

VFX Studios White Paper**Technical Report**

The Impact of Rolling Shutter Readout Speed on Artifacts When Filming LED Video Walls

1. Introduction

The Challenge

The proliferation of LED video walls in virtual production (VP), broadcast studios, live events, and extended reality (XR) stages has revolutionized visual storytelling and content creation. These dynamic displays offer unprecedented flexibility in creating immersive environments and backgrounds. Concurrently, Complementary Metal-Oxide-Semiconductor (CMOS) sensors utilizing a rolling shutter mechanism remain the dominant technology in many digital cinema and broadcast cameras due to factors like cost-effectiveness and high resolution. This convergence presents a significant technical challenge: capturing a display that refreshes its image sequentially (the LED wall) using a sensor that also captures the image sequentially, albeit in a different manner (the rolling shutter). The potential for temporal mismatches between these two processes can lead to undesirable visual artifacts in the final footage.

The Core Question

A critical question arises for technical professionals: Does employing a rolling shutter camera with a *faster* sensor readout speed consistently improve the visual outcome when filming LED walls by mitigating artifacts like scan lines and banding? Or could a faster readout, by resolving finer temporal details, potentially exacerbate these issues under certain conditions?

Report Purpose and Scope

This report aims to provide a comprehensive technical analysis of the complex interaction between rolling shutter sensor readout speed and the visual artifacts

encountered when filming LED video walls. It will delve into the operational principles of both rolling shutter sensors and LED displays, examine the genesis of common artifacts (including banding, scan lines, and moiré), specifically analyze the role of faster sensor readout times, explore the influence of related camera settings like shutter speed and angle, discuss the critical function of synchronization techniques like genlock and phase adjustment, and compare the performance of rolling shutter sensors against their global shutter counterparts. The goal is to equip technical professionals with the understanding needed to optimize image capture in these demanding scenarios.

Relevance

Understanding these intricate interactions is paramount for achieving high-quality, artifact-free footage, particularly in applications like In-Camera Visual Effects (ICVFX) where the LED wall serves as the final background, replacing traditional green screens and extensive post-production compositing. Eliminating visual flaws that betray the technology is essential for maintaining audience immersion and realizing the full potential of virtual production workflows.

2. Understanding the Core Technologies

2.1. Rolling Shutter Sensor Operation

Mechanism

Rolling shutter sensors capture images sequentially, unlike global shutter sensors where all pixels begin and end exposure simultaneously. The process typically involves scanning across the sensor array, row by row (or sometimes in blocks of rows, or from the center outwards). For each row (or block), pixels undergo a cycle of being reset to clear previous charge, then exposed to light for a defined duration (the shutter speed), and finally having their accumulated charge read out to be digitized. This readout 'wave' sweeps across the sensor.

Temporal Disparity

The fundamental consequence of this sequential operation is that different horizontal lines of the image are captured at slightly different moments in time. The time delay between the top row's exposure start and the bottom row's exposure start (or end) is determined by the sensor's readout time. This inherent temporal disparity across the frame is the root cause of characteristic rolling shutter artifacts when capturing motion

or rapid light changes, such as:

- **Skew:** Vertical lines appearing tilted when the camera or subject moves horizontally.
- **Wobble (Jello Effect):** Image distortion or warping when the camera vibrates.
- **Partial Exposure:** Fast flashes of light illuminating only a portion of the frame.

Sensor Readout Time

- **Definition:** Sensor readout time is the total duration required to scan and retrieve the image data from all the active pixel rows on the sensor for a single frame. It represents the time lag between the start of readout for the first row and the completion of readout for the last row.
- **Components:** The readout time is determined by the 'line time' – the time taken to read out a single row of pixels (typically measured in microseconds, e.g., 10 μ s) – multiplied by the total number of rows being read. The term 'frame time' is sometimes used synonymously with total readout time.
- **Influencing Factors:** Several factors influence a sensor's readout speed:
 - **Sensor Resolution:** Higher vertical resolution (more rows) generally leads to longer readout times, assuming other factors are equal.
 - **Region of Interest (ROI) / Crop Factor:** Reading out only a portion of the sensor (a smaller ROI or using a crop mode) reduces the number of rows scanned, resulting in a faster readout time.
 - **Bit Depth:** Reducing the bit depth of the captured data (e.g., from 14-bit to 12-bit) can sometimes allow for faster data transfer and thus faster readout.
 - **Sensor Architecture:** The sensor's design plays a crucial role. Features like multiple analog-to-digital converters (ADCs) processing columns in parallel or advanced architectures like stacked sensors (which integrate memory and processing layers directly with the sensor) dramatically increase readout speeds.
 - **Binning/Decimation:** These techniques, which combine data from adjacent pixels, can potentially affect readout time.
- **Measurement & Typical Values:** Sensor readout times vary widely. High-end cameras with stacked sensors (like the Nikon Z9/Z8 or Sony A1) can achieve speeds under 4ms. Good non-stacked sensors often fall in the 15-30ms range, while older or lower-end sensors might have readout times of 50ms or more. For context, Netflix recommends a readout speed below approximately 18ms for capturing plates intended for visual effects work to limit noticeable skew artifacts.

