Sub-Frame Virtual Production With Synchronized Lighting Systems And High-Frame-Rate Laser Projectors

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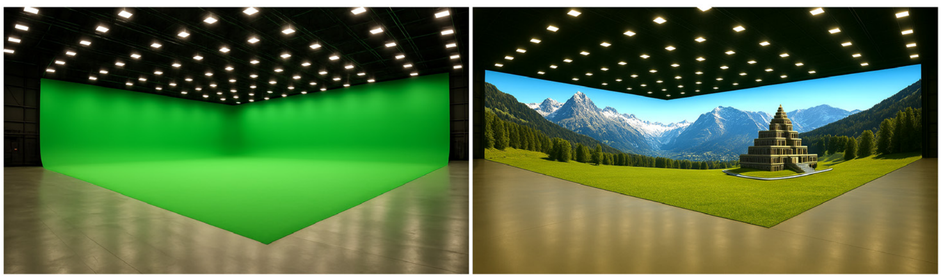


Figure 1: Green screen monochromatic soundstage vs real-time previsualization with projectors and Image Based Lighting.

Abstract: LED walls have become a staple in virtual production, offering immersive visuals and real-time previsualization. Yet, their high cost, rigid pre-production requirements, and technical limitations often force productions to revert to post-production fixes; undermining their promise of "final pixel" capture. As a result, traditional green/blue screen workflows remain the industry standard for high-end VFX due to their superior compositing flexibility. However, green screens introduce their own challenge: actor fatigue. Repeated exposure to featureless environments leads to disengagement and diminished performance; publicly acknowledged by many actors.
To resolve this, we introduce **Sub-Frame Virtual Production with Synchronized Lighting and High-Frame-Rate Laser Projectors**; a hybrid method that alternates green screen and projected imagery within a single exposure using synchronized high-speed lighting and high speed global shutter cameras. This enables the camera to capture clean chroma frames while actors engage with immersive projected environments in colossal sized studios at the fraction of the cost of traditional LED walls.
This dual-channel approach preserves post-production control while improving on-set creativity, lighting accuracy, and actor comfort; delivering a scalable, cost-efficient alternative to LED volumes. By merging the strengths of traditional VFX with real-time visualization, this workflow redefines what's possible in modern filmmaking.

Keywords: Virtual Production, Immersive, Algorithmic AI, Projectors, Green Screen, Synchronized Lights.

Figure 2: “Green/Blue screen fatigue” has become a significant liability for actors, affecting both their performance and overall well-being due to prolonged exposure to empty, featureless environments for days or even weeks at a time.

1 - INTRODUCTION

1.0 – LIMITATIONS OF GREEN SCREENS:

Despite decades of evolution and the widespread adoption of green and blue screen technologies, traditional chroma key compositing has reached a creative impasse; particularly for performers. While green screen workflows remain highly flexible for post-production and VFX integration, they impose a significant psychological and emotional cost on actors. Known colloquially as “green screen fatigue,” this phenomenon has been publicly acknowledged by major actors across the industry.

> *“That’s the first time I’ve done that. I mean, the definition of it is monotony. You’ve got good people. You’ve got other actors who are far more experienced at it than me. Can you differentiate one day from the next? No. Absolutely not. You have no idea what to do. I couldn’t even differentiate one stage from the next. They kept saying, ‘You’re on Stage Three.’ Well, it’s like, ‘Which one is that?’ ‘The blue one.’ They’re like, ‘Yeah. But you’re on Stage Seven.’ ‘Which one is that?’ ‘The blue one.’ I was like, ‘Uh, where?’”*
>
> Christian Bale

Christian Bale described the experience of performing in front of green screens as “the definition of monotony,” with days becoming indistinguishable ***due to the lack of environmental cues***. Chris Hemsworth admitted that ***prolonged green screen work felt “mind-numbing and exhausting,”*** and expressed a clear preference for practical environments. Elizabeth Olsen, known for portraying Wanda Maximoff, even described the process as “embarrassing,” especially when miming supernatural powers without a tangible set. Perhaps most poignantly, Sir Ian McKellen recounted his frustration during The Hobbit trilogy, where ***the isolation of green screen work led him to question his very craft .***

These testimonies highlight a fundamental shortcoming of traditional VFX pipelines: while technically efficient, they often alienate the very performers they rely on. The absence of real-time interaction, spatial reference, and emotional feedback reduces the actor’s ability to engage naturally with the scene, resulting in flat performances that may require additional direction or extensive reshoots. This not only impacts creativity but also adds indirect production costs through lost momentum and inefficient iteration cycles.

Figure 3: Even big productions like “The Mandalorian” rotoscopes their backgrounds and uses Green inner-frustums to compose in post and get rid of all the background, just to capture the reflextions on the characters helmets. The reality is that LED screens are not being used for “Final-Pixel” anymore on computer generated graphics scenes, except on driving plates, where LED screens are still the preffered and perfect use.

1.1 - LIMITATIONS OF LED WALLS:

LED walls have become the standard for virtual production in high-budget filmmaking, commercials and Sport Promos; particularly effective in controlled scenarios such as vehicle process shots. These environments benefit from real-time reflections, synchronized motion playback, and the immersive visual continuity that solves “Green/Blue Screen Fatigue” in actors.

Outside these specialized use cases, however, LED walls reveal substantial constraints. The initial cost of deploying large-scale LED volumes is only part of the equation; **the ongoing operational burden is far greater**. Even while idle, these systems demand continuous power; and constant recalibration of color and brightness across panels to ensure consistency. The labor and equipment needed to keep a volume tuned, often for weeks between setups; adds a hidden layer of expense that scales poorly across productions.

The goal of achieving “Final Pixel” in-camera for computer-generated backgrounds remains mostly aspirational. While the concept of recording finished frames live on set is appealing; technical realities such as resolution limits, dropped frames, refresh mismatches, and parallax artifacts frequently undermine the quality. As a result, many productions that begin with LED volume strategies ultimately fall back on post-production fixes; including rotoscoping actors, re-tracking motion, and replacing the entire background; **negating the core promise of real-time rendering.**

LED workflows also impose a rigid production structure. All environmental elements; lighting states, camera paths, actor positions;must be locked early in pre-production. This demand for premature precision limits spontaneity during filming; forcing creative teams to make decisions under technical pressure instead of performance-driven discovery. The pipeline becomes front-loaded with dependencies that are difficult to revise once physical production begins.

These issues are not isolated drawbacks; they form a systemic bottleneck that constrains the flexibility, accessibility, and iterative potential of virtual production as a whole. To move beyond these limitations, a new approach is needed; one that preserves immersive visualization on set while embracing the post-production freedom and affordability that modern workflows demand.

Figure 4: High-speed capture at 240fps enables sequential A/B frame recording at 120fps each. In the A Frame (left), only the projector is active while the synchronized high-speed lights are turned off. In the B Frame (right), the Projector is Off and the background is illuminated with green lighting, and the subject is lit with the appropriate ambient light. This A/B frame technique allows both realities to coexist simultaneously, allowing to split these realities in two or more.

1.2 - HIGH-SPEED SUB-FRAME VIRTUAL PRODUCTION WITH SYNCHRONIZED LIGHTING SYSTEMS AND HIGH -FRAME-RATE LASER PROJECTORS; A HYBRID ALTERNATIVE:

High-Speed Sub-Frame Virtual Production introduces a new paradigm in virtual production workflows; blending the compositing flexibility of green screen capture with the immediacy of on-set real-time environments. The system uses high-frame-rate laser projection and synchronized lighting; precisely timed with global shutter cameras; to alternate green-screen lighting and projected imagery within a single exposure window.

This alternating rhythm creates two synchronized layers per frame; one exclusively seen by the camera for chroma key isolation; and another visible to the cast and crew for immersive scene context. The result is a dual-purpose environment; enabling intuitive performances and live creative adjustments without sacrificing post-production fidelity.

Beyond practical efficiency; this method opens conceptual and technical possibilities rarely explored in traditional pipelines. High-Speed Sub-Frame Virtual Production enables **alternative realities to coexist on set**; not just for previsualization, but as a framework for embedding auxiliary visual data into the production timeline. Applications **such as alpha matte generation applying Paul Debevec’s Green+Magenta technique**; **AI-assisted segmentation; immersive 3D layer separation; and procedural lighting overlays** become achievable with this system. These once esoteric but increasingly critical workflows introduce a new frontier for research and development that the industry must actively monitor and take advantage of this new parallel alternative reality available to the VFX industry.

As standards like **SMPTE ST-2110-41/42 evolve**, so too will the ecosystem of synchronized metadata that can support these experimental layers. This ensures that all projection, lighting, camera, and motion tracking data remains frame-accurate; paving the way for a clean and interoperable post pipeline.

By decoupling live visualization from final image capture; High-Speed Sub-Frame Virtual Production provides an efficient, creative, and scalable solution for modern virtual production needs; one that supports performance, improvisation, and post-production freedom simultaneously.

Figure 5: Full Spectrum Lights with PBL (Phisics Based Lighting System)

1.3 - FULL SPECTRUM SYNCHRONIZED IMAGE-BASED LIGHTING:

A key element in High-Speed Sub-Frame Virtual Production is lighting fidelity; accurately reproducing virtual scene lighting on real subjects. Full Spectrum Synchronized Lighting Systems achieve this by using raytraced data to drive high-speed RGBWW fixtures in sync with projection and camera capture.

These lighting cues are orchestrated using sub-frame accuracy in intensity, color, and timing; even when multiple light sources operate within a single exposure window. This creates lighting that behaves as though it originates from the virtual world itself, supporting accurate reflections, shadow alignment, and exposure dynamics in real time.

