

CLOUD ARENA: STREAMING REAL-TIME RAY-TRACED VIRTUAL PRODUCTION ICVFX ENVIRONMENTS ACROSS GLOBAL CLOUD INFRASTRUCTURE

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Figure A The "Ray Tracing FTW" set

ABSTRACT

Virtual Production (VP) ICVFX systems traditionally rely on tightly coupled local infrastructure in which render nodes, camera tracking systems, operator workstations, synchronization hardware, and display processors coexist on a shared low-latency network. While cloud computing has transformed offline rendering and digital content creation workflows, real-time Virtual Production remains largely dependent upon local GPU resources due to concerns regarding latency, synchronization, and deterministic frame delivery.

This paper presents Cloud Arena, a collaborative proof-of-concept investigation conducted by Chaos Innovation Lab and CenterGrid to evaluate the feasibility of operating Chaos Arena and Chaos Vantage across geographically distributed cloud infrastructure. Using a milestone-based methodology, the investigation progressively migrated rendering, orchestration, and operator services into cloud-hosted virtual machines located in Hamilton, Ohio, United States of America while validation activities were conducted from the Netherlands and Bulgaria.

The results demonstrate that cloud-hosted rendering, cloud-hosted orchestration, remote operator workflows, and globally distributed validation environments are practical without modification to the underlying rendering system. Contrary to initial expectations, transport latency did not emerge as the primary limitation. Instead, deterministic synchronization and frame alignment across independently rendered outputs became the principal technical challenge.

The paper concludes by proposing a future cloud-native synchronization architecture based on deterministic frame generation, metadata-preserving transport, frame alignment services, and synchronized presentation pipelines capable of supporting large-scale LED volume deployments.

CCS CONCEPTS

- Computing methodologies → Virtual Production
- Computing methodologies → Real-time rendering
- Networks → Distributed systems
- Computer systems organization → Cloud computing
- Applied computing → Media arts

KEYWORDS

Virtual Production, ICFVFX, Cloud Rendering, Chaos Arena, Chaos Vantage, Distributed Rendering, Real-Time Ray Tracing, LED Volumes, NDI, Synchronization, Cloud Infrastructure

1 INTRODUCTION

Virtual Production has transformed modern filmmaking by combining real-time rendering, camera tracking, and large-scale LED display systems into a unified production environment. By allowing computer-generated environments to be rendered interactively and displayed in-camera, Virtual Production enables directors, cinematographers, and visual effects teams to collaborate within a shared visual context during principal photography.

Despite advances in rendering technology, most Virtual Production systems continue to rely on a fundamental architectural assumption: critical services must remain physically co-located. Render nodes, operator systems, camera tracking devices, synchronization hardware, and LED processors are typically deployed within a common facility and interconnected through dedicated high-speed local-area networks.

This assumption has persisted largely because Virtual Production introduces requirements not commonly encountered in traditional cloud-rendering environments. Unlike offline rendering workflows, Virtual Production requires continuous real-time rendering, deterministic frame delivery, camera-tracking responsiveness, and synchronized presentation across multiple display surfaces.

The rapid maturation of cloud GPU infrastructure raises an important question. If rendering workloads can successfully operate within cloud-hosted environments, is physical co-location still required?

The Cloud Arena investigation originated from this question. The project began as a low-cost proof-of-concept jointly conducted by Chaos Innovation Lab and CenterGrid. Rather than developing new rendering technologies, the objective was intentionally constrained: determine whether an existing production-grade Virtual Production platform could successfully operate when its components were deployed across geographically distributed cloud infrastructure.

1.1 The Rise of Virtual Production

Over the last decade, Virtual Production ICFVFX has evolved from an experimental workflow into a mainstream production methodology. Advances in GPU performance, real-time ray tracing, LED display technologies, and camera tracking systems have enabled increasingly sophisticated in-camera visual effects workflows.