It is crucial to distinguish sensor readout time from the camera's shutter speed. Shutter speed dictates the exposure duration for *each individual row* of pixels. In contrast,

sensor readout time represents the total duration required to scan and retrieve data from the *entire active sensor area*. The rolling shutter mechanism inherently staggers the start and end of exposure across rows. Therefore, even with a very fast shutter speed (e.g., 1/1000s), a sensor with a slower readout time (e.g., 30ms) will still exhibit a significant temporal difference between when the top and bottom of the frame are captured. This distinction is vital because artifacts arising from LED wall interactions depend on both factors: the duration each pixel observes the LED state (shutter speed) and the time window over which the entire LED state is sampled sequentially by the sensor (readout time).

2.2. LED Video Wall Display Characteristics

Image Generation

LED video walls are modular display systems composed of numerous individual light-emitting diodes (LEDs) arranged in a grid to form pixels. These LEDs are typically grouped into modules or panels, and their operation (on/off state and brightness) is controlled by driver Integrated Circuits (ICs) often located on the same Printed Circuit Board (PCB) within the panel.

Refresh Rate (Hz)

The refresh rate of an LED display specifies how many times per second the display controller *attempts* to redraw the entire image presented to it. For on-camera applications, very high refresh rates, such as 3840Hz or even 7680Hz, are commonly recommended. This high rate helps ensure that the rapid on/off cycling of the LEDs is not perceived as flicker by the camera sensor. It's important to note that this internal refresh rate is typically much higher than the frame rate of the video signal being fed to the wall (e.g., 24, 30, 50, or 60 frames per second). Each incoming video frame might be displayed or 'refreshed' multiple times by the LED panel's internal system.

Scan Pattern / Scan Rate / Multiplexing

- **Mechanism:** Contrary to how a simple monitor might work, LED walls typically do not illuminate all pixels simultaneously for the entire duration of a refresh cycle. Instead, they employ a technique called multiplexing or scanning. Driver ICs are connected to multiple LEDs (often entire rows or segments of rows), and they sequentially activate these groups of LEDs for short periods within the overall refresh cycle. The human eye's persistence of vision integrates these rapid flashes into a seemingly continuous image.

- **Scan Ratio:** This ratio quantifies the multiplexing scheme. It's expressed as a fraction (e.g., 1/8, 1/16, 1/32) indicating the number of LED pixels or lines connected to a single driver IC output.⁷ A 1/16 scan ratio implies that the driver cycles through 16 groups of LEDs sequentially to illuminate its assigned portion of the panel. A *smaller denominator* (e.g., 1/8) means *fewer* lines are controlled per driver IC, requiring *more* driver ICs overall. Conversely, a *larger denominator* (e.g., 1/32) means *more* lines are controlled per driver IC, requiring *fewer* drivers.
- **Impact:** The scan ratio significantly impacts performance and cost. Panels with a *higher scan ratio number* (larger denominator, e.g., 1/32) are more cost-effective due to fewer required driver ICs. However, this means each group of LEDs is illuminated for a shorter duration within the cycle, which can make it harder to achieve high brightness, high effective refresh rates, and good performance at low brightness levels. Panels with a *lower scan ratio number* (smaller denominator, e.g., 1/8 or even 1/1, sometimes called "static scan") generally provide *superior on-camera performance*. They offer potentially higher effective refresh rates, better brightness, and improved stability (fewer scan line artifacts), especially during camera movement or with rolling shutters, but come at a higher cost due to the increased number of driver ICs needed. Therefore, for virtual production, a lower scan ratio number like 1/8 is generally preferred over 1/16 or 1/32.

Pulse Width Modulation (PWM)

To control the perceived brightness of individual LEDs, especially for achieving different colors and grayscale levels, LED displays commonly use Pulse Width Modulation (PWM). Instead of varying the voltage (which is less practical for LEDs), PWM rapidly switches the LEDs fully on and fully off. The ratio of the 'on' time to the total cycle time (the duty cycle) determines the average light output and thus the perceived brightness. Higher PWM frequencies and greater bit depth (more discrete steps in the duty cycle) allow for smoother dimming, finer grayscale representation, and reduce the likelihood of flicker being captured by cameras, especially at lower brightness levels.

The terms "Refresh Rate," "Scan Rate," and "PWM Frequency" are distinct yet interconnected concepts critical to understanding LED wall behavior on camera. The headline "Refresh Rate" (e.g., 3840Hz) often refers to the target update frequency for the entire panel image, representing how often the driving electronics aim to start a new display cycle. However, the "Scan Ratio" (e.g., 1/16) describes the physical mechanism of sequentially illuminating segments of the panel *within* each refresh cycle. "PWM Frequency" relates to the rapid on/off switching used for brightness control *during* the time a segment is actively lit. A high overall refresh rate might still exhibit artifacts if the scan ratio number is very high (e.g., 1/32), because each segment is lit for only a brief

fraction of the total cycle. If the camera's shutter captures an incomplete scan sequence due to this high multiplexing, banding can occur. Similarly, low-frequency PWM, particularly when dimming the panel significantly, can introduce its own flicker or banding artifacts that are independent of the main refresh or scan timing. Therefore, evaluating an LED panel for on-camera use requires looking beyond the main refresh rate figure and considering the scan ratio (lower numbers like 1/8 are generally better for cameras) and the PWM characteristics, especially how the panel performs at the lower brightness levels typically used in studio environments.

