A forward bias method for lag correction of an a-Si flat panel detector

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Purpose: Digital a-Si flat panel (FP) x-ray detectors can exhibit detector lag, or residual signal, of several percent that can cause ghosting in projection images or severe shading artifacts, known as the radar artifact, in cone-beam computed tomography (CBCT) reconstructions. A major contributor to detector lag is believed to be defect states, or traps, in the a-Si layer of the FP. Software methods to characterize and correct for the detector lag exist, but they may make assumptions such as system linearity and time invariance, which may not be true. The purpose of this work is to investigate a new hardware based method to reduce lag in an a-Si FP and to evaluate its effectiveness at removing shading artifacts in CBCT reconstructions. The feasibility of a novel, partially hardware based solution is also examined.

Methods: The proposed hardware solution for lag reduction requires only a minor change to the FP. For pulsed irradiation, the proposed method inserts a new operation step between the readout and data collection stages. During this new stage the photodiode is operated in a forward bias mode, which fills the defect states with charge. A Varian 4030CB panel was modified to allow for operation in the forward bias mode. The contrast of residual lag ghosts was measured for lag frames 2 and 100 after irradiation ceased for standard and forward bias modes. Detector step response, lag, SNR, modulation transfer function (MTF), and detective quantum efficiency (DQE) measurements were made with standard and forward bias firmware. CBCT data of pelvic and head phantoms were also collected.

Results: Overall, the 2nd and 100th detector lag frame residual signals were reduced 70%–88% using the new method. SNR, MTF, and DQE measurements show a small decrease in collected signal and a small increase in noise. The forward bias hardware successfully reduced the radar artifact in the CBCT reconstruction of the pelvic and head phantoms by 48%–81%.

Conclusions: Overall, the forward bias method has been found to greatly reduce detector lag ghosts in projection data and the radar artifact in CBCT reconstructions. The method is limited to improvements of the a-Si photodiode response only. A future hybrid mode may overcome any limitations of this method. © 2012 American Association of Physicists in Medicine. [DOI: 10.1118/1.3664004]

Key words: x-ray detector, flat-panel, lag, after-glow

I. INTRODUCTION

It has been shown that amorphous silicon (a-Si) flat panel (FP) detectors can exhibit lag that affects projection images in fluoroscopy and cone-beam CT (CBCT) reconstructions.^{1–7} Detector lag is defined as signal present in frames following the frame in which it was generated. In fluoroscopy, lag causes temporal blurring. For a-Si panels designed to be used for mixed radiography and fluoroscopy applications, lag can cause severe ghosting of the high dose radiography image during low dose fluoroscopy.^{1,2,7} In CBCT reconstructions, detector lag can lead to streaking, blurring, and severe shading known as the radar artifact.^{2–5,7}

The radar artifact present in CBCT reconstructions using a-Si FPs is a circular artifact centered on the axis of rotation. The artifact radius is object dependent and is dictated by the

largest circle that can fit within the object. The artifact is generated from detector pixels that experienced different irradiation histories. Detector element positions that always fell within the object's x-ray shadow have a very different detector lag pattern from detector elements that transition from full x-ray intensity to object shadow. Figure 1 shows an example of the radar artifact seen for a CBCT scan and reconstruction of a 30 × 22 cm pelvic phantom. The difference between the two indicated ROIs, which should be zero for the reconstruction, is 20 HU.

The main source of detector lag in FP x-ray detectors is charge trapping in the a-Si.^{2,7,8} Defect states, known as charge traps, fill with charge during photodiode illumination and then release the charge during later detector frames. Lag artifacts, especially in CBCT images, arise from differences in the trapping history of different pixels in the FP.⁷

FIG. 1. $1 \times 1 \times 5$ mm reconstruction of a pelvic phantom ($30 \text{ cm} \times 22 \text{ cm}$) at 10 fps, offset detector geometry, and x-ray tube settings of 125 kVp, 80 mA, and 15 ms with the FP in dynamic gain mode. The difference between the two ROIs is 35 HU. Window, Center = 200, 0 HU.

There are several software methods that model and correct lag in a-Si FPs. Most determine a temporal impulse response and then deconvolve it from the raw detector data to remove the lag portion of the signal.^{1,4,9} However, using an impulse response assumes a linear, time-invariant (LTI) system and previous work has found that the measured impulse response is highly sensitive to the measurement technique.⁷ Furthermore, even in the best case scenario, residual error still exists in the LTI CBCT reconstructions.