Most commercial deployments utilize architectures similar to the model illustrated in Figure 1. Rendering systems, operator workstations, synchronization hardware, camera tracking devices, and display processors typically coexist within a tightly controlled local environment.

Figure 1. Traditional Virtual Production ICVFX deployment architecture

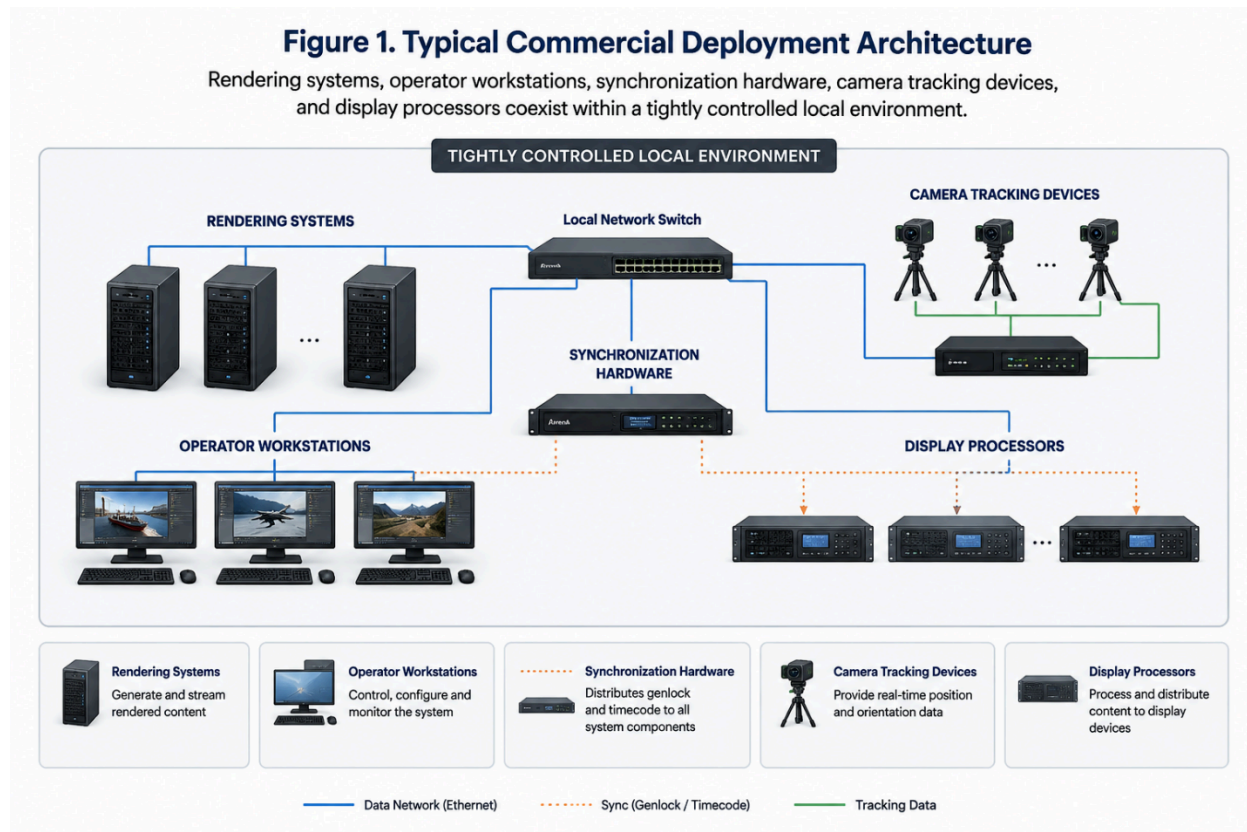


Figure 1. Traditional Virtual Production deployment architecture. Rendering, synchronization, operator control, tracking systems, and display processors are commonly deployed within a shared local-area network. Additional architectural details are provided in Appendix B3.