3. Camera-LED Interaction and Artifact Generation

3.1. Temporal Artifacts (Scan Lines, Banding, Flicker)

Fundamental Cause

The root cause of temporal artifacts like scan lines, banding, and flicker when filming LED walls lies in the interaction between the camera's discrete sampling process (its exposure time per frame and the sensor's readout mechanism) and the time-varying light emission from the LED panel (resulting from its sequential scanning/multiplexing and PWM brightness control). Artifacts manifest when the camera sensor captures an inconsistent amount of light either across different spatial areas of the sensor within a single frame (due to rolling shutter interacting with LED scanning) or between consecutive frames (due to frequency mismatches).

Appearance and Types

These temporal artifacts can appear in several forms:

- **Rolling Bars/Flicker:** These are noticeable bands of different brightness moving (rolling) vertically or horizontally across the captured image of the LED screen, or sometimes as a global flicker affecting the entire screen's brightness from frame to frame. This is often a symptom of a frequency mismatch between the camera's frame rate (and potentially its shutter speed) and the LED wall's input signal frequency or its internal refresh cycle. Lack of proper synchronization (genlock) between the camera, LED processor, and content source is a primary cause.
- **Static Lines/Bands:** These appear as fixed, thin horizontal lines, which can be either brighter or darker than the surrounding area. This type of artifact commonly occurs when the duration the camera's shutter is open is not an integer multiple of the LED panel's PWM cycle time or its scan line refresh time. Capturing a partial PWM cycle results in a slight brightness difference for those

sensor rows.

- **Scan Line Artifacts:** These are visual lines or bands directly related to the LED panel's physical scan ratio or multiplexing method.⁵ They become particularly apparent during fast camera movements, like pans or tilts, especially with rolling shutter cameras. The moving scan of the sensor interacts with the sequential illumination pattern of the LED panel, revealing the underlying structure. Panels with a *lower scan ratio number* (e.g., 1/8, fewer lines per driver) generally reduce the visibility of these artifacts compared to those with *higher scan ratio numbers* (e.g., 1/32, more lines per driver),
- **Low Brightness Banding:** Temporal artifacts are frequently more pronounced when LED panels are operated at lower brightness levels. This is because PWM dimming becomes more dominant, the duty cycle of the LEDs is shorter, and the effective refresh rate might decrease, making inconsistencies easier for the camera to capture.

Influence of Rolling Shutter

The inherent line-by-line scanning mechanism of rolling shutter sensors makes them particularly susceptible to capturing these temporal variations across different parts of the frame. Because there is a time delay as the sensor reads from top to bottom, different rows of the sensor are exposed to the LED wall at slightly different points in the wall's refresh, scan, or PWM cycle. If the LED's state changes significantly during the sensor's readout period, this difference will be recorded as variations in brightness across the frame (banding or scan lines). Global shutter sensors, capturing the entire frame simultaneously, avoid this specific type of intra-frame variation caused by the sensor's own scan.

It's important to recognize that similar-looking artifacts, such as horizontal banding or lines, can stem from multiple distinct causes within the complex interplay of camera and LED systems. Reports attribute these issues variously to mismatches in refresh rates, problems with the LED scan rate, interference with PWM cycles, incorrect shutter speed synchronization, errors in genlock or phase alignment, or the fundamental interaction of the rolling shutter scan itself. The final visual artifact results from the interaction of all these time-based processes: the camera's exposure duration, the sensor's scan timing, the LED's input signal frame rate, the LED's internal refresh and scan mechanism, and the LED's PWM frequency. An issue in any single area, or a particularly unfavorable combination of these timings, can lead to visible artifacts. For instance, banding might arise because the shutter speed is incompatible with the PWM frequency, or because the rolling shutter scan interacts poorly with the physical scan lines of the LED panel, or because the genlock phase relationship is incorrect. Consequently, diagnosing and resolving banding or scan line issues necessitates a systematic approach, involving

testing and adjusting multiple parameters—such as shutter speed/angle, genlock phase, and potentially LED processor settings if accessible—rather than assuming a single universal fix.

3.2. Spatial Artifacts (Moiré)

Cause

Moiré is a distinct type of artifact that arises from spatial interference, not temporal mismatches. It occurs when the regular grid pattern of the LED pixels on the video wall interacts with the regular grid pattern of the photosites on the camera's image sensor. This interaction creates a new, superimposed pattern (the moiré pattern) that is not present in the original scene or on the LED display itself. It is essentially a form of spatial aliasing.

Appearance

Moiré patterns typically manifest as swirling, wave-like patterns, concentric rings, or sometimes as false color artifacts overlaid on the image of the LED screen. The appearance and intensity of moiré are highly sensitive to changes in the camera's distance from the wall, the viewing angle, the lens's focal length, the aperture setting (which affects depth of field), and the focus point.

Distinction from Temporal Artifacts

It is crucial to differentiate moiré from temporal artifacts like scan lines or flicker. Moiré is a spatial phenomenon related to the geometric relationship between the LED grid and the sensor grid. It can occur even with perfectly synchronized systems and even when using cameras with global shutters. Scan lines and flicker, conversely, are time-based artifacts resulting from mismatches in frequencies or timing between the display and the camera's exposure. **Importantly, because Moiré stems from the physical grid interaction, it is not directly caused or influenced by the sensor's readout speed, unlike temporal artifacts which can be affected by how quickly the sensor scans the image.**

Mitigation

Addressing moiré primarily involves manipulating the physical and optical relationship between the camera and the LED wall, or choosing appropriate hardware:

- **Camera Distance:** Increasing the distance between the camera and the LED

wall is often effective, as it reduces the relative size of the LED pixel grid in the camera's view.