This technology is a core pillar of the Reality Environment Simulation System (RESS); a modular framework that treats each frame as a real-world simulation synchronized with SMPTE-2110-41/42 Metadata. Within RESS, lighting, projection, chroma capture, and motion control are unified under a synchronized metadata protocol, making lighting programmable, repeatable, and scalable.

By simulating reality instead of merely approximating it, RESS sets the foundation for the next generation of virtual production, where an environment that offers both compositing flexibility and real-time previsualization becomes the perfect combination; empowering actors, directors, and VFX artists to work more creatively and collaboratively on set without affecting each other's bottom line. The actor can act, the VFX artist can create before, during, or after production, and the creative process doesn't stop because "technical hiccups" so the Director can keep moving through their productions days.

Figure 6: High-Speed blended frames vs Algorithmic AI frame reconstruction.

1.4 - LIMITATIONS OF HIGH-SPEED SUB-FRAME VIRTUAL PRODUCTION FOR 24FPS FOOTAGE:

While High-Speed Sub-Frame Virtual Production thrives in high-frame-rate environments such as 120fps or 240fps, or even slower frame-rates such as 60fps; it encounters functional limits when applied to standard 24fps cinematography. The challenge lies in temporal resolution; with fewer micro-windows available per frame, there is limited space to alternate green-screen lighting and projected content without visible flicker or light contamination.

This constraint affects exposure design, that when those intra-frames are combined, they produce noticeable multi-frame blending creating a non-optimal optic flow.
Under such conditions, sub-frame alternation becomes difficult to isolate cleanly; often resulting in overlapping visual information or insufficient light levels. These issues reduce the effectiveness of the sub-frame method and compromise the quality of chroma key or projection fidelity.

To address this, this methodology introduces a solution through Intra-Frame AI Interpolation. This less controversial use of AI technique allows simulated sub-frame intervals to be generated artificially between real captured frames. By leveraging algorithmic AI models that can reconstruct missing intermediate frames with near-photoreal accuracy.

These synthetic frames function as temporal bridges; enabling systems operating at 24fps to emulate the advantages of high-speed alternation without the missing intra-frames lost in the previsualization process. The result is a hybrid acquisition workflow; where immersive previsualization and real-time lighting feedback can still occur on set; and missing sub-frame data is reconstructed intelligently during post.

This approach transforms the limitation of lower frame rates into an opportunity for assisted enhancement. While current implementations remain resource-intensive and are best suited for pipeline-level post-processing; the rapid development of GPU-based inference engines and multi-modal training data suggests that real-time intra-frame generation may soon be feasible.

As High-Speed Sub-Frame Virtual Production continues to evolve; its integration with AI-driven frame synthesis will become an essential pathway for bringing immersive, frame-accurate workflows to traditional film formats; ensuring that legacy frame rates no longer restrict next-generation of creative tools.

Figure 7: Sub-Frame Virtual Production with Synchronized Lighting Systems and High-Frame-Rate Laser Projectors Set.

1.5 - OBJECTIVES AND CONTRIBUTIONS OF THIS STUDY:

The aim of this study is to define, document, and validate a scalable alternative to current LED wall-based production methods; introducing High-Speed Sub-Frame Virtual Production as a technically viable and cost-efficient hybrid approach. This methodology addresses key industry pain points; ranging from the excessive infrastructure demands of LED volumes to the inflexibility of rigid previsualization workflows; while introducing new creative and operational opportunities grounded in precise timing, modular design, and intelligent data capture.

At its core, this research presents a unified system architecture that leverages laser projection, synchronized high-speed lighting, global shutter cameras, and SMPTE ST-2110-based metadata orchestration to deliver immersive environments in real-time without compromising compositing quality. By decoupling what the camera captures from what the cast and crew see on set; High-Speed Sub-Frame Virtual Production maintains a clean chroma channel for visual effects pipelines while simultaneously preserving creative feedback loops during production.
This paper contributes to the field in the following ways:

• **A sub-frame synchronization methodology** that enables alternating projection and lighting cycles within a single camera frame; allowing separate channels for visual reference and green screen capture;

• **A hybrid production workflow** that empowers actors with immersive visuals during performance while preserving clean chroma frames for compositing;

• **A synchronized lighting system design** capable of working in harmony with projectors and lighting; allowing for flexible image-based lighting setups and ambient reinforcement;

• **An orchestrated metadata layer using ST-2110-41/42**; ensuring that all devices; cameras, projectors, lights, and motion control systems; share common Δt (delta time) synchronization;

• **Support for Emerging AI Workflows:** We explore the integration of intra-frame interpolation systems that enable AI-generated synthetic frames for low-frame-rate footage; making it possible to extend sub-frame capabilities into traditional 24fps cinematography using metadata-informed reconstruction and new alternative uses;

• **Exploration of New Use Cases:** The method opens a wide field of experimental and future-facing applications; including alpha matte streaming, 3D object segmentation, dynamic light shaping, and immersive depth mapping; all of which are achievable when synchronized sub-frame data is treated as programmable visual layers.

By consolidating these technical components into a coherent, flexible production framework; this study lays the groundwork for a **next-generation virtual production toolkit**. The result is a methodology that not only meets the demands of today's production challenges; but is also extensible enough to accommodate the tools, standards, and creative ambitions of tomorrow.

Figure 8: Kino Flo MIMIK-120 + Christie Digital M-4k Series Laser Projector with 240fps Mirage Pro + RED V-Raptor with Phantom Track (A/B Frames).

3.0 - METHODS INTRODUCTION

This section outlines the technical methodology behind Sub-Frame Virtual Production, a hybrid workflow that combines the flexibility of green screen with the immersive feedback of real-time projection. By alternating sub-frames between projected visuals and chroma-key frames using synchronized lighting and high-frame-rate projectors, actors benefit from real-time context while post-production retains full compositing control.

3.0.1 - PURPOSE OF THE METHODOLOGY

The aim is to solve the limitations of both green screens and LED volumes. LED walls provide real-time feedback but are costly and prone to dropped frames; green screens are flexible but leave actors disengaged. SFVP bridges the gap by providing real-time environmental cues during sub-frames not captured by the camera, while chroma-key frames remain clean for compositing.

3.0.2 - INTEGRATION WITH SMPTE-2110

SMPTE ST-2110, especially its 41/42 metadata extensions, is key to synchronizing all system components at nanosecond precision. This enables seamless coordination of camera exposure, light cues, and projection timing.

3.1 - CAMERA CONFIGURATION FOR SUB-FRAME VIRTUAL PRODUCTION

To facilitate Sub-Frame Virtual Production, precise camera configuration is paramount. Synchronization across the entire ecosystem; media server, lighting system, laser projector, and camera; is foundational to ensure accurate alternation between projected environments and chroma key exposures within a single frame cycle.

3.1.1 - CAMERA REQUIREMENTS

High-speed sub-frame capture necessitates the use of global shutter sensors or, where available, fast rolling shutter alternatives with minimal readout latency. This is critical to preserve the integrity of the alternating light states; green-screen and projection; within micro-second windows. A slower shutter translates to reduced effective exposure for projector-based content, diminishing visible brightness and spatial coherence due to shutter overlap with the laser frame interval.

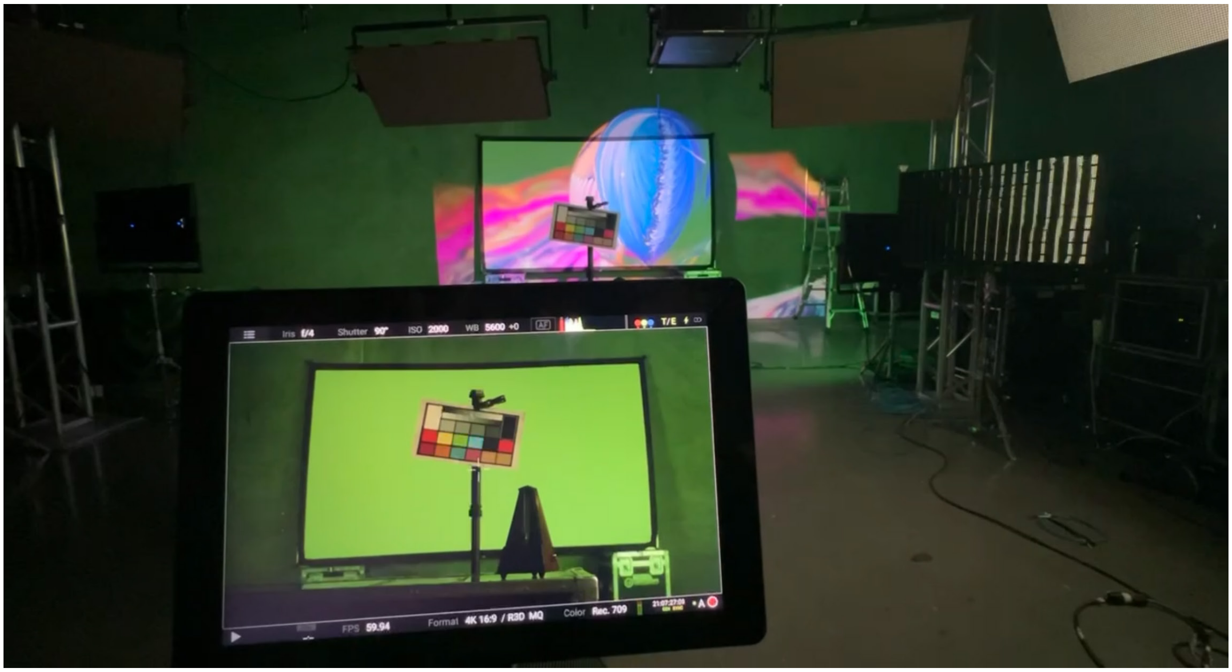


Figure 9: Kino Flo MIMIK-120 + Christie Digital M-4k Series Laser Projector with 240fps Mirage Pro + RED V-Raptor with Phantom Track (A/B Frames).