Several hardware approaches also exist to remove lag from an a-Si FP detector. One approach is to insert empty frames (x-ray source turned off) between acquired x-ray frames to flush the lag signal out of the detector during acquisition.³ While much of the lag signal is removed this way because it decays exponentially, the introduction of empty frames increases scan time for CBCT. Furthermore, charge trapped at deeper energy levels in the band gap will not have emptied and may still contribute to the detector output. Alternatively, another method uses LEDs to illuminate the a-Si and saturate the traps between detector readout and x-ray illumination.⁷ With this approach, lag is actually increased in the panel, but is made into a completely uniform offset. In addition, any lag due from the scintillator remains unaffected.

A similar hardware-based trap saturation approach that operates the photodiodes in a forward bias mode has been introduced.^{10,11} For a standard imaging mode for the Varian 4030CB detector, the a-Si photodiode is placed in a reverse bias mode and then disconnected via a thin-film transistor (TFT) from the readout circuitry prior to illumination, which is shown in Fig. 2(a). When illumination ends, the photodiode is reset to the reverse bias state by the readout electronics. For the new trap saturation method, known as the forward bias (FB) method, a positive voltage is briefly applied across each photodiode, thus inducing a much larger than normal current through the diode. This circuit state is shown in the schematic in Fig. 2(b). The larger current has the effect of uniformly filling all charge traps in the photodiodes across the spatial extent of the detector. After the

FIG. 2. Circuit diagram of pixel with forward bias modification. (a) The pixel in reverse bias, disconnected from the readout electronics during the illumination stage. (b) The pixel in the forward bias stage where a large current is pushed through the photodiode.

forward bias scan, the photodiode is reset to the reverse bias state and photodiode illumination can occur.

This work explores the lag ghost and CT artifact reduction capabilities of the FB method and compares it to a standard imaging mode. Limitations of the FB method are discussed, as well as the feasibility of a hybrid lag reduction method that uses the FB method in conjunction with a software correction. Such a hybrid mode may mitigate the limitations of the FB method.

The paper is organized as follows. Section II describes the experiments done on a Varian 4030CB detector modified to run either the FB or standard imaging firmware. Experiments to measure the lag reduction effectiveness are also described, as well as typical detector measurements such as SNR, modulation transfer function (MTF), and detective quantum efficiency (DQE). Finally, the idea of a hybrid software–hardware mode is introduced. Section III presents the results of those experiments, and Sec. IV discusses those results and future work that can be done to further improve the FB method.

II. METHODS AND MATERIALS

A Varian 4030CB flat panel x-ray detector was modified to operate in the FB mode as part of a table-top x-ray system.^{10,11} The modified detector was able to operate in the 0.5 and 4 pF fixed-gain modes (with analog gain = 1) as well as standard imaging modes with a 2×2 pixel binning.¹² All experiments were conducted at either at 15 or 10 fps to achieve sufficient SNR. For pulsed fluoroscopy, the FB firmware has a maximum pulse width of 18 ms for a frame rate of 15 fps and 32 ms (the x-ray generator maximum) for 10 fps. For most experiments, the forward bias parameters were set to achieve a charge per pixel that was more than sufficient for adequate lag removal.

The 0.5 and 4 pF FB modes are nearly identical, with the main difference being the size of the integration capacitors. Select lag removal measurements are shown for one or the other mode as evidence that the FB works for both, and the FP SNR, MTF, and DQE are presented for both. For the CBCT experiments, only the 4 pF mode could be used since the large x-ray exposures needed to penetrate the phantoms would have saturated the 0.5 pF mode. Eventually, a CBCT

Hybrid Method

FIG. 3. Timing diagram of the hybrid method combining the forward bias mode with standard mode.

imaging mode that combines the 0.5 and 4 pF FB modes into a dual or dynamic gain FB mode would be desirable from a noise and dynamic range perspective.