- **Focus and Aperture:** Using a wider aperture (e.g., f/1.4, f/2.8) creates a shallower depth of field. By focusing precisely on the subject in front of the wall and allowing the LED wall itself to be slightly out of focus, the sharp grid pattern is softened, reducing moiré.
- **Camera Angle:** Sometimes, slightly changing the camera's angle relative to the LED wall can disrupt the grid interference pattern and reduce moiré.
- **Optical Low-Pass Filter (OLPF):** Many cameras incorporate an OLPF (also known as an anti-aliasing filter) in front of the sensor. This filter subtly blurs the image at a microscopic level, specifically to combat spatial aliasing artifacts like moiré and false color. External OLPFs can also be used.
- **LED Panel Choice:** Selecting LED panels with a finer pixel pitch (smaller distance between pixels) for the intended minimum viewing distance can help, as the grid structure becomes less resolvable by the camera sensor. Panels with a higher fill factor (less black space between pixels) may also perform better.

4. Analyzing the Impact of Sensor Readout Speed

4.1. General Benefits of Faster Readout (Rolling Shutter)

A faster sensor readout speed in cameras equipped with rolling shutters offers significant advantages, primarily by mitigating the artifacts inherent to the sequential capture process itself.

- **Reduced Motion Artifacts:** The most noticeable benefit is a reduction in classic rolling shutter distortions like skew and wobble (jello effect). By minimizing the time difference between capturing the top and bottom rows of the frame, faster readout ensures that fast-moving subjects or camera movements result in less geometric distortion.
- **Improved Temporal Consistency:** Because the entire sensor scan completes more quickly, the image represents a narrower slice of time. This improved temporal consistency across the frame can be beneficial when capturing dynamic scenes, including those involving rapidly changing LED displays, potentially reducing the severity of broad temporal variations captured across the sensor's scan.

4.2. Faster Readout and LED Scan Lines/Banding: A Nuanced Relationship

When considering the specific interaction with LED walls, the effect of a faster rolling

shutter readout speed on scan lines and banding is more complex than a simple universal improvement.

- **Potential for Improvement:** A faster readout inherently reduces the *temporal disparity* created by the camera's own scanning process. If banding artifacts are primarily caused by the rolling shutter capturing significantly different phases of a relatively *slow* LED refresh or scan cycle across its top-to-bottom scan, then reducing the duration of that scan (i.e., faster readout) should lessen the severity of this broad banding effect. Cameras known for faster readout speeds (generally below 18ms, as recommended by Netflix for plate capture), such as the Sony Venice 2, RED V-Raptor, ARRI ALEXA Mini LF, or cameras featuring stacked sensors, are consistently reported to yield better results with LED walls compared to cameras with slower readout speeds (e.g., 30ms or higher). Furthermore, utilizing sensor crop modes (like Super35 on a full-frame sensor) often increases readout speed by reducing the number of lines scanned, and this is frequently cited as a technique to help mitigate LED artifacts.
- **Potential for Revealing Finer Artifacts:** The question arises whether a faster readout, by capturing temporal events more accurately, could inadvertently make *finer* artifacts more visible.
 - A slower readout process inherently involves a degree of temporal averaging or 'smearing' as the scan progresses down the sensor over a longer period. This natural averaging might obscure very rapid fluctuations in the LED's light output, such as the fine line structure resulting from a high scan ratio number (e.g., 1/32, more lines per driver) or high-frequency PWM flicker used for dimming.
 - Conversely, a faster readout captures the state of each sensor line more 'instantaneously' relative to its neighbors. This improved temporal resolution means it can more accurately record sharp transitions in the LED's output. If the LED exhibits very fine temporal structure, the faster readout might render these transitions faithfully, potentially making them visible as fine, sharp lines *if synchronization (phase and shutter angle/duration) is not perfectly optimized*. The relationship noted in , where the number of visible bands depends on the light's cycling frequency versus the sensor readout rate, suggests that changing the readout rate could alter the *appearance* (perhaps fewer, wider bands, or sharper, finer bands) or even the *visibility* of these artifacts based on the specific frequencies involved.
 - However, the bulk of practical advice and industry experience emphasizes that faster readout is generally preferable. This suggests that the significant benefits of reducing the camera's own temporal distortion and

capture window usually outweigh the theoretical risk of resolving finer LED artifacts more clearly. It implies that achieving precise synchronization and shutter tuning remains the primary method for dealing with these fine artifacts, and faster readout simply provides a cleaner baseline signal from the camera itself. The issue might be less about *resolving* fine lines and more about how the specific readout speed interacts with the specific LED frequencies, potentially creating different beat patterns or interference effects.