Figure 1. Supplement S1 Hi res image link:

<https://cgvirtualstudio.com/wp-content/uploads/2026/06/Fig-1-Tradtional-Workflow.png>

While effective, these architectures inherently limit geographic flexibility and infrastructure scalability.

1.2 Problem Statement

The widespread adoption of cloud computing has transformed animation, visual effects, simulation, and content creation workflows. Cloud-hosted GPU resources now provide scalable access to rendering infrastructure previously available only through significant capital investment.

However, real-time Virtual Production remains largely dependent upon local hardware deployments. Concerns regarding latency, synchronization, tracking responsiveness, and frame determinism have historically discouraged cloud-based deployment models.

As a result, relatively little empirical data exists regarding the behavior of production-oriented Virtual Production systems operating across geographically distributed cloud infrastructure.

1.3 Research Question

The central research question investigated by Cloud Arena is:

Can a professional real-time ray-traced Virtual Production platform successfully operate across geographically distributed cloud infrastructure without modification to the underlying rendering system?

1.4 Contributions

This paper makes five primary contributions:

Table B1. Primary Contributions of the Cloud Arena Investigation

Contribution	Validation Method	Outcome
Cloud-hosted Chaos Vantage rendering	Milestone 01	Successfully operated within GPU-passthrough virtual machines
Cloud-hosted Arena orchestration	Milestone 02	Arena Server successfully migrated to cloud infrastructure
Global workflow validation	Milestone 03	Workflow operated across North America and Europe
Incremental validation methodology	Three-stage milestone framework	Provided repeatable deployment strategy
Synchronization analysis	Cross-milestone observations	Identified deterministic frame alignment as primary challenge

2 RELATED WORK

2.1 Cloud Rendering

Cloud computing has become a foundational technology within modern digital content creation pipelines. Distributed rendering infrastructures have demonstrated significant scalability for offline rendering workloads, while GPU virtualization technologies have enabled professional creative applications to operate remotely from centralized infrastructure.

Advances in GPU passthrough, remote display protocols, and cloud workstation technologies have further reduced the distinction between local and remote computing environments. These developments have enabled artists to access high-performance resources independent of physical location.

However, most published cloud-rendering research focuses primarily on offline rendering, simulation, and content creation workflows rather than real-time Virtual Production systems.

2.2 Virtual Production Systems

Virtual Production environments introduce requirements significantly different from conventional cloud-rendering workloads. Real-time rendering systems must continuously respond to camera movement, operator interaction, and production events while maintaining deterministic visual output.

Modern Virtual Production platforms typically integrate:

- Real-time rendering engines
- Camera tracking systems
- Lens metadata acquisition
- Multi-display synchronization
- LED volume presentation systems

These requirements create dependencies on synchronization and timing mechanisms that are often absent from traditional cloud-rendering architectures.

2.3 Remote Production

Recent industry developments have demonstrated growing interest in remote and distributed production workflows. Cloud-assisted production systems have enabled remote review, virtual scouting, collaborative content creation, and geographically distributed production teams.

While these solutions validate aspects of remote operation, relatively little published research exists examining fully ray-traced Virtual Production systems operating across geographically distributed cloud infrastructure with rendering, orchestration, and operator services separated by thousands of kilometers.

2.4 Limited Empirical Evidence

Existing literature demonstrates the viability of cloud rendering and remote production workflows independently. However, limited empirical evidence exists regarding the operation of production-oriented Virtual Production systems deployed across globally distributed cloud infrastructure.

Cloud Arena contributes empirical observations from a real-world deployment of Chaos Arena and Chaos Vantage spanning multiple countries and multiple deployment models. The investigation focuses not on theoretical architectures, but on the practical behavior of an existing production platform operating within cloud-hosted infrastructure.