3.1.2 - STANDARD 60FPS ACQUISITION PIPELINE

For this workflow we will be using a RED V-Raptor with Phantom Track feature.

FOR CONVENTIONAL 59.94FPS/60FPS PRODUCTIONS:

- System Genlock: Entire pipeline (Media Server, Projector, Lighting, Camera) must be PTP-synchronized.
- Camera Frame Rate: 59.94fps or 60fps
- Shutter Angle: ≤ 180° (To retain half the frame time for alternating lighting/projector states)

This configuration ensures standard real-time playback compatibility while allocating sub-frame windows for isolated chroma exposure or projected previsualization. Note that this restricts the camera to only “see” the first half of each frame unless dual-capture systems are employed.

3.1.3 - ADVANCED 120FPS ACQUISITION FOR DUAL-STATE SEPARATION AND 60FPS OUTPUT PER STATE.

For workflows requiring both green screen and live projection states to be isolated within the same frame cycle, a 120fps acquisition pipeline is recommended. This enables an A/B frame architecture:

OPTION A – RED V-RAPTOR DUAL OUTPUT (NO PHANTOM TRACK):

- Genlock: Full system sync
- Camera Frame Rate: 120fps (or 119.88fps)
- Shutter Angle: 360° (Full sensor exposure)
- Live Output: Single-SDI stream delivering clean A or B frame
- Post-Process: A/B frame separation (manual via script)

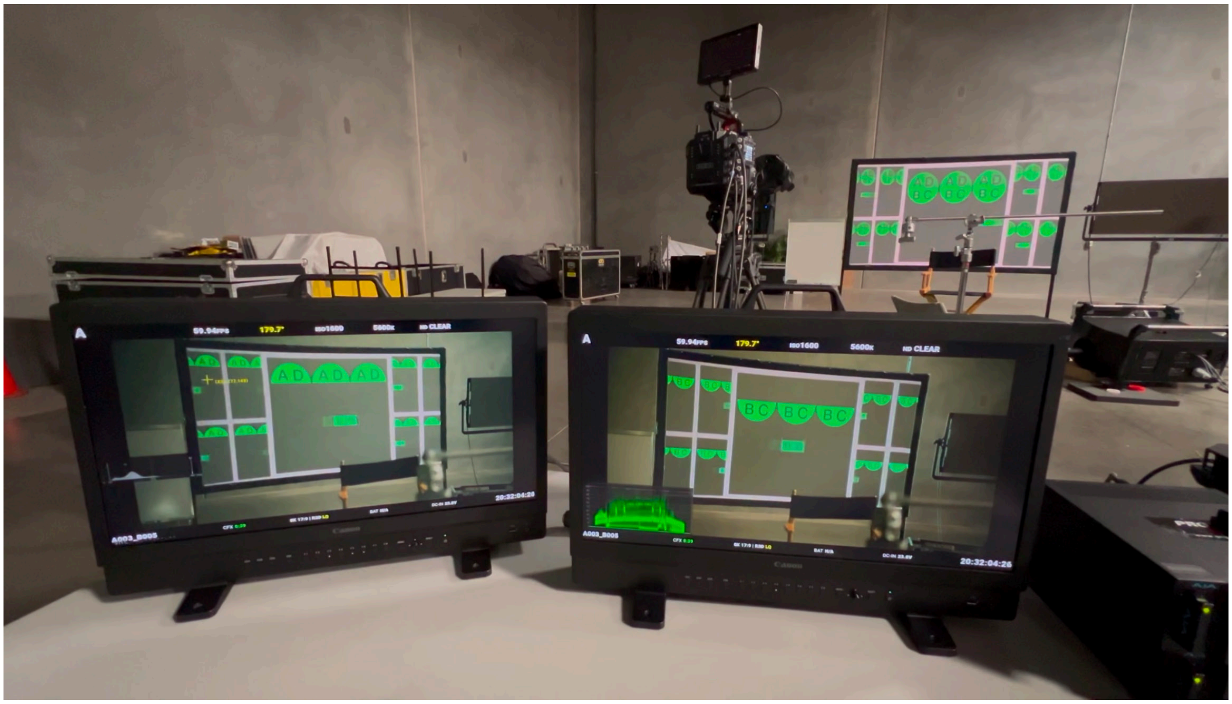


Figure 10: Christie Digital M-4k Series Laser Projector with 240fps Mirage Pro + RED V-Raptor with Phantom Track (A/B Frames).

OPTION B – RED V-RAPTOR DUAL OUTPUT WITH PHANTOM TRACK MODULE:

• Genlock: Full system sync
• Camera Frame Rate: 120fps (or 119.88fps)
• Shutter Angle: 180° (Phantom Track interprets 180° as full exposure per half-frame)
• Live Output: Dual-SDI stream delivering clean A/B frame separation
• Post-Process: Internally decoded A/B tracks can be processed without manual splitting
These configurations enable fully im
mersive previsualization for talent while maintaining clean, post-processable chroma frames for VFX teams. The dual-frame architecture aligns perfectly with SMPTE-2110-41/42 timecode workflows, maintaining precise Δt offsets across all devices.

3.1.4 - 240FPS ACQUISITION FOR 24FPS DELIVERABLES VIA AI FRAME INTERPOLATION

To accommodate traditional 24fps final output while still leveraging sub-frame hybrid workflows, frame interpolation is employed and high-speed shooting allows smooth 24fps with virtual shutter angle control:
• Camera: RED V-Raptor + Optional Phantom Track
• Capture Rate: 240fps
• Shutter Angle: 180° (interpreted as 360° open if Phantom Track is used)
• Output: Live dual-frame A/B separation via 2 SDI outputs.
• Post-Process: AI-based intra-frame interpolation to synthesize “virtual” shutter angles and motion blur for 24fps delivery is applied based on the 120fps usable frames.

This approach allows low-frame-rate projects to benefit from the spatial fidelity and creative flexibility of high-speed sub-frame projection without visual compromise.

Figure 11: CyberGaffer PBL + Kino Flo

3.2 – SUB-FRAME IMAGE-BASED LIGHTING SETUP

Achieving sub-frame precision in Image-Based Lighting (IBL) requires an orchestration of frame-level synchronization across projectors, cameras, and lighting systems. This method leverages high-frame-rate laser projectors; operating at up to 480fps; and synchronized lighting systems capable of switching at microsecond intervals, allowing for alternating projection and lighting frames within a single camera shutter cycle.

3.2.1 – FRAME ALTERNATION FOR HIGH-FIDELITY LIGHT CAPTURE

The foundational principle of Sub-Frame Image-Based Lighting is to alternate lighting and projection on a frame-by-frame or even intra-frame basis, matching the timing precision required by high-speed, global shutter camera sensors. For example, when operating at 480fps with a 180° shutter, the exposure window spans approximately 2.08 milliseconds per frame. Within this micro-window, we can precisely alternate between green screen exposure and projected image-based lighting, enabling the simultaneous acquisition of clean chroma data and immersive lighting information.

3.2.2 – KINO FLO MIMIK 120 + MEGAPIXEL HELIOS:

Industry-First Lighting Integration
The only lighting system currently capable of delivering full-spectrum RGBWW reproduction at film-grade fidelity; while supporting sub-frame synchronization up to 900fps at 30,000Hz at 10,000 Nits; is the Kino Flo MIMIK 120, powered by Megapixel’s Helios system. This unique pairing allows SMPTE ST-2110 integration with metadata packets to orchestrate every lighting cue with nanosecond precision, making it the first viable solution for real-time, delta-synchronized lighting at cinematic standards.

3.2.3 – FROM IMAGE-BASED LIGHTING (IBL) TO PHYSICS-BASED LIGHTING (PBL):

The next evolution beyond IBL is Physics-Based Lighting (PBL); a process that derives light behavior not just from pixel values but from radiometric and photometric models of light interaction. Inspired by the foundational research of Paul Debevec, and updated with algorithmic-AI-driven simulation systems, PBL (short for Physics-Based-Lighting) enables more precise environmental replication based on HDRI maps or CGI-derived light fields.