II.A. Lag removal measurements

The rising step-response function (RSRF) is defined as the system response to the application of a constant input. Similarly, the falling step-response function (FSRF) is defined as the system response to the removal of a constant input. The RSRF and FSRF for the Varian 4030CB FP were first measured under visible light illumination for 0.5 pF standard and FB modes. The CsI scintillator in the FP is transparent to light, which allows for direct photodiode illumination with the detector cover removed. The RSRF measurements were made by illuminating the detector for 256 frames followed by 256 frames of FSRF measurements. A 2D array of LEDs under computer control and synchronized to the detector readout at 10 fps was used for illumination. Several different FB protocols were chosen that injected varying amounts of charge into each photodiode between every frame to determine the overall effectiveness of the forward bias technique as a function of injected charge.

Step response tests were also performed under x-ray irradiation at a fixed FB protocol of 20 pC/diode for the 4 pF detector modes for both the FB setup and standard modes. For these tests, the RSRF and FSRF were each measured for 600 frames. For further comparison, a piece of CsI scintillator coupled to a crystalline silicon photodiode was irradiated in a similar setup. The crystalline silicon photodiode should have no charge traps, and thus no lag signal of its own. The measured response is therefore that of the scintillator alone. All of the data were normalized to the average of the last 10 frames of the measured RSRF.

A step-wedge phantom was used to measure the ability of the FB method to visually reduce lag ghosts in the a-Si FP. Following 500 frames of irradiation, 500 frames of the FSRF were collected for a standard dual gain imaging mode and a low gain (4 pF) FB mode. The x-ray protocol was 100 kVp, 30 mA, and 13 ms at 15 fps. The resulting ghost contrast of the step-wedge phantom was measured for lag frames shortly following the end of x-ray exposure, and for 100 frames after. The first lag frame is defined as the first frame with no irradiation from the x-ray tube. The contrast was measured

as the mean signal level difference between the darkest and brightest part of the phantom.

The FB method was further compared to a lag suppression method that uses N empty frames to flush the lag signal from the detector referred to here as flush- N .³ During the empty frames, no x-rays are produced by the system, and any data collected by the detector is purely a detector lag signal. Assuming the detector is always operated at the highest frame rate possible, acquiring the same number of projections as in a standard mode requires scans that are a factor of $(N + 1)$ times longer. For comparison purposes, the $N = 1$ flush method was simulated by fitting an impulse response to the detector FSRF in standard mode.⁷ The impulse response for the flush-1 method is found by resampling the standard impulse response and keeping only the even samples. Then, the equivalent step-response for the flush-1 method where only every other frame has x-rays can be used to compare against the standard mode and FB mode at an identical exposure.

A multiexponential impulse response of the FP can be written as

$$h(k) = b_0\delta(k) + \sum_{m=1}^M b_m e^{-a_m k}, \quad (1)$$

where k is the discrete x-ray frame number, M is the number of exponential terms in the impulse response, typically between two and four,^{4,7,9} and $\delta(k)$ is the impulse function of magnitude 1.0. The term containing the impulse function represents the portion of the input signal that is unaffected by lag. Given $h(k)$, the actual FP output is,

$$y(k) = x(k) * h(k). \quad (2)$$

The output of the FP is $y(k)$, which includes the effects of lag, and the signal input prior to the effects of lag is $x(k)$.

The impulse response for the flush-1 method can be written as the even numbered samples of $h(k)$, or

FIG. 4. Using a pulsed light source synchronized with the detector at 10 fps, measured RSRF and FSRF data are plotted vs charge injected into the photodiodes for 0.5 pF standard and FB modes. The improvement in the measured RSRF and FSRF correlates well with the amount of charge injected. For 5.8 and 15.4 pC/diode, reductions in first frame lag of 93% and 95% are achieved, respectively.

FIG. 5. X-ray measurements of the (a) RSRF and (b) FSRF for the 4 pF FB mode, standard mode, and a silicon photodiode with CsI scintillator. The RSRF is not fully corrected because it is limited by the temporal response of the scintillator, which is measured with a crystalline silicon photodiode. The asymmetry of the scintillator response is quite evident in the FSRF measurement since it looks near ideal for the FB mode.

$$h_{flush-1}(k) = b_0\delta(k) + \sum_{m=1}^M b_m e^{-2a_m k}. \quad (3)$$

Here, the frame number k is interpreted slightly different than before. The frame index counts only those frames meant to be nonempty. The equivalent FSRF of such a system can be written as

$$s_{flush-1}(k) = \sum_{m=1}^M \frac{b_m}{1 - e^{-2a_m}} e^{-2a_m k}. \quad (4)$$

II.B. SNR, MTF, and DQE

For measuring SNR, the MTF, and the DQE, an RQA5 spectrum was used.¹³ For the x-ray source used for these

measurements, the RQA5 calibration corresponds to an x-ray tube setting of 71 kVp and 21 mm of additional Al filtration. X-ray exposures were measured with an Invision ion chamber.