Table B2. Comparison with Prior Research

Capability	Cloud Rendering Research	Remote Production Research	Traditional VP Systems	Cloud Arena
Cloud GPU utilization	✓	Partial	Limited	✓
Real-time rendering	Partial	Partial	✓	✓
Camera tracking integration	X	Partial	✓	✓

Capability	Cloud Rendering Research	Remote Production Research	Traditional VP Systems	Cloud Arena
Distributed operation	Partial	✓	✓	✓
Virtual Production focus	X	Partial	✓	✓
Multi-country deployment	Rare	Partial	X	✓

3 CHAOS ARENA ARCHITECTURE

Chaos Arena is a software-based Virtual Production platform designed to coordinate real-time ray-traced rendering, camera tracking, operator interaction, and synchronized display presentation. Unlike traditional game-engine-based Virtual Production solutions, Arena utilizes Chaos Vantage as its primary rendering engine, enabling physically accurate ray-traced visualization within a production environment.

The baseline Arena architecture consists of three principal software components:

- Arena Server
- Arena Renderer
- Arena Operator

A supporting Chaos License Server manages software licensing and node authorization across the deployment.

Figure 2. illustrates the standard Arena deployment model used as the baseline architecture for the Cloud Arena investigation.

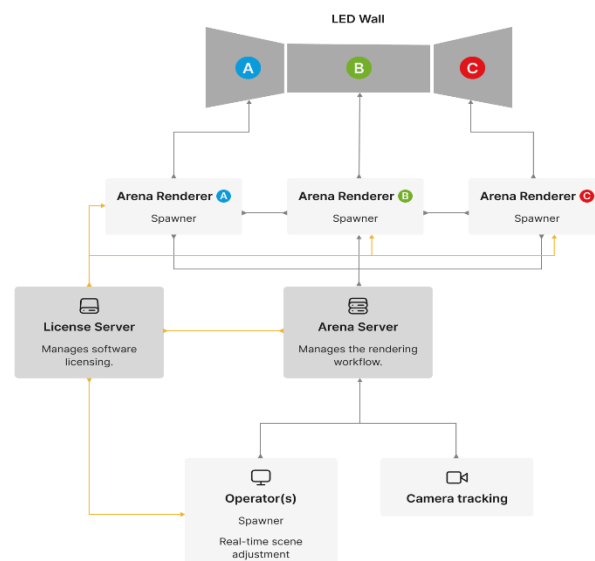


Figure 2. Traditional Chaos Arena deployment architecture. Arena Server coordinates camera tracking, scene management, synchronization services, and operator communication while multiple Arena

Figure 2. Supplement S2 Hi res image link:

<https://cgvirtualstudio.com/wp-content/uploads/2026/06/Fig2.png>

Renderer nodes generate imagery for segmented LED wall displays. Additional component details are provided in Appendix B3.

3.1 Arena Server

Arena Server functions as the central orchestration layer of the system. It manages communication between operator systems, camera tracking devices, rendering nodes, and synchronization services.

Primary responsibilities include:

- Render-node management
- Scene distribution
- Camera tracking integration
- Resolution management
- Focus and lens metadata distribution
- Synchronization services
- Operator communication

Within a traditional deployment, Arena Server commonly resides on the same workstation as Arena Operator or other production-control systems.

3.2 Arena Renderer

Arena Renderer serves as the image-generation component of the platform and utilizes Chaos Vantage as the underlying rendering engine.

Each renderer is responsible for generating imagery associated with a specific display region or LED wall segment. In multi-display environments, multiple renderer instances may operate simultaneously while maintaining synchronization through Arena Server.

Arena Renderer receives scene updates, camera transformations, lens metadata, and synchronization instructions from Arena Server before generating the final ray-traced image output.

3.3 Arena Operator Nodes

Arena Operator provides the primary user interface through which production personnel interact with the system.

Typical operator functions include:

- Scene loading
- Environment control
- Asset management

- Lighting adjustment
- Production monitoring
- Render-node management

Operator systems communicate directly with Arena Server, which distributes commands throughout the deployment.