Achieving an artifact-free image when using rolling shutter cameras with LED walls involves harmonizing multiple interacting frequencies: the camera's frame rate, the sensor's readout scan rate, the shutter duration (exposure time per row), the LED wall's input signal rate, the LED's internal refresh/scan rate, and the LED's PWM frequency. Altering the sensor readout speed changes a key variable in this complex temporal equation. While generally beneficial because it minimizes the camera's inherent temporal smearing, a faster readout fundamentally shifts the timing relationship between the sensor's scan and the LED's dynamic patterns. It is conceivable that for a *specific*, coincidental combination of LED characteristics and other camera settings, a particular (perhaps slower) readout speed might accidentally result in less visible interference—a 'lucky' mismatch—than a faster one. However, relying on such coincidences is impractical for professional workflows. Therefore, while faster readout is *generally desirable* as it reduces the camera's contribution to temporal artifacts and shortens the overall time window of capture, it does not obviate the critical need for precise synchronization (through genlock and phase adjustment) and careful shutter tuning. A faster readout might alter the *appearance* of artifacts resulting from imperfect synchronization (perhaps leading to finer lines instead of broader bands), but achieving perfect synchronization remains the ultimate goal. The primary, reliable benefit of faster readout lies in minimizing the inherent rolling shutter distortions (skew, wobble) and providing a more temporally coherent capture from the camera's perspective.

5. Mitigation Techniques and Contributing Factors

Successfully capturing clean images of LED walls requires employing several mitigation techniques, often in combination, to address the potential temporal and spatial artifacts.

5.1. Shutter Speed / Angle Adjustment

- **Purpose:** The primary goal of adjusting the camera's shutter speed (exposure time per row) or shutter angle (fraction of the frame cycle the shutter is open) is to align the *duration* of the camera's light gathering period with the cyclical light

emission patterns of the LED display, particularly its PWM cycles and scan refresh. The aim is to ensure the sensor consistently captures a whole number of LED cycles during each exposure, preventing the recording of partial cycles which manifest as brightness variations or banding.

- **Method - Manual Tuning:** This process typically requires careful, iterative testing on set while viewing the camera feed.
 - **Starting Point:** A common starting point is a 180-degree shutter angle (or the equivalent shutter speed, typically $1 / (2 * \text{frame rate})$).
 - **Incremental Adjustments:** Make small, incremental adjustments to the shutter angle or speed while observing the camera's monitor or viewfinder for flicker or banding artifacts. Using shutter angle often provides finer increments of control compared to standard shutter speed fractions.
 - **Fine-Tuning Features:** Many professional cameras offer specialized features like "Synchro Scan" (Panasonic) , "Variable Shutter" / "ECS" (Sony) , or similar functions that allow extremely precise, non-standard shutter speed adjustments (e.g., 1/51.3s instead of 1/50s). These are highly effective for dialing in the exact shutter duration needed to match the LED's specific frequency and eliminate artifacts. Consult the camera manual for specific operation.
 - **Visual Confirmation:** Continue adjusting until the artifacts are minimized or eliminated on the monitor. It might be necessary to test different settings as artifacts can sometimes shift or change appearance rather than disappear completely. Recording short clips and scrubbing through them quickly can help reveal subtle flicker.
- **Method - Processor-Led Tuning (ShutterSync/ShutterFit):** An alternative approach involves using advanced features on compatible LED processors (like Brompton's ShutterSync® or NovaStar's ShutterFit).
 - **Process:** Instead of adjusting the camera, the user inputs the desired camera shutter angle or speed into the LED processor's software.⁶⁸ The processor then automatically adjusts the LED panel's refresh timing to synchronize precisely with the camera's exposure duration.
 - **Benefit:** This allows the cinematographer to choose their preferred shutter setting for creative purposes (like motion blur) without being constrained by the need to avoid LED artifacts.
- **Limitations:** Finding a "magic" shutter speed/angle that completely eliminates artifacts is not always possible, especially when dealing with lower-quality LED panels that may use inconsistent or low-frequency PWM, or whose frequencies might drift. Additionally, the optimal shutter setting for artifact removal might conflict with the cinematographer's desired level of motion blur (often tied to the 180-degree rule), forcing a creative compromise. In complex scenarios with

multiple different light sources or frequencies, eliminating flicker from one source might introduce it from another.

5.2. Genlock and Phase Synchronization

- **Genlock (Reference Sync):** Genlock is fundamental for synchronizing the timing of multiple devices in a video system. In the context of filming LED walls, it ensures that the camera's frame capture rate and timing are locked to the same reference clock as the LED wall's processor and the media server providing the content. This prevents large-scale temporal artifacts like rolling bars, image tearing, or frame-to-frame flicker that occur when these systems operate asynchronously (free-running). Implementing genlock requires a master sync generator distributing a reference signal (e.g., tri-level sync or black burst) to compatible inputs (Ref In, Genlock In) on all critical components.
- **Phase Adjustment (Sync Shift/Delay):** While genlock synchronizes the *start* and *rate* of the frame cycles, phase adjustment allows for fine-tuning the *timing offset* between the camera's shutter opening and the start of the LED wall's refresh cycle within that synchronized framework. This is crucial because the camera shutter is typically open for only a portion of the full frame period. Correct phase alignment ensures that the camera's exposure window consistently captures a complete, single frame of content from the LED wall, avoiding artifacts like partial frame updates (blending) or capturing incomplete PWM or scan cycles at the beginning or end of the exposure, which can cause fine banding or static lines.
 - **Method:** This adjustment is typically performed using controls labeled "Phase Offset," "Sync Delay," "Timing Adjust," or similar, often found within the LED processor's software interface or sometimes on the sync generator itself.
 - **Procedure:** While viewing the camera feed, make small, incremental adjustments to the phase offset value. The adjustment units might be in microseconds (μs), lines and pixels, degrees (0-360), or percentage of a frame (0-100%). The goal is often to shift any visible static lines or bands vertically until they move off the top or bottom edge of the camera's view. Start with larger increments (like microseconds) and then refine with smaller units if needed.
 - **Multi-Camera Considerations:** If adjusting the phase on the main LED processor affects all cameras, but artifacts persist differently on individual cameras, it may be necessary to use a sync generator that allows for individual phase offsets per output channel feeding each camera, or adjust phase within the camera itself if supported.