For the SNR measurements, the noise level was calculated as the standard deviation of large ROIs in flat field images, and the signal was calculated as the average. Gain corrections for the detector modes were performed prior to the experiments and whenever detector modes were switched, and offset corrections were performed prior to each acquisition.

For the MTF and DQE measurements, mAs settings for the x-ray source were chosen that resulted in signals above the electronic noise level of the detector and whose SNR was x-ray quantum limited. For the 0.5 and 4 pF detector

FIG. 6. Projection images of a step-wedge phantom. For a standard dual gain imaging mode, images taken at (a) frame 0 (last irradiation frame) (window, level = 27 000, 13 500 counts), (b) lag frame 2 (window, level = 400, 180 counts) with contrast = 355, (c) and lag frame 100 (window, level = 50, 25 counts) with contrast = 44. For the FB mode, (d) frame 0, (e) lag frame 2 with contrast = 42, and (f) lag frame 100 with contrast = 13. The FB images have been scaled to match the dynamic range of the dual gain images and have the same window and level.

FIG. 7. Comparing the FSRFs from the FP in standard mode, simulated flush-1 mode, and FB mode.

modes, exposures of 523 and 1383 nG/frame were used to achieve this. A tungsten edge was used to calculate the pre-sampling MTF of the a-Si FP in forward bias and standard imaging modes. The MTF was measured in the both the horizontal and vertical directions. The noise power spectrum (NPS) and DQE were also measured for the different modes, according to the method described in the IEC standard.¹³

II.C. Detector mode switching

Saturating the charge traps in a-Si photodiodes, either by light illumination or forward biasing, may limit the detector performance. First, charge trap saturation creates larger offset currents inside the detector, which may increase the dark noise of the system. Second, it takes some length of time during each detector frame to apply the FB current for trap saturation. Thus, either the x-ray frame time needs to be lengthened, and/or the time available for x-ray exposure within the frame needs to be shortened. For the modified FB panel the time needed to supply the trap saturating current is further lengthened because the current source and sink specifications of the charge amplifiers limit the ability to forward bias every pixel at the same time.

One approach to mitigate these limitations would be to create a hybrid method as depicted in Fig. 3. In this method, the photodiodes are forward biased every frame prior to the x-ray exposure. When the x-ray exposure is initiated, the frame timing reverts to a standard mode and a short delay of several frames (N_{delay}) follows to allow the detector to adjust to the new frame timing. The x-ray tube and generator would have to be synchronized with the detector to take into account the number of delay frames. After the delay frames, $N_{\text{acquisition}}$ frames with standard timing collect the x-ray exposure until it has ended, at which point the detector reverts back to a forward bias mode.

Our experience has been that switching the detector timing characteristics (i.e., switching from a FB timing to a standard timing) results in large detector offset drifts for many frames following the mode switch. These offset currents may still be smaller than those created by forward

TABLE I. Signal and noise values for 0.5 pF detector modes.

Exposure nG/frame	Standard			FB			Comparison SNR% Difference
	Signal	Noise	SNR	Signal	Noise	SNR	
146	895	24.5	36.6	875	25.7	34.1	-6.9
290	1792	34.4	52.1	1729	35.3	49.0	-5.9
523	3252	46.2	70.3	3133	47.2	66.4	-5.7
830	5161	58.7	87.9	4963	59.3	83.7	-4.8
1085	6756	67.2	100.5	6481	67.4	96.1	-4.3

biasing the photodiode. Software lag corrections^{4,7} could then be used to remove any residual lag that occurs during x-ray irradiation.

An advantage of this switching approach over a software-only correction is that if some of the charge traps remain saturated from the FB stage, a followup software method would have to characterize and correct for a smaller residual detector lag. That smaller signal might be better corrected by current LTI methods, since linear approximations to nonlinear systems work better for smaller deviations around an operating point. Current software-only methods are still prone to residual error after correction.^{4,7} A second advantage of the hybrid approach is that the FP detector would be placed into a known trap state prior to x-ray exposure, essentially erasing any potential effects from previous exposures.