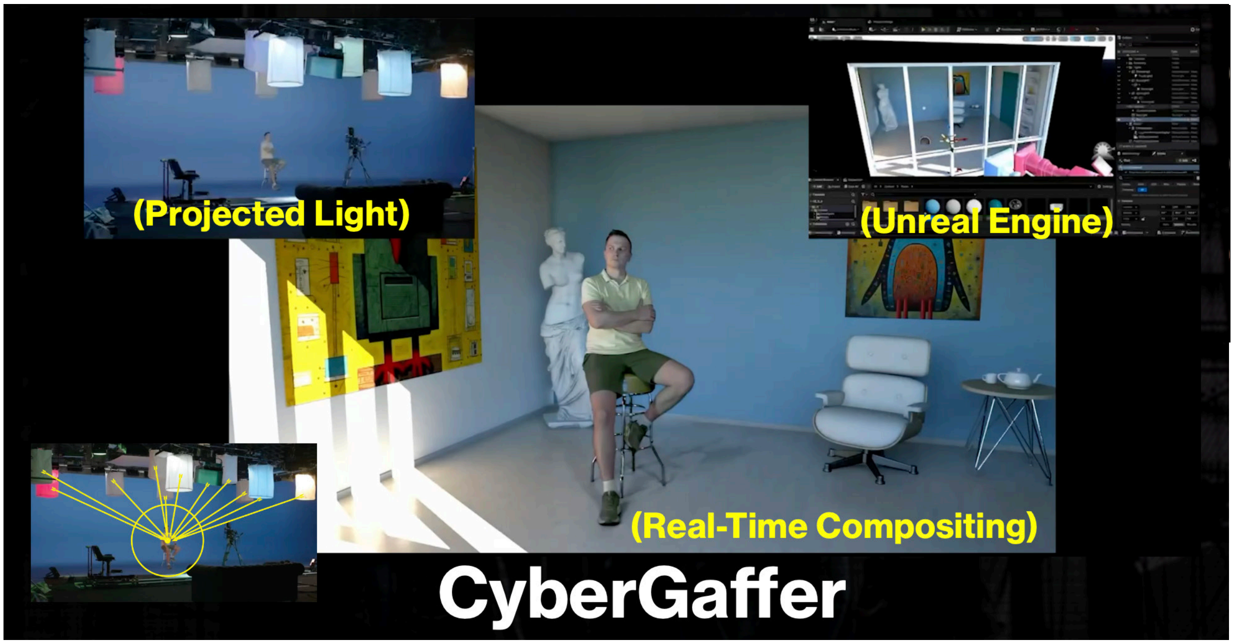


Figure 12: www.CyberGaffer.com

3.2.4.1: IN THIS SYSTEM:

• Step 1: Each fixture is recorded individually using a white ball reference to map its RGBWW response.
• Step 2: A light model is generated and imported into the control system for post-processing.
• Step 3: Algorithmic prediction calculates the optimal spectral mix and intensity per fixture to recreate accurate lighting from a 360° HDRI source for real time processing.

CyberGaffer has pioneered this technique by generating a per-fixture light response matrix, enabling any spatial light arrangement to approximate hemispheric lighting fidelity without the intrusiveness of dome setups. This AI-assisted system adheres to Inverse Square Law principles that compensates for irregular fixture layouts, allowing creative flexibility while maintaining photorealistic accuracy.

3.2.5 – DIFFERENTIATING PIXEL MAPPING VS PHYSICS-BASED LIGHTING

It is important to distinguish PBL from conventional pixel-based light sampling, where color data is simply mapped from an HDRI or video feed to DMX fixtures. While functional, such pixel mapping lacks the mathematical precision and volumetric awareness required for accurate environmental light simulation.
PBL, by contrast, simulates true light falloff, diffusion, occlusion, and bounce characteristics, producing physically coherent light behavior that improves not only the believability of the scene but also the efficiency of on-set lighting workflows. This methodological distinction parallels the evolution from RGB to RGB+ lighting systems; similar in structure, but fundamentally different in capability. Is for that reason why we have to create a clear distinction between both practices and a new name to clearly know what method is being used.

Figure 13: Orchestrated Sub-Frame Kino Flo MIMIK-120 + Christie Digital 240fps Sub-Frame with Mirage Pro

3.3 – HIGH-SPEED SUB-FRAME LASER PROJECTOR SETUP

With the help of Christie Digital Laser Projectors M-4k Series Mirage Pro Upgrade Option, this setup supports high-frame-rate operation at 2K resolution up to 480Hz, making it ideal for multi-layer sub-frame workflows that demand precision synchronization and performance scalability.
This system enables alternating frames within a single shutter exposure, facilitating simultaneous projection of chroma key elements and real-time previsualization for performers; without sacrificing clean compositing channels for post-production.

3.3.1 – SUB-FRAME PROJECTION WORKFLOW

The projector's HFR capabilities allow for intra-frame segmentation, typically divided into four synchronized sub-frame windows per frame. These windows can be assigned independently to Green Screen inputs, Previsualization A/B frames, and auxiliary data layers. Each interval is imperceptible to the human eye but selectively captured by global shutter cameras precisely synchronized to these time windows via SMPTE ST-2110 PTP.
This workflow provides a hybrid production environment where:

- The actor perceives a projected, photorealistic scene.
- The camera captures an isolated green frame for chroma key compositing.
- Lighting states and environmental reflections are dynamically synchronized in real time.

The result is a dual-channel acquisition pipeline: immersive on-set performance meets clean visual data capture.

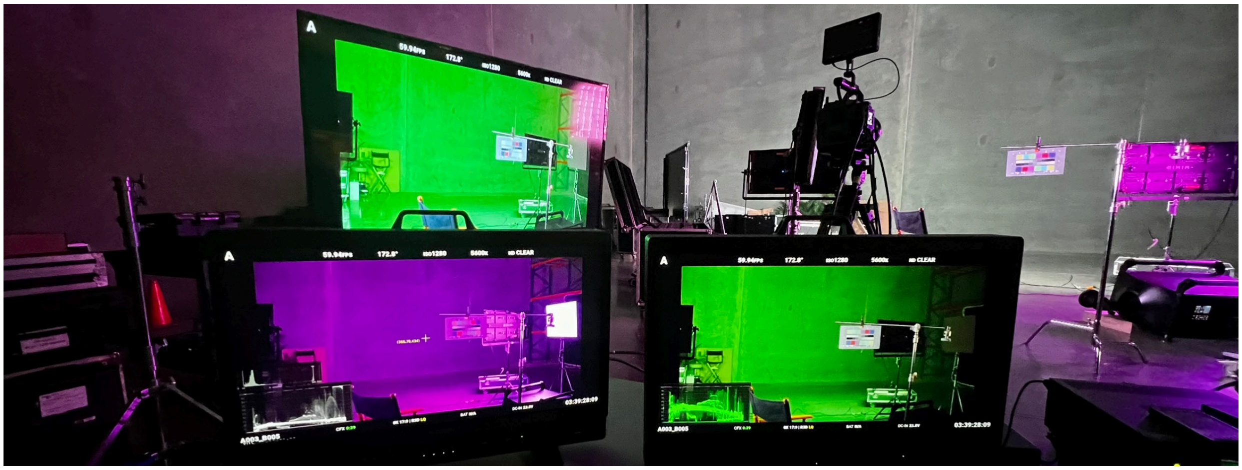


Figure 14: Green/Magenta Sub-Frame R&D validation.

3.3.2 – ALTERNATIVE PROJECTION MODES AND ALPHA MATTE ENHANCEMENT

Beyond the Green + Previz method, the system is also compatible with Green/Magenta alternating frames; a concept pioneered by Paul Debevec; to improve alpha matte clarity. This alternate projection strategy allows for the generation of higher-contrast key signals, which AI-based post-production tools can segment more efficiently. Although this method increases post-processing overhead, it shows strong promise for:
- Cleaner alpha extraction.
- Semantic layer separation.
- AI-assisted compositing pipelines.

Our R&D validates this as a future-ready approach for studios prioritizing depth-based segmentation and volumetric VFX work.

3.3.3 – MULTI-PROJECTOR BLENDING FOR LARGE-SCALE ENVIRONMENTS

The Christie M-Series supports built-in geometric correction and edge blending, enabling seamless image stitching across multiple projectors. This functionality is critical for:
- Panoramic projection across curved green screens.
- Immersive surround visuals on large soundstages.
- Flexible aspect ratios for varied production requirements.

This makes it a superior solution for productions where LED walls may be cost-prohibitive or spatially restrictive.

3.3.4 – DEPLOYMENT EFFICIENCY AND POWER OPTIMIZATION

A fully calibrated sub-frame projection and lighting setup can be deployed in under 6 hours, including SMPTE-2110 time sync, lens alignment, and ambient light calibration. This fast turnaround makes it suitable for:
- Mobile/episodic production teams.
- Stage-in/stage-out setups.
- Multi-location VFX plates acquisition.

Moreover, in contrast to LED volumes; which consume power continuously even in idle states; laser projectors require zero idle power draw, presenting a significant cost-saving and energy efficiency advantage over time.

3.3.5 – PERFORMANCE ENHANCEMENT AND TALENT EXPERIENCE

By projecting real-time previsualization imagery onto physical backdrops, the system drastically reduces green screen fatigue, an issue cited by actors like Christian Bale, Elizabeth Olsen, and Sir Ian McKellen . This method restores spatial awareness, emotional presence, and contextual cues for actors; leading to more natural performances and reducing the need for extensive direction or retakes.

3.4 - SCREEN PROJECTOR SETUP FOR SUB-FRAME VIRTUAL PRODUCTION

The laser projection system for Sub-Frame Virtual Production is designed to operate in sync with high-speed lighting and global shutter cameras. For optimal safety, projection fidelity, and sub-frame accuracy, the screen setup should prioritize vertical surfaces (walls and cycloramas), deliberately excluding floor projection. This avoids direct exposure of laser output toward actors or crew, minimizing the risk of retinal strain and maintaining safe working conditions within the volume.

3.4.1 - PROJECTION DISTANCE AND SPILL CONTROL

While short-throw lenses are capable of achieving precise projections from distances as short as two feet, we recommend a 10–20 feet buffer zone between the projector and the projection surface. This spacing mitigates green or blue chroma spill, ensures uniform beam divergence, and follows traditional VFX lighting principles for isolating talent from keyed backgrounds. This buffer also creates spatial separation for lighting arrays and camera rigs without compromising projection coverage or intensity falloff.