3.4 Traditional Deployment Model

A minimum Arena deployment requires at least one Arena Server, one Arena Renderer, and one Arena Operator instance. Additional render nodes may be added to support larger LED volumes or higher-resolution display configurations.

Traditional deployments generally assume:

- Shared local-area networking
- Dedicated synchronization hardware
- Physical proximity of all services
- High-bandwidth interconnects
- Low-latency communication paths

These assumptions simplify synchronization and frame delivery but limit deployment flexibility and infrastructure scalability.

Cloud Arena was specifically designed to determine whether these assumptions could be relaxed while maintaining operational functionality.

Table B3. Chaos Arena System Components

System Component	Subcomponents	Responsibilities
LED Wall System	Segments A–C	Displays rendered imagery
Arena Renderer	Renderer A–C, Spawner	Generates imagery for assigned display regions
Arena Server	Central orchestration service	Synchronization, tracking, scene management
Camera Tracking System	Mars Vive, OptiTrack, Mo-Sys, Stype	Position, orientation, lens metadata
Arena Operator	Control interface	Scene and production management
License Server	Licensing service	Software validation and licensing
Communication Layer	Internal services	Data transport and coordination

Table B3 summarizes the primary system components investigated during the study.

4 EXPERIMENTAL METHODOLOGIES

The Cloud Arena investigation was intentionally structured as an incremental proof-of-concept rather than a full-scale engineering effort. The objective was to validate feasibility before committing significant development resources.

Rather than redesigning Chaos Arena for cloud operation, the investigation focused on determining whether the existing software could operate successfully within geographically distributed cloud infrastructure.

The methodology followed four guiding principles:

1. Begin with the simplest possible deployment.
2. Increase complexity only after successful validation.
3. Avoid modifications to Arena source code.
4. Validate assumptions before dedicating engineering resources.

This approach enabled rapid experimentation while minimizing infrastructure costs and engineering overhead.

4.1 Design Philosophy

The project was developed around a milestone-driven validation strategy.

Each milestone isolated a specific architectural assumption commonly associated with traditional Virtual Production deployments. Once validated, the next milestone increased deployment complexity while preserving operational functionality.

The progression followed three phases:

- Milestone 01 — Cloud Renderer Validation
- Milestone 02 — Cloud Server Validation
- Milestone 03 — Global Workflow Validation

Figure 3. illustrates the progression of the investigation.



Figure 3. Milestone-based validation strategy used throughout the Cloud Arena investigation. Each milestone incrementally increased architectural complexity while validating a specific deployment assumption.

Figure 3. Supplement S3 Hi res image link:
<https://cgvirtualstudio.com/wp-content/uploads/2026/06/progression-of-the-investigation.png>

4.2 Cloud Infrastructure

Cloud infrastructure was provisioned through CenterGrid's Virtual Studio platform located in Hamilton, Ohio, USA.

The environment utilized Windows 11 virtual machines hosted on a Type-1 hypervisor with dedicated GPU passthrough. NVIDIA RTX A6000 GPUs were assigned directly to virtual machines, allowing Arena services to access hardware-accelerated rendering resources without software-based GPU virtualization.

The cloud infrastructure was intentionally configured using commercially available technologies rather than custom hardware to evaluate practical deployment viability.

Table B4. Cloud Infrastructure Utilized Throughout the Cloud Arena Investigation

Infrastructure Component Specification	
Cloud Provider	CenterGrid Virtual Studio
Data Center Location	Hamilton, Ohio, USA
Deployment Model	Cloud-hosted GPU Virtual Machines
Host Platform	Bare-Metal Servers
Virtualization	Type-1 Hypervisor
Guest Operating System	Windows 11
GPU Configuration	Dedicated GPU Passthrough
Primary GPU Resources	NVIDIA RTX A6000 GPUs
Remote Access	Parsec
Virtual Networking	Hamachi
Arena Version	Chaos Arena v1.5

Table B4. summarizes the cloud infrastructure utilized throughout the investigation. Detailed infrastructure specifications are provided in Appendix B4.