To determine the feasibility of such a detector mode, the detector output for several hundred frames was captured after switching from a 4 pF FB mode to a standard 4 pF detector mode. The experiment was repeated three times for different periods of time (10 and 60 s) spent in the FB mode. Note, this experiment used no irradiation on the detector since only offset currents were of interest.

II.D. CBCT reconstructions

CBCT data sets of two different phantoms were acquired: a pelvic phantom (30 cm × 26 cm) and a uniform acrylic

FIG. 8. SNR measurements taken at several exposures for both 0.5 and 4 pF FB and standard modes. The SNRs are close (within 7%) for the FB and standard modes, but the FB mode is always less than the standard mode for low and high gain.

FIG. 9. Vertical and horizontal MTF data taken for the a-Si FP in standard and FB modes for (a) 0.5 pF modes and (b) 4 pF modes.

head phantom (20 cm $\times$ 16 cm). Each phantom was scanned in three different detector modes: (1) a standard dynamic gain mode, (2) a standard low gain (4 pF integration capacitor) mode, and (3) a low gain mode with forward biasing. In each mode the pixels were binned 2×2 , giving a detector resolution of 0.388 mm. The detector was operated in each mode at 10 fps for 625 projections. The tube protocols were chosen to give high SNR. For the pelvic phantom, a pulsed fluoroscopy protocol of 125 kVp, 80 mA, and 30 ms was used in an offset detector geometry (16 cm offset). For the uniform acrylic head phantom, a tube protocol of 125 kVp, 63 mA, and 20 ms was used. For all setups a 10:1 antiscatter grid, an 8:1 Al bowtie filter, and 1.0 mm Ti plus 0.25 mm Cu filter were used. The x-ray beam was also collimated to 2 cm in the cone beam direction at the detector for data acquisition to minimize any scatter effects. Appropriately sized normalization phantoms were used for all data sets, which further reduced the effects of beam hardening and scatter.¹⁴ Filtered backprojection was used to reconstruct the data sets at a reconstruction pixel size of 1 mm² for the pelvic phantom

and 0.5 mm² for the head phantom. The slices were averaged to a thickness of 5.0 mm to reduce noise.

A pair of ROIs, 10 pixels on each side, which straddles the obvious lag artifact boundary in the dynamic gain reconstructions was defined. The radar artifact error is defined as the difference in mean signal between the two ROIs.

III. RESULTS

III.A. Lag removal measurements

Measured RSRF and FSRF data taken with visible light irradiation are shown in Fig. 4 for different amounts of charge injected into the photodiodes during the forward bias cycle. For increasing amounts of charge, the measured responses approach the ideal step-response. At 5.8 pC/diode, a lag reduction of 93% is achieved for the first frame lag. Almost tripling the injected charge to 15.4 pC/diode gives a 95% reduction in first frame lag. Little improvement is seen for greater amounts of charge injected. For the remainder of this work, the FB protocol was set to 20 pC/photodiode, which is above the amount necessary for 95% first frame lag removal and a convenient value for the hardware implementation. Specifically, groups of eight detector rows were simultaneously forward biased with 4 V at a 100 kHz rate. Any excess charge has a minimal effect on the pixel dynamic range because most of the leaked charge is removed via extra reset cycles and analog charge subtraction prior to A/D conversion.

Figure 5 shows measured RSRF and FSRF data under x-ray irradiation with an FB charge injection of 20 pC/diode for 4 pF modes. The x-ray FSRF data in Fig. 5(b) is very similar to the FSRF under light illumination in Fig. 4. However, the RSRF response in Fig. 5(a) looks different than the RSRF with light. While the x-ray RSRF with FB shows improvement over the standard x-ray RSRF, it is still less than the ideal response. This is due to the temporal limitations of the CsI scintillator. Also shown in Fig. 5(a) is the RSRF measurement for a crystalline silicon photodiode with a detachable piece of CsI scintillator. The crystalline silicon photodiode should have a near ideal response since it has no charge traps and subsequently no lag. However, an exponential rise of around 0.7% over 600 frames is still seen in the

FIG. 10. DQE measurements for the FB and standard modes for the a-Si FP using 0.5 and 4 pF integration capacitors. Some variation is observed among the standard modes and FB modes. Both standard modes have slightly higher DQE values than both FB modes. A DQE decrease for the FB modes is expected because of the noise increase and signal decrease of the FB modes.