3.4.2 - SUB-FRAME LIGHT AUGMENTATION AND SURFACE RESPONSE

Although laser projectors can generate chroma sub-frames (e.g., full-frame green for keying), we recommend using synchronized MIMIK-120 sub-frame lights for broader coverage and better control over color temperature and spectral consistency. These lights are designed to operate within the same high-frame-rate sub-frame loop, enabling synchronized ambient and image-based lighting (IBL) that mirrors the projection's visual cues and enhances integration.
When extending beyond two sub-frames per frame (e.g., for segmentation masks, AI overlays, or matte generation), the use of lighting-based chroma becomes not only preferable but necessary.

3.4.3 - SCREEN REFLECTIVITY AND CONTRAST RATIO OPTIMIZATION

High-speed laser projection benefits significantly from low-gain, high-contrast projection surfaces. Instead of traditional white screens, which amplify spill and reduce black levels, we recommend projection fabrics or coatings with 30/70 or 40/60 black-to-white reflectivity ratios. These semi-absorbent surfaces allow sharper contrast, deeper blacks, and reduced green spill contamination on talent and physical props.
The gray-walled stage + green-floored configuration introduces a dual-shade chroma strategy, enabling stronger vertical keying while preserving a traditional chroma plane for feet and shadow anchoring. This method benefits 3D tracking and AI segmentation while remaining post-production-friendly.

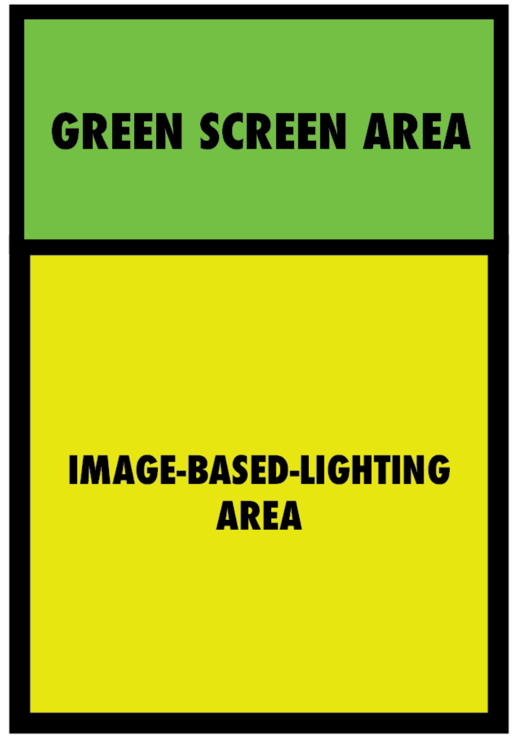


Figure 15: Recommended IBL with Green Screen Areas

A recommended 10-20 foot talent-to-wall buffer zone further minimizes light bounce and chroma contamination. On a 25x25 ft stage, this layout allows enough spatial flexibility to scale IBL simulations or render expansive panoramic previsualization environments.

3.4.4 - SCALABILITY AND POWER EFFICIENCY

Unlike LED walls, laser projection systems are modular, faster to deploy, and dramatically less demanding in terms of power consumption and thermal management. In a standard 160x60x20 ft soundstage, up to four or eight M4k 50K projectors can be deployed to create full-environment projection volumes or targeted scenic coverage.

Such systems can be quickly dismantled, repurposed, or re-rigged for new angles and blocking setups without the weeks-long setup time or calibration loops required by LED volumes. This makes laser projection a more flexible and scalable solution, particularly for short duration productions that require rapid scene transitions or travel-based location stages.

3.4.5 - PROJECTORS AS “FINAL PIXEL” SOLUTIONS

While Sub-Frame Virtual Production primarily emphasizes deferred rendering workflows, it’s important to acknowledge emerging use cases of laser projectors in final pixel delivery. Cinematographer Eric Hasso, notably, has pioneered a methodology for using film plates with laser projectors to achieve high-quality final composites on-set; especially for vehicle scenes and reflection-heavy scenarios. His work exemplifies the creative flexibility of projectors when paired with traditional white flags placed over cars to simulate in-camera reflections effectively.

For productions seeking similar final pixel strategies, Eric’s work offers an innovative blueprint for integrating laser projection as a cost-effective and performant alternative to LED volumes. More about his process can be found at igelkottstudios.com.

Figure 16: www.igelkottstudios.com

3.5 – MEDIA SERVER SETUP FOR SUB-FRAME VIRTUAL PRODUCTION

The deployment of media servers within a Sub-Frame Virtual Production environment is no longer governed by brand allegiance or operator familiarity. Instead, it demands strict adherence to time-synchronized, multi-output, high-performance playback requirements, in full integration with laser projection and lighting systems driven by SMPTE ST-2110-41/42 orchestration. Platforms such as Disguise, Pandora's Box, Pixera, and Assimilate LiveFX are all viable, provided they are configured to support sub-frame precision, high-bandwidth media handling, and real-time camera-tracked rendering.

3.5.1 – CORE CAPABILITIES REQUIRED

To support the demands of hybrid green-screen and projector-based workflows with synchronized lighting systems, all media servers must meet the following functional requirements:

• 3.5.1.1 – Quad Or Higher Independent Outputs:
A minimum of four simultaneously addressable outputs are required. These outputs support frame interleaving workflows such as:
◦ A/B alternating frames for projection vs. chroma
◦ Green/Magenta alternating color streams for Alpha Matte generation
◦ Left/Right eye stereo projection at 120fps per eye for immersive 3D

• 3.5.1.2 – Real-Time 3d Mesh Mapping And Warping:
The ability to apply distortion correction via custom 3D meshes is essential for accurate projection across non-planar surfaces (e.g., curved cycloramas). This feature must maintain spatial coherence with tracked camera data.

• 3.5.1.3 – Frame-Locked High-Bandwidth Playback:
Media servers must support stable real-time playback at high bitrates, utilizing fast caching methods (e.g., NVMe SSDs) and avoiding dropped frames at all costs. All outputs should be timecode-synchronized via ST-2110-41 Delta-Time (Δt) signals for nanosecond-accurate frame alignment.

• 3.5.1.4 – Camera Tracking And Metadata Ingestion:
Seamless integration with camera tracking systems (e.g., Mo-Sys, Vive Mars, OptiTrack) is required. Media servers must process lens parameters, position data, and time-aligned metadata, either directly or via middleware, using ST-2110-41 structured metadata protocols.

3.5.2 – RECOMMENDED ENHANCEMENTS FOR FULL PIPELINE INTEGRATION

To align with the broader orchestration vision of Sub-Frame Virtual Production, additional capabilities are encouraged:

• 3.5.2.1 – Smpte St-2110 Compatibility:
Media servers should be designed for or adapted to SMPTE ST-2110-41/42 metadata orchestration, allowing timestamped projection data to be synchronized alongside other sub-frame elements (lights, cameras, robotics).

• 3.5.2.2 – OpenColorIO Color Pipeline Support:
Integration with OpenColorIO ensures that projection content, chroma key exposure, and composited footage share a unified color space, reducing post-production mismatch and facilitating real-time grading previews
.

• 3.5.2.3 – OSC, DMX, and Lighting Cue Integration:
Real-time control signals (e.g., OSC or DMX) should be supported for synchronization with image-based lighting systems, enabling dynamic ambient response or programmed lighting transitions frame-accurately aligned with playback.

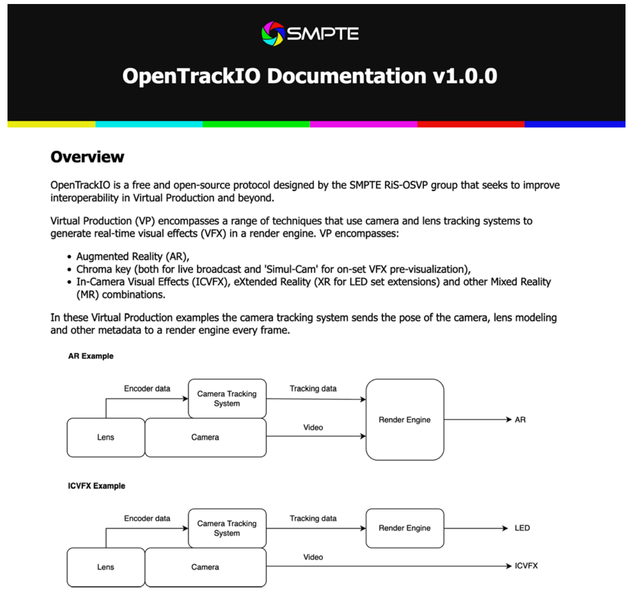
• 3.5.2.4 – GPU Acceleration for AI and ML Pipelines (Optional):
In anticipation of upcoming real-time interpolation or segmentation tasks, support for GPU-accelerated inference models is advantageous. This prepares the system for future integration with on-set AI-enhanced compositing or previs.

3.6 - METADATA RECORDING

At the heart of Sub-Frame Virtual Production lies the need for a precise, unified metadata architecture; one that spans all aspects of the modern production pipeline, including audio, video, camera tracking, lens metadata, motion control systems, color workflows, lighting states, and synchronized projection data. To orchestrate this ecosystem with sub-frame accuracy, a future standard SMPTE ST-2110-41/42 will be adopted as the backbone for metadata transport and synchronization.

3.6.1 - USING THE KLV (KEY-LENGTH-VALUE)
Leveraging Precision Time Protocol (PTP) timestamps, ST-2110-41 enables real-time metadata encapsulation with nanosecond precision. This granularity ensures that all metadata; from positional tracking to lighting cues and camera deltas; is recorded and associated with its corresponding video frame, maintaining deterministic alignment across all departments. This is not only crucial for on-set playback and sub-frame alternation but also for post-production tasks such as compositing, AI-assisted segmentation, and physics-based rendering.