4.3 Networking Architecture

A primary objective of the investigation was to minimize architectural changes to the existing Arena platform.

To accomplish this, networking was implemented using commercially available software solutions.

Hamachi was selected to create a unified virtual private network spanning all participating systems. This approach enabled Arena services to communicate as though operating within a common local network despite geographic separation.

Parsec was utilized for remote workstation access and image transport due to its low-latency operation and support for high-quality remote visualization workflows.

The resulting architecture allowed cloud-hosted services, operator systems, validation workstations, and tracking devices to communicate through a shared logical network topology.

4.4 Milestone Strategy

The investigation progressed through three validation milestones.

Milestone 01 focused on determining whether Chaos Vantage and Arena Renderer could successfully operate inside a cloud-hosted virtual machine utilizing GPU passthrough.

Milestone 02 evaluated migration of Arena Server into cloud infrastructure and examined the effects of consolidating orchestration and rendering services within the cloud environment.

Milestone 03 expanded the architecture into a fully distributed deployment spanning the United States, the Netherlands, and Bulgaria while incorporating production-style validation systems, camera tracking hardware, and remote display endpoints.

Milestone Objective

01 Validate cloud-hosted rendering

02 Validate cloud-hosted orchestration

03 Validate globally distributed workflows

Successful completion of each milestone established the foundation for the next phase of the investigation and ultimately enabled evaluation of a cloud-native Virtual Production workflow spanning multiple countries.

5 MILESTONE 01 — CLOUD RENDERER VALIDATION

The first phase of the Cloud Arena investigation focused on validating whether Chaos Vantage and Arena Renderer could successfully operate within a cloud-hosted virtual machine utilizing GPU passthrough. This milestone represented the simplest possible cloud deployment and was designed to test the most fundamental assumption of the project: can a production-grade real-time renderer function remotely without modification?

5.1 Objective

Milestone 01 sought to validate five key requirements:

- GPU passthrough functionality
- Chaos Vantage operation within a virtual machine
- Arena Renderer operation within a virtual machine
- Remote operator control across international distances
- Long-distance camera-tracking data transport

The architecture intentionally preserved the traditional Arena deployment model. Arena Server and Arena Operator remained on a physical workstation located in the Netherlands while Arena Renderer was migrated into CenterGrid cloud infrastructure in Hamilton, Ohio.

5.2 Infrastructure

The cloud environment consisted of a Windows 11 virtual machine configured with direct GPU passthrough using NVIDIA RTX A6000 resources. Arena Renderer and Chaos Vantage were installed within the virtual machine without modification.

Arena Server and Arena Operator remained on a Dell Precision 7750 workstation located in Enschede, Netherlands. Camera-tracking data was generated through a tracking-data emulation system and transmitted through the virtual network.

The resulting deployment operated across an approximate geographic separation of 9,900 km between the rendering infrastructure and production-control systems.

Table B5. Cloud Infrastructure Utilized Throughout the Cloud Arena Investigation

Component	Location	Hardware	Software
Cloud Render Node	Hamilton, Ohio USA	2 × NVIDIA RTX A6000, 64 GB RAM, 2 TB Storage	Windows 11, Chaos Arena v1.5, Arena Renderer, Chaos Vantage, Hamachi, Parsec
Operator / Server Workstation	Netherlands	Dell Precision 7750, NVIDIA RTX 5000, 16 GB VRAM, 64 GB RAM, 1 TB Storage	Windows 10, Arena Operator, Arena Server, Tracking Data Streamer, Hamachi, Parsec
Helper Node/ Secondary Ground Machine	Netherlands	Intel NUC 11 PHKi7C, NVIDIA RTX 2060, 6 GB VRAM, 64 GB RAM, 1 TB Storage	Windows 10, Parsec

5.3 Networking

Networking was established using Hamachi virtual networking to create a unified logical network between cloud-hosted and ground-based systems.