It is essential to understand that genlock, while necessary, is often not sufficient on its own to eliminate all temporal artifacts when filming LED walls. Multiple sources confirm that even with a stable genlock signal applied to all components, residual artifacts like fine banding or static lines can persist. Genlock synchronizes the overall frame timing, but it doesn't automatically guarantee that the camera's specific exposure window (determined by shutter timing and duration) aligns perfectly with the LED panel's internal sub-frame operations (scanning and PWM). This is where phase adjustment becomes critical, allowing the alignment of the camera's exposure *within* the LED's refresh cycle. Furthermore, shutter speed/angle tuning addresses the alignment of the exposure *duration* with the LED's finer temporal structures, like PWM frequency. Therefore, a robust workflow mandates implementing genlock *and* subsequently performing precise phase adjustments and potentially shutter tuning during camera tests to achieve a clean image. Relying solely on establishing a genlock connection is typically inadequate.

5.3. Advanced Synchronization (ShutterSync, ShutterFit, etc.)

Recognizing the limitations of only adjusting camera parameters, some LED processor manufacturers have developed advanced synchronization features. Technologies like Brompton Technology's ShutterSync® and NovaStar's ShutterFit allow the timing of the *LED processor itself* to be adjusted to precisely match the *camera's* specific shutter angle or speed. Instead of forcing the camera operator to find a potentially restrictive shutter setting that works with a fixed LED timing, these systems allow the operator to choose their desired shutter setting for creative reasons (e.g., motion blur), and then tune the LED wall's refresh behavior to synchronize with that specific camera setting. This approach effectively eliminates banding artifacts caused by mismatches between the shutter duration and the LED's PWM or refresh timing, offering greater creative flexibility to the cinematographer.

5.4. LED Panel Characteristics

The inherent properties of the LED panels themselves play a significant role in their on-camera performance:

- **Scan Ratio:** As previously discussed, panels with a *lower scan ratio number* (smaller denominator, e.g., 1/8, 1/4, or 1/1) generally exhibit fewer scan line artifacts and offer better performance compared to those with *higher scan ratio numbers* (larger denominator, e.g., 1/16 or 1/32). This is because each LED segment is illuminated for a larger portion of the refresh cycle, reducing the chance of capturing incomplete scans, especially with camera motion or rolling shutters.

- **Refresh Rate:** Higher maximum refresh rates (e.g., 3840Hz minimum, with 7680Hz or higher preferred for high frame rate shooting) provide more temporal headroom, making the display less sensitive to camera shutter settings and reducing the likelihood of flicker.
- **Driver IC Quality:** The performance of the driver ICs dictates the achievable refresh rates, PWM frequency, bit depth, and overall stability, particularly at low brightness levels. High-quality drivers contribute significantly to artifact-free images.
- **Brightness Settings:** Artifacts, particularly those related to PWM dimming, can sometimes be mitigated by running the LED panels at their maximum brightness (where PWM influence might be less) and controlling the overall image brightness further upstream in the signal chain (e.g., on the media server or image processor). This approach aims to keep the LED duty cycles more consistent.

6. Global Shutter vs. Rolling Shutter for LED Walls

The choice between a global shutter and a rolling shutter camera significantly impacts the process and potential challenges of filming LED walls.

6.1. Global Shutter Advantages

Cameras equipped with global shutter sensors offer distinct advantages in LED wall environments:

- **Simultaneous Exposure:** The defining characteristic of a global shutter is that all pixels on the sensor begin and end their exposure at the exact same time. This fundamentally eliminates the temporal disparity across the frame inherent in rolling shutters, thereby eradicating artifacts like skew, wobble, and partial exposure caused by the sensor's scan.
- **Simplified Synchronization Interaction:** While genlock is still essential to synchronize the camera's frame rate with the rest of the system, the absence of a progressive sensor scan simplifies the temporal interaction with the LED wall's refresh cycles. Global shutters are inherently less prone to the specific type of scan line artifacts caused by the interplay between the camera's own sequential readout and the LED's sequential illumination.
- **Ideal for VP/ICVFX:** Global shutters are widely considered the preferred choice for demanding virtual production and ICVFX applications. They are particularly beneficial when capturing high-speed action against the LED background, generating clean plates for visual effects work, or working with high frame rate

content on the LED wall, as they ensure precise temporal accuracy across the entire image.

- **Handles Flickering Light Better:** The simultaneous capture makes global shutters less susceptible to the banding artifacts often caused by flickering artificial lights (including potentially problematic PWM from LEDs) compared to rolling shutters.