FIG. 11. Timing diagrams for (a) standard and (b) forward bias imaging modes.

crystalline silicon RSRF, which represents the response of the CsI scintillator.

Figure 6 shows the persistence of lag ghosts for a standard dual gain imaging mode and the low gain FB mode. Figures 6(a) and 6(d) show images of the phantom during irradiation for both methods. Lag frames 2 and 100 are also shown in Figs. 6(b) and 6(c) and Figs. 6(e) and 6(f). A large reduction in the ghost contrast is seen for the FB method over the standard dual gain mode. The contrast is 355 and 44 detector counts for the standard mode lag frames. The contrasts for those two lag frames are reduced to 42 and 13 detector counts (88% and 70% reduction) for the FB method. Note, the 100th lag frame for the FB method is noisier than its standard mode counterpart because the FB mode is using a low gain (4 pF) integration capacitor. In this mode x-ray photons produce a smaller signal than in high gain modes, which translates into a higher dynamic range and a higher quantum-limited exposure for the low gain mode. The non-forward biased dual gain mode uses a smaller (0.5 pF) integration capacitor which results in a higher SNR for low exposures.

Figure 7 compares the measured FSRF of the FP in a standard mode, the simulated FSRF of the FP using a flush-1 mode, and the measured FSRF for the FB method. All measurements and simulations were based on an x-ray protocol of 125 kVp, 10 mA, and 22 ms that gave a detector signal of 26% of saturation. Clearly, the flush-1 method greatly reduces the residual lag seen in the FSRF, but still almost half of the lag signal remains. Furthermore, the frame rate has been reduced by a factor of two to accommodate the empty frame between every collected signal frame. Further improvement in the FSRF could be achieved with the flush

method by including more empty frames, but greater reductions in frame rate would be necessary.

III.B. SNR, MTF, and DQE

Table I lists the signal, noise, and SNR data for the a-Si FP in standard and FB 0.5 pF modes. The FB firmware gives both higher noise and reduced signal as compared with the standard mode, leading to SNR reductions of up to 7% in magnitude, which decrease with increasing exposure. The noise was also measured with no exposure as an estimate of the electronic noise for the 0.5 pF modes. For the standard mode it was measured as 4.4 and for the FB mode it was measured as 7.4. However, it is unclear whether this fully explains the increase in overall noise in Table I for each exposure. Further investigation of the noise properties of the FB mode will be the subject of future work.

Figure 8 shows SNR measurements taken at several exposures for both high and low gain modes. For each gain mode, the FB method and a standard mode are compared. The straight line on the graph is a fit to the highest exposure data points of a square root input exposure relationship. The line indicates what the data should look like in a quantum noise, or photon, limited case. The high gain (0.5 pF) data appears to be quantum limited for all collected exposures, but the low gain (4 pF) data dips below the quantum exposure line for the lowest three collected exposures. Overall, the SNRs are close (within 7%) for the different modes, but the standard mode always has a higher SNR than the corresponding FB mode.

The standard firmware and FB MTFs (horizontal and vertical) for the 0.5 pF integration capacitor [Fig. 9(a)] and the

FIG. 12. (a) Detector output after switching from a 4 pF FB mode to a 4 pF standard imaging mode. Three data sets were collected for both 10 and 60 s in a FB mode. (b) Maximum and mean differences between the six data acquisitions (on a per frame basis).

FIG. 13. $1 \times 1 \times 5$ mm reconstructions of a pelvic phantom ($30 \text{ cm} \times 22 \text{ cm}$) at 10 fps, offset detector geometry, and x-ray tube settings of 125 kVp, 80 mA, and 15 ms. (a) Dynamic gain and (b) low gain (4 pF) reconstructions using a standard, nonforward bias mode. (c) Reconstruction using a forward bias, low gain mode (4 pF). Window, Center = 250, 0 HU. $0.5 \times 0.5 \times 5$ mm reconstructions of an acrylic head phantom ($20 \text{ cm} \times 16 \text{ cm}$) at a tube technique of 125 kVp, 63 mA, and 20 ms are shown for (d) dynamic gain, (e) low gain, and (f) low gain forward bias detector modes. Window, Center = 100, 0 HU.