3.6.2 - SMPTE-RIS (OSVP):
The SMPTE Rapid Industry Solutions (RIS) On-Set Virtual Production (OSVP) working group is actively defining industry standards for this next-generation metadata ecosystem. Through collaborative input from manufacturers, studios, and VFX professionals, new open metadata kits such as CAMDKit, OpenLensIO, OpenTrackIO, and OpenColorIO have already been released. These foundational components are designed to integrate seamlessly into the ST-2110-41/42 pipeline, enabling real-time and deferred rendering workflows alike.
For modern virtual production systems, this metadata orchestration provides several key advantages:
• Frame-accurate playback of all dynamic elements (camera moves, light states, projection frames, etc.).
• Seamless post-production with metadata that lives natively alongside image data throughout the pipeline.
• Automated calibration and verification of system components using delta-time comparisons.
• Future-proofing through extensible formats supporting JSON, FreeD, DMX, CAN-BUS, and more.


SMPTE

OpenTrackIO Documentation v1.0.0

Overview

OpenTrackIO is a free and open-source protocol designed by the SMPTE RiS-OSVP group that seeks to improve interoperability in Virtual Production and beyond.

Virtual Production (VP) encompasses a range of techniques that use camera and lens tracking systems to generate real-time visual effects (VFX) in a render engine. VP encompasses:

- Augmented Reality (AR),
- Chroma key (both for live broadcast and 'Simul-Cam' for on-set VFX pre-visualization),
- In-Camera Visual Effects (ICVFX), eXtended Reality (XR for LED set extensions) and other Mixed Reality (MR) combinations.

In these Virtual Production examples the camera tracking system sends the pose of the camera, lens modeling and other metadata to a render engine every frame.

Figure 17: OpenTrackIO.org

The metadata recorded via ST-2110-41/42 effectively will become the digital twin of the production environment, capturing the holistic state of every production frame; not just what the camera sees, but how it was created.

To follow the latest developments and access tools like CAMDKit, visit the SMPTE OSVP initiative at:
https://www.smpte.org/ris and
https://www.opentrackio.org/

Figure 18: 240fps Frame Blended footage

3.7 – INTRA-FRAME AI INTERPOLATION AND VIRTUAL SHUTTER ANGLE SYNTHESIS

The adoption of Sub-Frame Virtual Production at the industry-standard 24 frames per second (fps) presents unique technical and perceptual challenges. While high-speed environments like 120fps or 240fps are ideal for capturing alternating green-screen and projection passes, working at 24fps imposes severe constraints on the available micro-windows per frame. A naïve A/B alternating scheme operating at 48fps—24fps for each layer—produces perceptible flicker, which is both visually disruptive and neurologically uncomfortable for audiences. This is due to the absence of sufficient temporal resolution to isolate each visual channel cleanly.

3.7.1 – TEMPORAL FLICKER AND INFORMA TION LOSS

When operating at 24fps, dividing the frame interval for alternating exposures leads to substantial loss of motion continuity and shutter smoothness. Since each 1/24th second frame (~41.66ms) is shared between two content layers, each layer effectively receives only ~20ms of exposure. This fragmentation reduces motion blur, introduces strobing artifacts, and diminishes the overall visual fidelity. Compounding this issue is the fact that only half of each motion's true arc is captured, causing loss of continuity between frames.

To preserve both motion integrity and visual smoothness, we must reconstruct the lost motion using artificial intelligence-driven frame interpolation algorithms, enabling the system to emulate higher frame rates and motion blur retrospectively.

3.7.2 – FRAME INTERPOLATION: BRIDGING TEMPORAL GAPS

AI-based frame interpolation has emerged as a powerful tool, long used in consumer display devices to increase content frame rates for smoother playback (often associated with the "soap opera effect"). However, the goal here is inverted: instead of converting 24fps to 60fps for smoother motion, we use 240fps source captures to construct more accurate and compositable 24fps footage—a process requiring the interpolation of nuanced intra-frame movements.

In this method, a timeline running at 240fps generates 5 sub-frames for each 1/24th second. However, due to alternating green/projection passes, only half of these sub-frames are usable per modality. This leads to gaps in motion and lighting continuity—precisely where frame interpolation is essential.

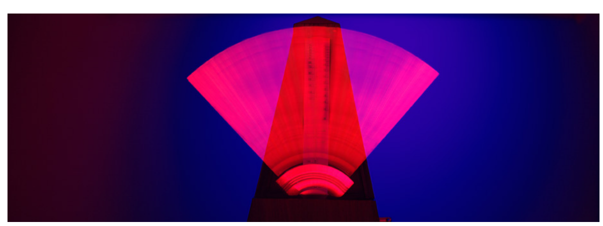


Figure 19: Algorithmic-AI Frame Reconstruction.

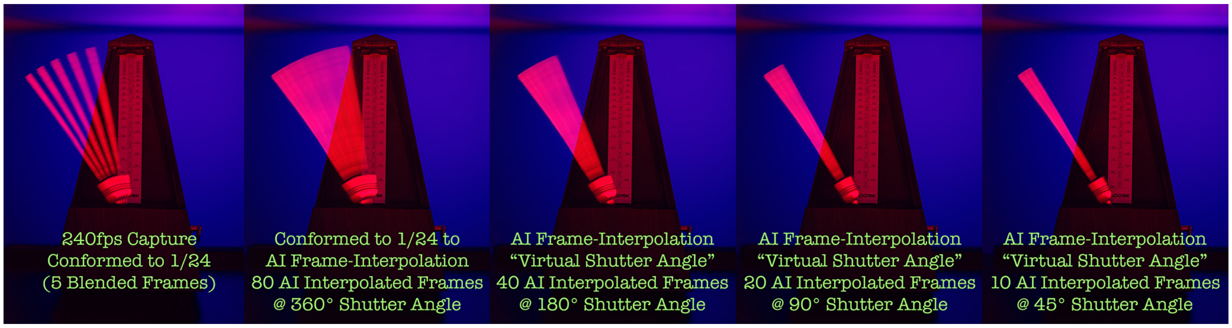


Figure 20: Virtual Shutter Angle with Algorithmic-AI Frame Reconstruction.

3.7.3 – THE VIRTUAL SHUTTER ANGLE CONCEPT

By leveraging frame interpolation to blend between motion samples, we can simulate different shutter angles computationally. A 180° shutter angle traditionally captures motion across half of the frame interval. With AI interpolation, we can synthetically expand this blur across the full interval, essentially emulating a 360° virtual shutter angle. Conversely, reducing the number of interpolated frames can simulate narrower shutter angles, allowing for creative control in post-production. This technique decouples the optical capture from the aesthetic result, enabling cinematographers to manipulate motion blur as a creative parameter, rather than being constrained by camera settings on set.

3.7.4 – INTERPOLATION MODELS AND THEIR STRENGTHS

There are multiple open-source and commercial models available to perform frame interpolation. Each has unique strengths:

- RIFE (Real-Time Intermediate Flow Estimation): Optimized for real-time playback, RIFE offers high performance with decent quality—ideal for on-set previews.
- FLAVR: Avoids optical flow entirely; useful in high-motion scenarios with minimal ghosting.
- FILM (Google Research): Excels at handling large object motion and occlusions.
- DAIN (Depth-Aware Interpolation): Incorporates depth for parallax-corrected in-betweens.
- SVP & FlowFrames: User-friendly and GPU-accelerated, useful for batch processing.
- Topaz Video AI: The leading commercial solution in this space. Its proprietary models, including Apollo, Chronos, and Aion, push the frontier of quality.

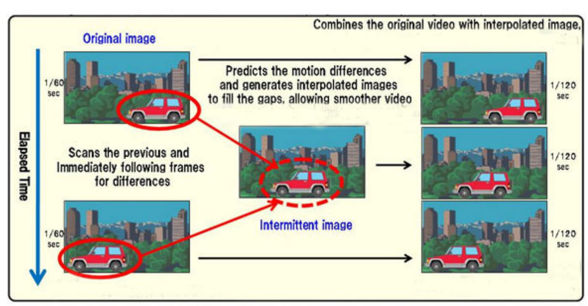
3.7.5 – ALION: THE INDUSTRY-READY MODEL

For this white paper's methodology, we conducted extensive testing using Topaz Video AI's "Aion" model, an evolution of Apollo with support for large motion reconstruction. Aion uses Support Vector Regression (SVR) to infer movement between frames with remarkable temporal coherence. In testing, Aion was used to interpolate 5 captured frames into 80 synthetic subframes per 1/24th second, simulating motion continuity that rivals native high-speed footage.

This results in 384 synthesized frames per second, effectively converting hybrid-captured material into smooth, photorealistic 24fps footage with full motion blur and no perceptual gaps.

3.7.6 – REGRESSION VS NON-REGRESSION INTERPOLATION

Our tests demonstrated that interpolation models without predictive regression—like Chronos and Chronos Fast—fail to reconstruct intra-frame blur adequately, resulting in ghosting and visual stutter. These non-regression models proved insufficient for the demands of sub-frame virtual production and were therefore excluded from further testing.



