First, there is considerable uncertainty in the characterized photodiode responses for the hCMOS sensors fielded in GLEH; those sensors were tested before the oscillation problem was fully understood, so their oscillation characterization measurements are noisy and clipped. Additionally, due to this limited data, the oscillation for all frames was predicted using the Frame 3 oscillation (the most complete), even though slight frame-to-frame differences are known to exist. Second, there is a discrepancy between measurements on Dante and GLEH: predictions of GLEH pinhole measurements using the Dante spectra and GLEH filters significantly underpredict the corresponding measurements. This discrepancy requires further investigation; our most plausible explanation is the different diagnostic lines of sight to the hohlraum (143° for Dante compared with 161° for GLEH). To account for these and other factors not included in this proof-of-principle result, the prediction was scaled in amplitude to match the data. The prediction was also adjusted slightly in time to account for relative jitter or timing drift between Dante and GLEH (the hCMOS sensors in GLEH can reach temperatures above 80°C, where important thermal drift can occur, which was not accounted for here). Ideally, with a more accurate diagnostic source profile, better characterization data, and precise diagnostic timing, these factors would not be necessary.

Because of the limitations described earlier, work is ongoing to make this procedure more accurate and predictive. However, the reasonable agreement between prediction and measurements in Fig. 8 indicates that this is a promising method for removing oscillations from x-ray diffraction measurements. The hCMOS sensors for the new FIDDLE diagnostic are much better characterized than those used in GLEH; if the x-ray backlighter used can be well understood, this algorithm could yield useful results.

V. CONCLUSION

Hybrid-CMOS sensors are a transformational diagnostic tool with many current and future applications at the NIF and other high-energy-density experimental platforms. While background oscillations pose a significant challenge to these sensors, they are consistent, characterizable, and often correctable through data processing and computational means. A proof-of-concept algorithm for these corrections has been presented. While future hCMOS designs (including the Daedalus sensors currently being tested) will have reduced background oscillations from the Icarus version currently
fielded, they are unlikely to be eliminated due to the large photocurrent rate of change inherent in a fast photodiode, making this an important consideration for hCMOS diagnostic design and data analysis.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

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M. S. Dayton: Conceptualization (equal); Methodology (equal); Software (equal); Writing – original draft (equal); Writing – review & editing (equal).
C. Trosaile: Conceptualization (equal); Investigation (equal); Methodology (equal); Supervision (equal).
L. R. Benedetti: Conceptualization (equal); Investigation (supporting); Validation (equal).
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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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