4 pF integration capacitor [Fig. 9(b)] are nearly identical. A small drop-off near the low frequencies seen in all of the MTFs is due to low frequency scatter in the detector cover and scintillator.

Figure 10 shows DQE measurements for the FB and standard modes for the a-Si FP panel using 0.5 and 4 pF integration capacitors in a 2×2 binning mode. While there is some variability in the measured DQE for the two standard modes (and the same is true for the two FB modes), both FB modes have a smaller DQE than both standard modes. The DQEs for the standard modes were both corrected for lag according to the IEC standard,^{13,15} so their larger DQEs are not due to larger detector lag. Finally, the clinically relevant 1×1 binning mode for fluoroscopy and radiography should give identical DQEs for exposures high enough to ensure that the detector output is x-ray quanta limited.

One explanation for the downward shift in DQE for FB modes is the increase in measured noise and a decrease in the measured signal. The smaller signal is due to charge traps with time constants of just a few milliseconds, which release their charge in between readout and the final FB pixel reset. Figure 11(a) shows an abstract timing diagram for a standard detector mode and Fig. 11(b) shows a timing diagram for a FB mode. There is approximately 30 ms between the end of the readout stage and the end of the last reset stage for the FB mode. Any trapped charge that is released during that time period is removed by the reset process, regardless of whether it originated from the FB current or photon generated charge. The result is that the FB mode will collect a smaller signal than the standard mode, where the short-term lag signal would have been collected in the next frame. In a sense, this is signal that exists at the very boundary of what one would call either true signal or lag signal.

III.C. Detector mode switching

Figure 12 shows the repeatability results of switching from a FB mode to a standard imaging mode on the a-Si FP

in a 4 pF mode. Figure 12(a) plots the detector output in A/D counts for three experiments at 10 s and three more at 60 s. Overall, the FB mode-switching is highly repeatable for the FB times measured [Fig. 12(a)]. Figure 12(b) shows the average and maximum errors between each of the experiments, with the average difference quickly falling to below 1 A/D count after 38 frames. For the 10 and 60 s data analyzed separately, the average differences fall to below 1 A/D count even faster (after 7 and 14 frames for the 10 and 60 s data, respectively). In the current setup it was not possible to measure shorter FB times, but it is expected that the results would also be highly repeatable. Furthermore, the output signals decay away quickly to values below 100 counts within 100 frames, so no significant decrease in the detector dynamic range is expected.

III.D. CBCT reconstructions

The radar artifact due to lag is quite visible in dynamic gain CBCT reconstructions of pelvic [Fig. 13(a)] and head [Fig. 13(d)] phantoms. In Fig. 13(a), the radar artifact error is 35 HU, and for Fig. 13(d), the error is 20 HU. The ROIs where the errors are calculated are indicated as white rectangles. Previously, the same acrylic head phantom was measured to have an artifact of 24 HU in dynamic gain mode⁷ at a frame rate of 15 fps. The longer frame time at 10 fps reduces the lag artifact away from the object boundary. Figures 13(b) and 13(e) are similar reconstructions, but use low gain data only. Because of the higher noise, the radar artifact is visually less noticeable, but similar in measured magnitude. The radar artifact error for Fig. 13(b) is 36 HU, and for Fig. 13(e) is 23 HU. Figures 13(c) and 13(f) show the reconstructions from a low gain FB mode. The radar artifact is visibly reduced in the FB mode for the pelvic phantom when compared to the standard modes. While the error is also reduced in the head phantom, it is less visible simply because the uncorrected error starts off much smaller. For Fig. 13(c), the radar artifact error is 7 HU, an artifact

reduction of 81%, and for Fig. 13(f) the error is 12 HU, which represents a 48% error reduction.

IV. DISCUSSION AND CONCLUSIONS

Overall, the forward bias method shows promise in removing lag from a-Si FPs, reducing the contrast of lag ghosts, and removing the radar artifact from CBCT reconstructions. The contrast of lag ghosts was reduced by 70%–88%, and shading artifacts in CBCT reconstructions were reduced by 48%–81%. The electronic noise levels for the FB method in fluoroscopy and low gain CBCT reconstructions can be improved by combining the already implemented 0.5 and 4 pF detector modes into a combined dual or dynamic gain FB imaging mode.