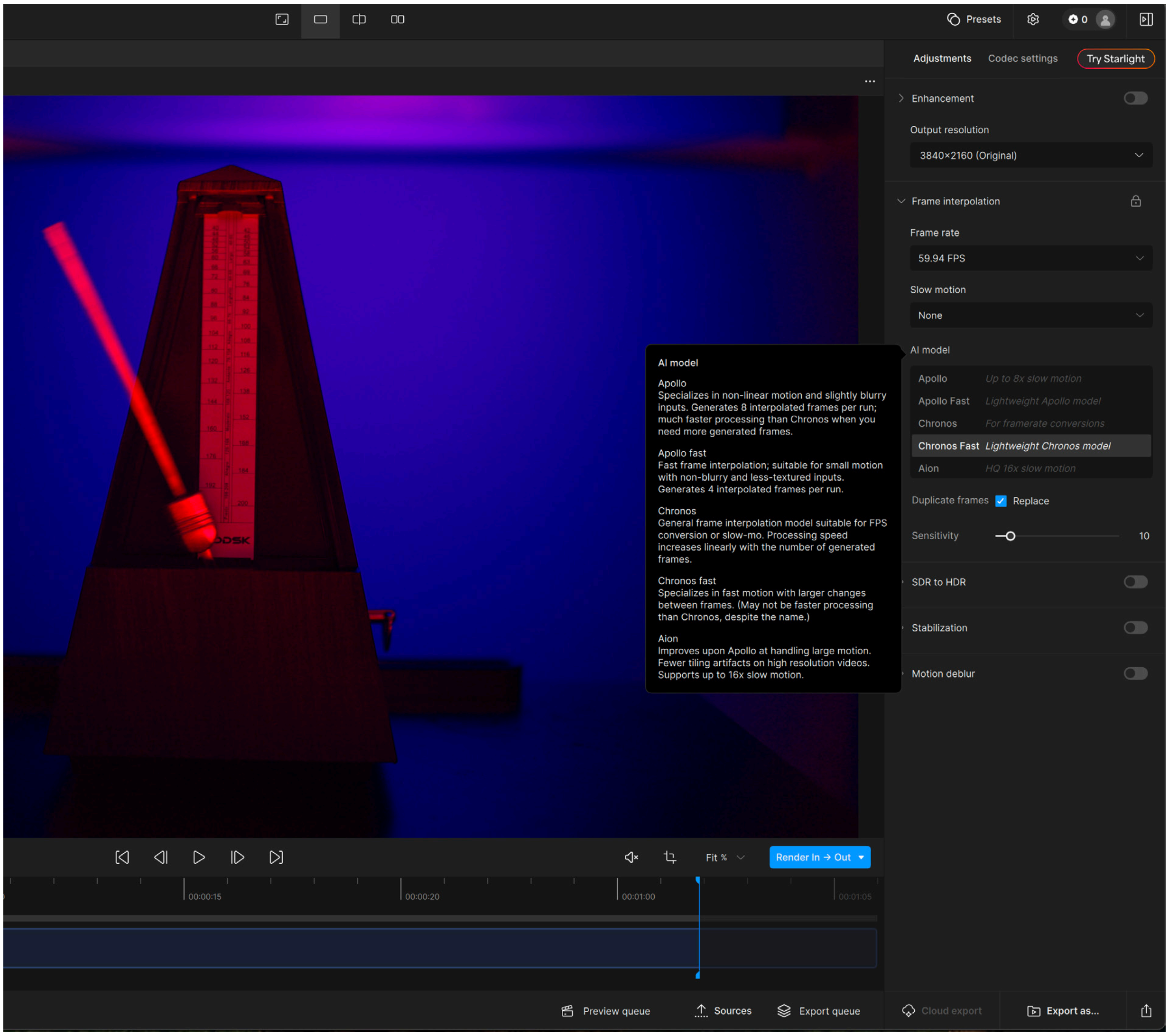


Figure 21: Topaz AI Video with “Alion” AI Model (x16 frame interpolation out of 2 Frames

Figure 22: 240fps Frame Blended footage

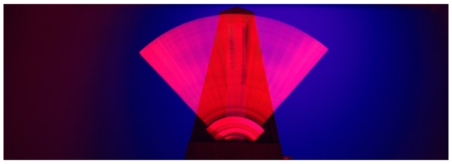


Figure 23: Algorithmic-AI Frame Reconstruction.

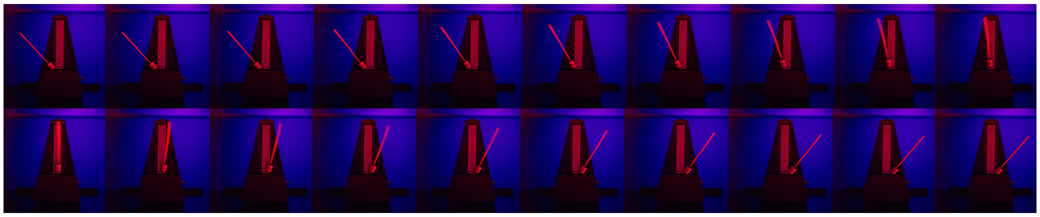


Figure 24: Original capture frames (180 degree result)

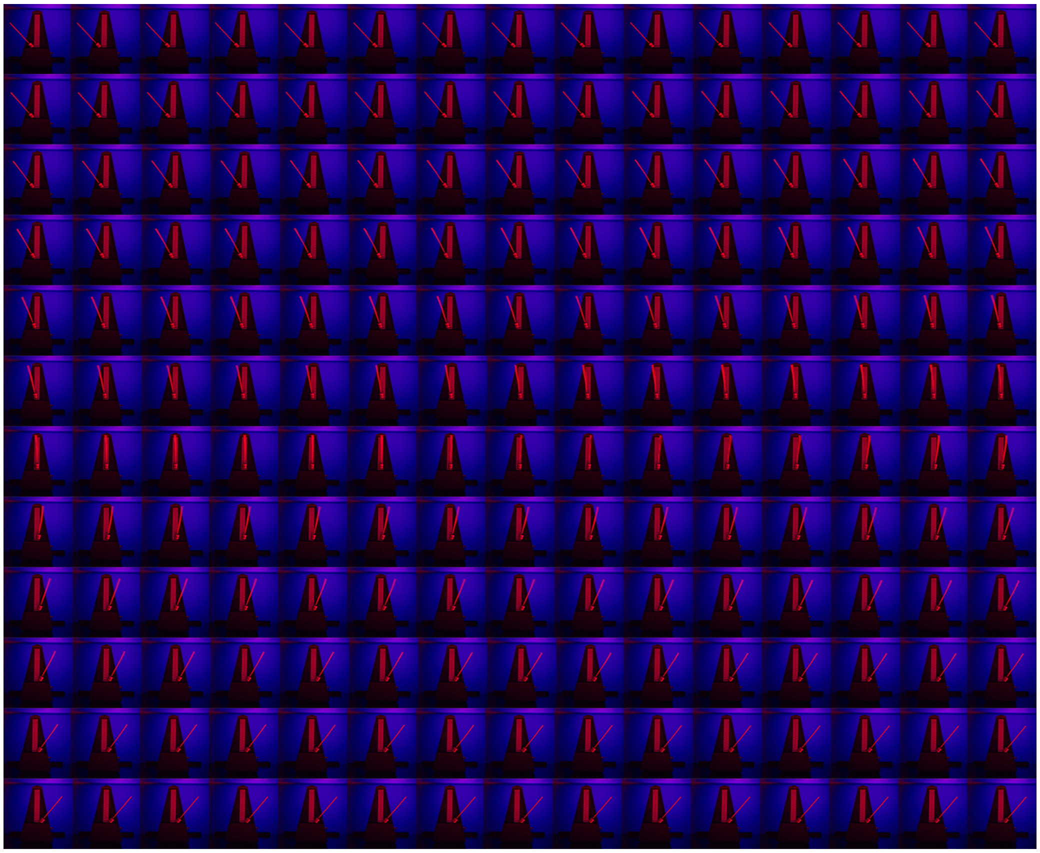
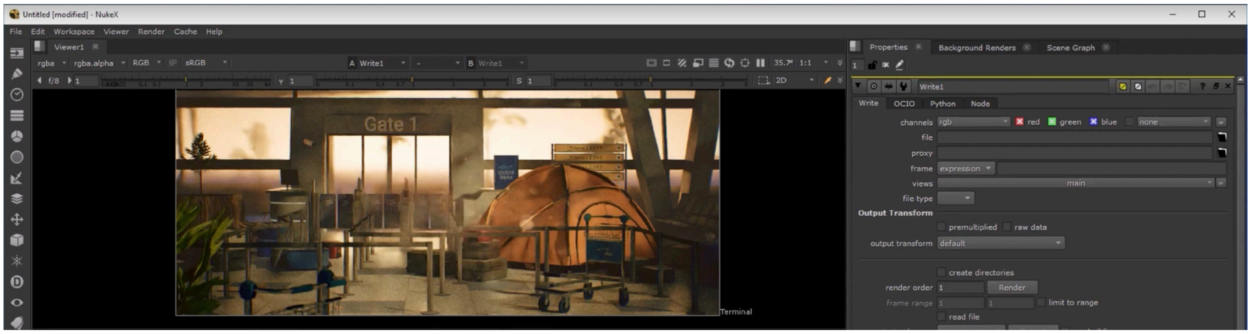


Figure 25: Alion model (x16 Frame interpolation reconstruction)



3.8 - DEFERRED RENDER WORKFLOW:

Hybridizing Real-Time Visualization with Post-Production Precision

In the evolving landscape of virtual production, the concept of capturing “final pixel” in real-time remains more aspirational than practical. While tools like Unreal Engine offer stunning real-time visualizations, these systems are ultimately constrained by rendering compromises, system latency, and real-time computational limits. As a result, real-time rendering should be positioned as a previsualization layer; an on-set assistive tool; not as the definitive image pipeline for final delivery with CGI pipelines.

Deferred rendering workflows provide a robust alternative, prioritizing the decoupling of live-action capture from real-time rendering constraints. This approach empowers cinematographers and performers with immersive environments during production while preserving the freedom to finalize visuals with high-fidelity tools such as Nuke, Fusion, or AI-assisted render engines in post.