Remote visualization and operator access were provided through Parsec. Camera-tracking information and Arena communications were transported across the same virtual network infrastructure.

This configuration enabled Arena Renderer to appear as a standard network-connected rendering node despite operating within a cloud-hosted environment.

Table B5A. Milestone 01 Networking Architecture

Networking Component	Technology	Function	Outcome
Virtual Private Network	Hamachi	Created a unified logical network connecting cloud-hosted and ground-based systems	Enabled transparent communication between distributed Arena components
Remote Visualization	Parsec	Provided low-latency remote desktop access and visualization	Allowed remote monitoring and operation of cloud-hosted resources
Arena Communications	Hamachi Virtual Network	Transported Arena Server and Arena Renderer control traffic	Maintained normal renderer-server communication across international distances
Camera Tracking Transport	Hamachi Virtual Network	Carried tracking and metadata information between locations	Successfully delivered tracking data to cloud-hosted renderer systems
Cloud Renderer Connectivity	Combined Networking Stack	Presented cloud-hosted Arena Renderer as a standard network-connected node	No software modifications required for cloud deployment

5.4 Results

Milestone 01 successfully demonstrated stable operation of both Chaos Areana and Arena Renderer within a cloud-hosted virtual machine.

GPU passthrough performance proved sufficient for real-time ray-traced rendering workloads, while Arena communication remained functional across transcontinental distances. Operator interaction, scene loading, and tracking-data transport all operated as expected.

Most importantly, no modifications were required to either Chaos Vantage or Arena Renderer to achieve successful operation.

Figure 4 illustrates the Milestone 01 architecture.

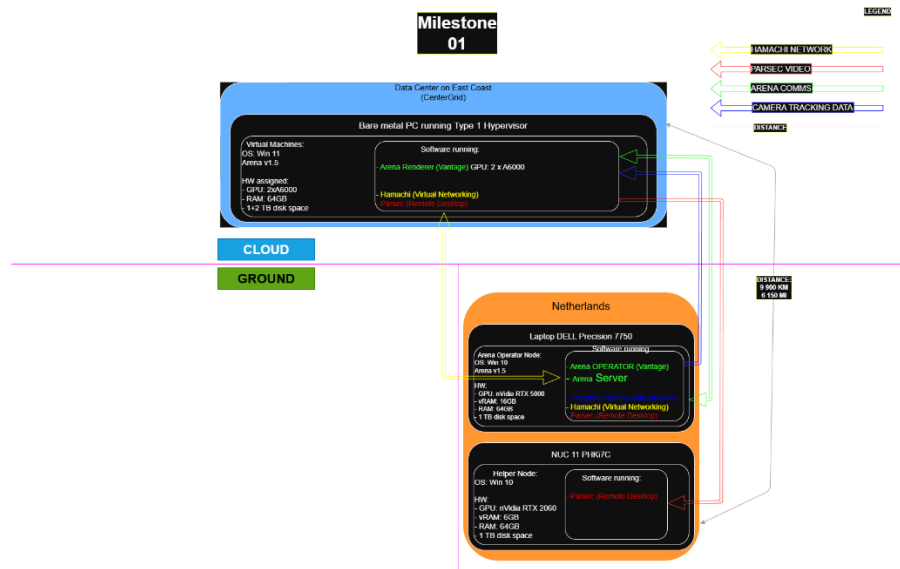


Figure 4. Milestone 01 cloud-renderer validation architecture. Arena Renderer operated within CenterGrid cloud infrastructure while Arena Server and Arena Operator remained in the Netherlands. The deployment successfully demonstrated cloud-hosted rendering across approximately 9,900 km.

Figure 4. Supplement S4 Hi res image link

https://cgvirtualstudio.com/wp-content/uploads/2026/06/Structure_M1.drawio.png

Table B6 summarizes the primary findings of Milestone 01.