Some possible limitations of the FB method are evident from the experiments. First, to achieve adequate signal level for the CBCT acquisition of the pelvic phantom, the frame rate had to be reduced from 15 to 10 fps. With the addition of the forward bias scan of each detector row and associated resets to clear excess charge, the pulsed x-ray window width is currently limited to 18 ms at 15 fps. This is in part due to the specific charge amplifiers used on the Varian 4030CB FP. Future FPs could use more powerful charge amplifiers and reduce the overall forward bias time. Another limitation of both the FB method and the light saturation method⁷ is the inability to correct temporal changes in the system not due to the a-Si photodiode, such as the temporal response of the scintillator, which has a known hysteresis effect,¹⁶ and temporal characteristics of the x-ray tube and generator.

The light saturation method works in a similar fashion to the FB method by using light instead of charge to fill the traps inside the a-Si between frames.⁷ Both methods reduce the residual RSRF to less than 1% [Fig. 5(a)]. However, the light saturation results leave a first frame residual lag greater than 2% for reset light durations up to 250 μ s. The FB method has a residual first frame lag of less than 0.3% in Fig. 5(b). For the current version of the FB method, a FB time of only 40 μ s for each pixel is needed.¹⁰ Thus, once more powerful charge amplifiers are implemented inside of the FP, each photodiode could be forward biased simultaneously, reducing the FB time to 40 μ s. Furthermore, more powerful charge amplifiers should lead to a shorter reset cycle since all pixels, or at least multiple rows, could be reset at once. After such a hardware change, the overall frame time increase from the forward bias method would be less than a few ms, instead of the current 30 ms.

Other possible limitations of the FB method are the reduced pixel sensitivity and the increased noise. A small increase in measured noise is to be expected, since larger dark currents are present in the FP that are removed by analog subtraction prior to the A/D conversion. The SNR measurements were repeated with other FB protocols between 6 and 20 pC/diode, but no significant difference in the FB SNR was seen. Because the FB method is effective at removing the lag signal, perhaps some of that discarded lag signal was collected in the standard mode and treated as

pixel signal. Further investigation into this phenomenon is the subject of future work.

Trap state densities for a-Si that span 10^{14} – 10^{19} ($\text{cm}^{-3}\text{eV}^{-1}$) for energies 0.1–0.8 eV below the conduction band have been measured.¹⁷ Other measurements of a-Si for solar cells have measured trap densities of 4×10^{17} ($\text{cm}^{-3}\text{eV}^{-1}$) at 0.45 eV below the conduction band edge.¹⁸ Even if only a narrow energy range is considered, such as 0.1 eV, total charge trap numbers of 4×10^{16} ($\text{cm}^{-3}\text{eV}^{-1}$) exist. Regardless of the exact number, the total number of trap states is similar to or larger than the number of electrons present for 5.8 pC/diode, which corresponds to a charge density of approximately 2×10^{15} e/cm³. Thus, it can be seen that a single frame of forward bias is insufficient to saturate all of the traps in the a-Si photodiode. Furthermore, the rates of charge uptake and emission decrease at deeper energy levels, with frequencies well below 1 Hz in existence for deep energy levels. Because of this, the deep trap states will not fill completely within a single frame at 10 or 15 fps. The two effects, the injected charge being smaller than the total number of traps and the longer time period needed to fill deep traps, contribute to the warm-up time for the detector that is greater than 1 h.² Once the detector is warmed up and the majority of charge traps filled, the 5.8 pC of forward bias charge every detector frame fills the fraction of traps that emptied since the previous frame.

A hybrid mode, which will also be the subject of future work, may mitigate some of the possible limitations of the FB method, while hopefully maintaining its lag and ghost reduction properties. We have shown that switching between different detector modes on the Varian 4030CB is highly repeatable and only causes a very small decrease in the dynamic range since the offset signals quickly and repeatedly decay to a few hundred detector counts. The advantages of a hybrid mode are the following: (1) image acquisition frame rates would equal those of a standard mode, (2) no large offset currents and thus no expected increase in dark noise, and (3) since the mode would have a standard timing during acquisition, it is expected that the pixel sensitivity, and thus SNR, would be equal to that of the standard firmware.

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