3.8.1 - SUB-FRAME VIRTUAL PRODUCTION ENABLING DEFERRED RENDERING

The Sub-Frame methodology introduced in this paper enhances the deferred render workflow through high-speed synchronization. Using global shutter cameras and SMPTE ST-2110-41/42 synchronized metadata, two visual layers are captured within a single exposure window:

- A green-screen frame, invisible to the human eye but cleanly captured by the camera.
- A projected real-time previsualization frame, visible to the cast and crew for emotional, spatial, and creative context.

This sub-frame alternation, timed with nanosecond-level Δt (delta time) precision, maintains compositing integrity while enabling natural performances. The immersive frame provides actors with immediate visual feedback; crucial in overcoming “green screen fatigue”; without compromising the clean keying and tracking required for post.

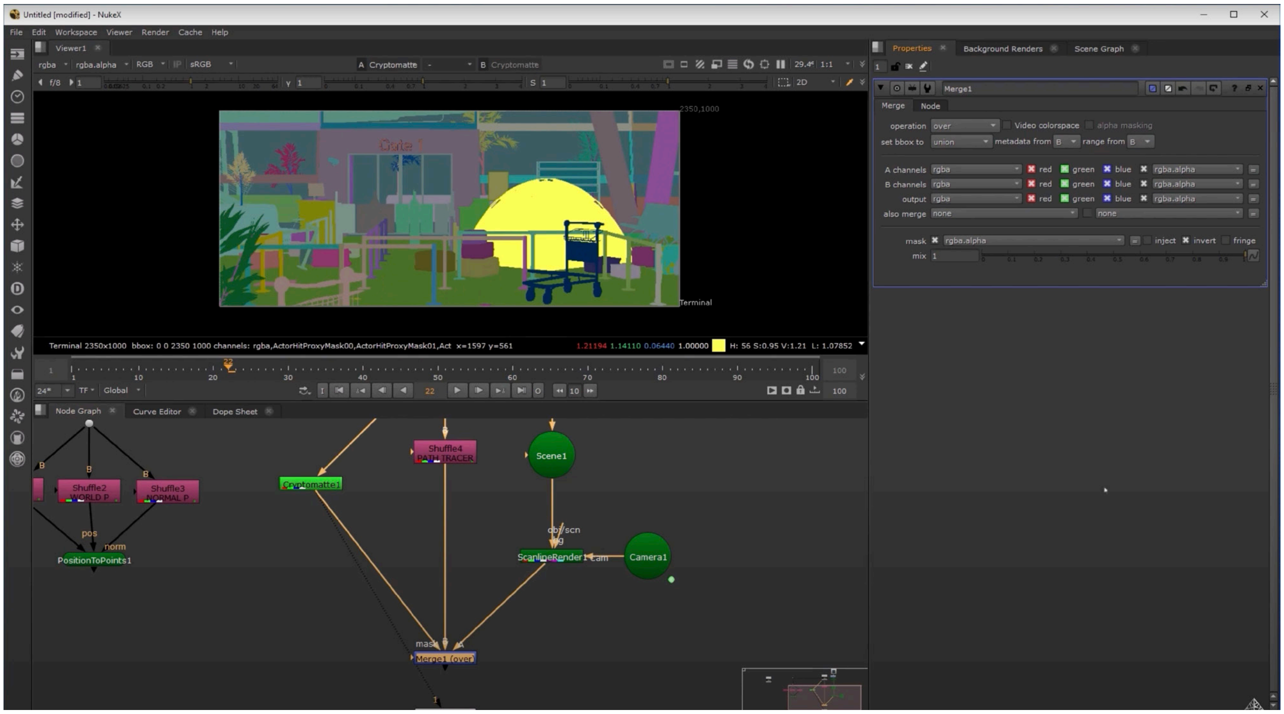
By embedding all relevant metadata (camera position, lens data, lighting cues, etc.) into the footage via SMPTE-2110, Sub-Frame workflows eliminate the need for redundant tracking passes or manual metadata alignment during post. This allows renders of the same Unreal Engine environment to be reproduced offline using tools like Nuke’s UnrealReader, with superior control over lighting, exposure, resolution, and parallax consistency.

3.8.2 - FROM REAL-TIME PREVIS TO FINAL-PIXEL PRECISION

In practical terms, this workflow enables the generation of high-quality renders immediately after the shoot, without requiring real-time output fidelity. During production, Unreal Engine or other 3D renderers generate low-latency previsualization feeds for director and actor reference. These frames guide creative intent and motion cues but are not used in the final composite.

Once the scene is captured, the same camera and tracking metadata; recorded with frame-accurate Δt precision; can be reapplied to re-render the environment in full quality. This enables:

- Post-processed “final pixel” renders using higher fidelity offline tools.
- AI-driven segmentation, reflections, and lighting overlays synchronized with the original performance.
- Clean chroma key isolation, avoiding real-time rendering artifacts like moiré, dropped frames, or compression losses.



Crucially, this decoupled approach restores creative flexibility, allowing directors to make nuanced adjustments after the fact without reshooting. Whether for last-minute lighting tweaks, environment changes, or stereo 3D refinement, the deferred render model future-proofs the production pipeline without sacrificing immediacy on set.

3.8.3 - CLOUD-BASED RENDERING AND PIPELINE INTEGRATION FOR DEFERRED WORKFLOWS

As deferred rendering becomes the preferred strategy in Sub-Frame Virtual Production, cloud-based solutions are emerging as the backbone of scalable rendering pipelines. By decoupling visualization from real-time constraints, productions gain the flexibility to shift rendering tasks to GPU-accelerated cloud services such as AWS Thinkbox, Azure Batch, or Google Cloud Render Farm, without compromising speed or fidelity.

Key Advantages of Cloud Integration:

• 3.8.3.1 - On-Demand Rendering Power: Production teams can tap into hundreds of GPUs simultaneously, drastically reducing render times for high-resolution sequences. This is particularly beneficial for immersive 3D or stereo 180°/360° content that exceeds the capabilities of on-premise hardware.

• 3.8.3.2 - Parallelized Multi-Version Output: Multiple versions of the same take (e.g., lighting variations, FX passes, different environments) can be rendered in parallel without impacting the live shoot or bottlenecking editorial decisions.

• 3.8.3.3 - Seamless Unreal-to-Nuke Pipeline: Using tools like UnrealReader (Nuke) or Disguise RenderStream, teams can ingest previsualized Unreal scenes with all associated metadata and re-render them with higher fidelity. With SMPTE ST-2110 delta time alignment, the same frame structure captured during the shoot is preserved during cloud rendering.

• 3.8.3.4 - Remote Collaboration and Instant Dailies: Cloud-based platforms allow VFX supervisors, colorists, and editors to review near-final quality composites within hours; often the same day. This enables on-location dailies review in HDR or stereo, vastly accelerating decision-making cycles.

tion. These platforms are now extending into deferred rendering with enhanced Unreal integrations and API hooks to trigger cloud render jobs based on captured metadata.

4 - SIGNIFICANCE AND BROADER IMPACT

High-Speed Sub-Frame Virtual Production represents more than an incremental improvement in filmmaking workflows; it signifies a strategic rethinking of how real and virtual elements can coexist on set; with precision, efficiency, and creative freedom. By shifting the paradigm from "final pixel in-camera" to "clean compositing-ready capture with immersive visualization"; this approach offers an agile and future-resilient framework for storytelling across all formats.

The significance lies in its accessibility and adaptability. Productions that were previously priced out of LED volume systems now have access to immersive environments with minimal infrastructure; enabling independent filmmakers, educational institutions, and live event teams to adopt virtual production workflows without needing to overhaul their technical ecosystem. The portability of this system means it can scale vertically within large studio pipelines or horizontally across location shoots, mobile units, and non-traditional soundstages.

In post-production, the synchronized metadata layer eliminates the friction between acquisition and finishing. By embedding delta-time values, lighting states, and lens data directly into the recorded media via SMPTE ST-2110; editors, compositors, and AI-driven tools have immediate access to the contextual information needed for automation, reconstruction, and versioning. This shift in data availability will increasingly define the pipelines of visual storytelling—from VFX-heavy features to real-time editorial feedback in television and streaming.

The impact of this methodology also extends well beyond entertainment. As a Reality Environment Simulation System (RESS), High-Speed Sub-Frame Virtual Production has direct applications in fields such as:

• XR and Volumetric Theater; where real-time audience interaction depends on environment fidelity and synchronized cues;
• Simulation Training and Defense; where sub-frame accuracy enables predictive AI models and reactive environments;
• Autonomous Robotics and Machine Vision; where synchronized lighting and segmentation layers improve sensor calibration and testing conditions;
• Digital Twins and Smart Manufacturing; where previsualization overlays and spatial reference systems enhance remote monitoring, diagnostics, and collaborative design;
• Multimodal AI Research; where live-captured environments paired with precise metadata create robust datasets for training vision-language and motion-interaction models.

By bridging physical performance with digitally orchestrated realities; High-Speed Sub-Frame Virtual Production opens the door to collaborative systems that are modular, interoperable, and time-aware. It removes the creative and economic limitations of static hardware-based systems; and replaces them with programmable environments that can evolve alongside the needs of both artists and engineers.

This convergence of performance, simulation, and computation places High-Speed Sub-Frame Virtual Production not just at the edge of film innovation; but at the core of a new generation of synchronized visual technologies.

Sub-Frame_Virtual_Production_with_Synchronized_Lighting_Systems_And_High-Frame-Rate_Laser_Projectors_2025_091_1600_v1r2

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