6.2. Rolling Shutter Considerations

Despite the advantages of global shutters, rolling shutter cameras remain prevalent and usable for LED wall filming, with certain considerations:

- **Ubiquity and Cost:** Rolling shutter CMOS sensors are more common in the market across various camera types (from DSLRs/mirrorless to high-end cinema cameras) and are generally less expensive to manufacture than global shutter sensors of similar resolution and performance.
- **Performance Variability:** As discussed extensively, the readout speed of rolling shutter sensors varies dramatically. Achieving good results with LED walls heavily depends on using a camera with a sufficiently fast readout speed (ideally <18ms, faster being better) to minimize the sensor's own temporal artifacts.
- **Mitigation Dependency:** Success with rolling shutter cameras in LED environments is highly dependent on the meticulous implementation of mitigation techniques. Proper genlock, precise phase adjustment, and careful shutter speed/angle tuning are absolutely critical to manage and minimize temporal artifacts.
- **Usability:** With careful setup, appropriate camera choice (fast readout), high-quality LED panels, and thorough testing, rolling shutter cameras can still produce excellent, artifact-free results for many LED wall applications. ARRI, for example, notes that once synchronization and phase are correctly applied, rolling shutter effects become "non-problematic" for their cameras in typical scenarios, though potential issues might arise at very high frame rates combined with long exposures.

6.3. Comparison Table: Rolling vs. Global Shutter for LED Wall

Filming

Feature	Rolling Shutter (Fast Readout, e.g., <18ms)	Rolling Shutter (Slow Readout, e.g., >30ms)	Global Shutter
Sensor Exposure Method	Sequential (Line-by-Line)	Sequential (Line-by-Line)	Simultaneous (All Pixels)
Inherent Skew/Wobble Artifacts	Minimal	Moderate to Severe	Eliminated
Susceptibility to LED Scan Lines/Banding*	Medium	High	Low (Less prone to <i>camera-scan</i> induced lines)
Need for Genlock	Essential	Essential	Essential (for frame rate sync)
Need for Precise Phase/Shutter Tuning	Critical	Critical	Helpful (for LED PWM/scan sync), less critical
Suitability for High-Speed Action on LED	Good	Poor	Excellent
Suitability for VFX Plates	Good (if readout fast enough)	Poor	Excellent
Cost (Sensor/Camera)	Generally Lower	Generally Lowest	Generally Higher
Availability	Wide	Wide	More Limited (but increasing)

**Assumes proper genlock is implemented and phase/shutter tuning is attempted.*

6.4. Sensor Readout Speeds of Common Virtual Production Cameras

Sensor readout speed is a critical factor for rolling shutter cameras, especially in virtual production. Faster speeds (lower ms values) generally reduce rolling shutter artifacts like skew and can improve performance with LED walls when properly synchronized. Global shutter cameras eliminate these rolling shutter artifacts entirely. Below are some measured readout speeds for popular cameras (Note: speeds can vary slightly depending on the specific recording mode and firmware version):

- **ARRI ALEXA 35:** 5.7ms (4.6K 16:9), 7.9ms (Open Gate 3:2)
- **ARRI ALEXA Mini LF:** 7.4ms
- **Sony VENICE 2:** < 3ms
- **Sony BURANO:** 18.9ms (8.6K FF), 16.9ms (6K FFc 25/30p), 14.8ms (6K FFc 60p)
- **Sony FX9:** 22.2ms (UHD Full Frame)
- **Sony a7S III:** 8.7ms
- **RED V-RAPTOR 8K VV:** 8ms (8K Full Frame)
- **RED V-RAPTOR [X] 8K VV:** Global Shutter
- **RED Komodo 6K:** Global Shutter
- **Blackmagic URSA Cine 12K LF:** 12ms (12K Open Gate), 5.5ms (8K/4K Full Frame)
- **Blackmagic URSA Mini Pro 12K:** (Similar sensor to Cine 12K, likely similar speeds)
- **Blackmagic PYXIS 12K:** 24.1ms (12K Open Gate), 13.5ms (8K/4K Full Frame)
- **Blackmagic Pocket Cinema Camera 6K Pro:** ~20ms
- **Blackmagic Cinema Camera 6K (Full Frame):** ~25ms (6K Open Gate)
- **Canon EOS C500 Mark II:** 15.8ms (6K RAW 17:9)
- **Canon EOS C400:** 9.5ms (6K FF 17:9), 7.4ms (4K FF 120fps), 6.9ms (4K S35)
- **Canon EOS R3:** 9.5ms (6K FF 17:9)

(Note: Global Shutter cameras capture the entire frame simultaneously, eliminating rolling shutter artifacts like skew and wobble. Their readout mechanism differs fundamentally from rolling shutter sensors.)

7. Synthesis and Conclusion

7.1. Answering the Core Question: Is Faster Readout Universally

Better?

The analysis indicates that a faster sensor readout speed in rolling shutter cameras is **generally advantageous** when filming LED video walls. Its primary benefit lies in significantly reducing the camera's inherent temporal artifacts, namely motion-related distortions like skew and wobble, which become increasingly problematic with slower readout speeds. By minimizing the time difference between capturing the top and bottom of the frame, faster readout provides a more temporally coherent image capture, which can also help lessen the severity of broad banding artifacts that might arise from the sensor scan interacting with slower LED refresh cycles or imperfect synchronization.

However, faster readout is **not a universal panacea** that eliminates all potential artifacts when filming LED walls. It does not remove the fundamental requirement for precise synchronization between the camera, LED processor, and content source using genlock and meticulous phase adjustment. Furthermore, careful tuning of the camera's shutter speed or angle remains essential to align the exposure duration with the LED's specific internal timing (scan cycles and PWM frequency) to avoid fine banding.

While largely theoretical and secondary to the benefits, it is conceivable that a very fast readout, by virtue of its improved temporal resolution, could render extremely fine, high-frequency artifacts originating from the LED panel itself (like rapid PWM flicker or scan micro-patterns) more sharply or distinctly compared to a slower readout that might inherently blur such rapid fluctuations, *especially if synchronization is not perfect*.

In conclusion, while faster readout speed (<18ms being a recommended benchmark) should be prioritized when selecting rolling shutter cameras for LED wall applications, it must be viewed as only one component of a comprehensive strategy. It makes achieving a clean image *easier* by reducing camera-induced temporal distortions, but it does not negate the challenges posed by the dynamic nature of the LED wall itself. Perfect synchronization and careful shutter tuning remain paramount regardless of readout speed.

7.2. Key Takeaways

- Filming LED walls successfully requires managing a complex interplay of time-based processes between the camera sensor's capture mechanism and the display's light emission characteristics.
- Synchronization, achieved through genlock for frame rate locking and precise phase adjustment for aligning exposure within the refresh cycle, is the most critical factor in eliminating major temporal artifacts like rolling bars and tearing.

- Fine-tuning the shutter speed or angle is essential to mitigate more subtle banding artifacts that arise from mismatches with the LED's PWM frequency or scan cycle timing.
- Faster rolling shutter readout speeds are generally beneficial, primarily reducing camera-induced motion artifacts (skew, wobble) and providing a more temporally coherent capture window, but they do not replace the need for robust synchronization and shutter tuning.
- Global shutter sensors inherently avoid rolling shutter artifacts and simplify the temporal interaction with the LED wall, making them the preferred technology for critical applications like high-speed action, VFX plate capture, and high-frame-rate virtual production, where available and economically feasible.
- The quality and specifications of the LED panel itself—particularly its scan ratio (lower numbers like 1/8 are better), refresh rate (higher is better), PWM implementation, and driver IC performance—significantly influence the potential for artifacts and the ease of achieving a clean image on camera.

7.3. Recommendations for Professionals

Based on the analysis of the interaction between camera sensors and LED walls, the following recommendations are provided for technical professionals aiming for optimal results:

- **Prioritize Rigorous Testing:** Given the number of variables involved, thorough testing is non-negotiable. Conduct camera tests using the exact combination of LED panels, processors, media servers, cameras, lenses, filters, and intended camera settings (frame rate, resolution, shutter angle/speed) planned for the production. Critically evaluate footage for artifacts under various conditions, including different content types (especially solid colors, gradients, and fine patterns), varying LED brightness levels, and representative camera movements (pans, tilts, zooms).
- **Implement Robust Synchronization:** Ensure a stable genlock signal is distributed to and correctly configured on all relevant components: cameras, LED processors, and media servers/playback systems. Dedicate sufficient time during setup and testing for precise phase adjustment (sync offset/delay) to align the camera's exposure window optimally within the LED's refresh cycle.
- **Master Shutter Tuning:** Learn to utilize the camera's shutter adjustment capabilities effectively. If available, leverage fine-tuning features like synchro scan or variable shutter for precise frequency matching. If limited to standard speeds/angles, meticulously test settings around the typical 180-degree starting point to find the value that minimizes or eliminates banding for the specific LED panel frequency, frame rate, and content being displayed. Investigate advanced

synchronization features like ShutterSync or ShutterFit if using compatible LED processors, as they offer greater flexibility.

- **Choose Cameras Wisely:** When using rolling shutter cameras, prioritize models with the fastest available sensor readout speeds (aiming for <math><18\text{ms}</math> where possible). Evaluate if using a cropped sensor mode (e.g., Super35 on a full-frame camera) provides a beneficial increase in readout speed for the specific shot requirements. For projects with demanding requirements (high-speed action, critical VFX plates, high frame rates) or where budget allows, strongly consider utilizing cameras with global shutter sensors (e.g., RED Komodo, V-Raptor XL [X], Sony VENICE 2 in GS mode, Sony A9 III) to eliminate rolling shutter artifacts and simplify synchronization challenges.
- **Scrutinize LED Specifications:** Look beyond headline figures like pixel pitch and maximum brightness when selecting LED panels for on-camera use. Pay close attention to the scan ratio (lower numbers like 1/8 or less are preferable to higher numbers like 1/16 or 1/32), the maximum refresh rate ($\geq 3840\text{Hz}$ minimum, $\geq 7680\text{Hz}$ desirable for HFR), PWM capabilities (high frequency, high bit depth), and the quality of the driver ICs , as these significantly impact susceptibility to artifacts.
- **Manage Moiré Separately:** Remember that moiré is a spatial artifact distinct from temporal banding and scan lines. Address moiré through careful camera positioning (distance, angle), lens choice, aperture control (shallow depth of field), the use of appropriate OLPFs, and selecting an LED pixel pitch suitable for the minimum required camera distance.

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