Validation Goal	Result
GPU Passthrough Functionality	✓ Successful
Chaos Vantage Operation in VM	✓ Successful
Arena Renderer Operation in VM	✓ Successful
Remote Operator Control	✓ Successful
Remote Camera Tracking Transport	✓ Successful
Long-Distance Network Viability	✓ Successful
Overall Milestone Status	Milestone 01 Passed

The successful completion of Milestone 01 established the technical feasibility of cloud-hosted rendering and provided the foundation for migration of additional Arena services.

6 MILESTONE 02 — CLOUD SERVER VALIDATION

Following successful validation of cloud-hosted rendering, the second phase of the investigation focused on migrating Arena Server into cloud infrastructure.

The objective was to determine whether Arena orchestration services could operate remotely while maintaining stable communication with operator systems located thousands of kilometers away.

6.1 Objective

Milestone 02 evaluated the feasibility of relocating Arena Server from the ground environment into the cloud.

Specific goals included:

- Validation of cloud-hosted Arena Server operation
- Reduction of intercontinental Arena service traffic
- Evaluation of cloud-centralized orchestration
- Assessment of operational stability

This milestone represented the first significant architectural transition toward a cloud-native deployment model.

6.2 Architectural Changes

In Milestone 01, Arena Server remained in the Netherlands while Arena Renderer operated in Ohio.

Milestone 02 relocated Arena Server into CenterGrid infrastructure and co-located it with Arena Renderer.

Arena Operator remained on the physical workstation in the Netherlands and continued to provide scene management, production control, and tracking-data integration.

This modification fundamentally altered communication paths within the deployment.

Previously, Arena Server and Arena Renderer communicated across the Atlantic Ocean. Following migration, those communications became local to the cloud environment.

Table B7. Milestone 02 Architectural Evolution

Component	Milestone 01	Milestone 02
Arena Operator	Netherlands	Netherlands
Arena Server	Netherlands	CenterGrid Cloud
Arena Renderer	CenterGrid Cloud	CenterGrid Cloud
Deployment Model	Hybrid (Server Local)	Cloud-Centric
Primary Objective	Validate Cloud Rendering	Validate Cloud-Hosted Arena Services

6.3 Infrastructure

Arena Server and Arena Renderer operated within CenterGrid cloud infrastructure utilizing GPU-enabled Windows 11 virtual machines.

Operator functions remained on the Netherlands workstation to preserve a realistic production workflow.

Table B8 Milestone 02 Detailed infrastructure specifications are provided in Appendix B8.

Layer	System Component	Hardware / Software	Key Specs	Role in Pipeline
Cloud Infrastructure (Primary Compute)	Datacenter	CenterGrid	Cincinnati / Hamilton, Ohio	Host environment for all cloud rendering + simulation
	Hypervisor	Type 1 Hypervisor	Bare-metal virtualization	VM orchestration layer
	VM OS	Windows 11	—	Host OS for Arena stack
	Virtual Production Stack	Arena v1.5	—	Core runtime system
	GPU Compute	NVIDIA RTX A6000 ×2	64 GB RAM, 2 TB storage	Real-time rendering + simulation
	Rendering Engine	Arena Renderer + Chaos Vantage	Ray-traced real-time output	Primary render execution
	Networking	Hamachi	Virtual LAN overlay	Unified cloud–ground network
	Streaming	Parsec	Low-latency frame transport	Operator visualization

6.4 Results

Milestone 02 successfully demonstrated stable operation of Arena Server within cloud infrastructure.

All major orchestration functions remained operational following migration, including scene management, renderer coordination, and communication with remote operator systems.

A notable observation emerged during this phase. Consolidating Arena services within the cloud reduced long-distance service-to-service communication and simplified deployment topology.

This finding suggested that future cloud-native deployments may benefit from centralizing orchestration services alongside rendering infrastructure rather than distributing them across geographic locations.

Figure 5 illustrates the Milestone 02 architecture.

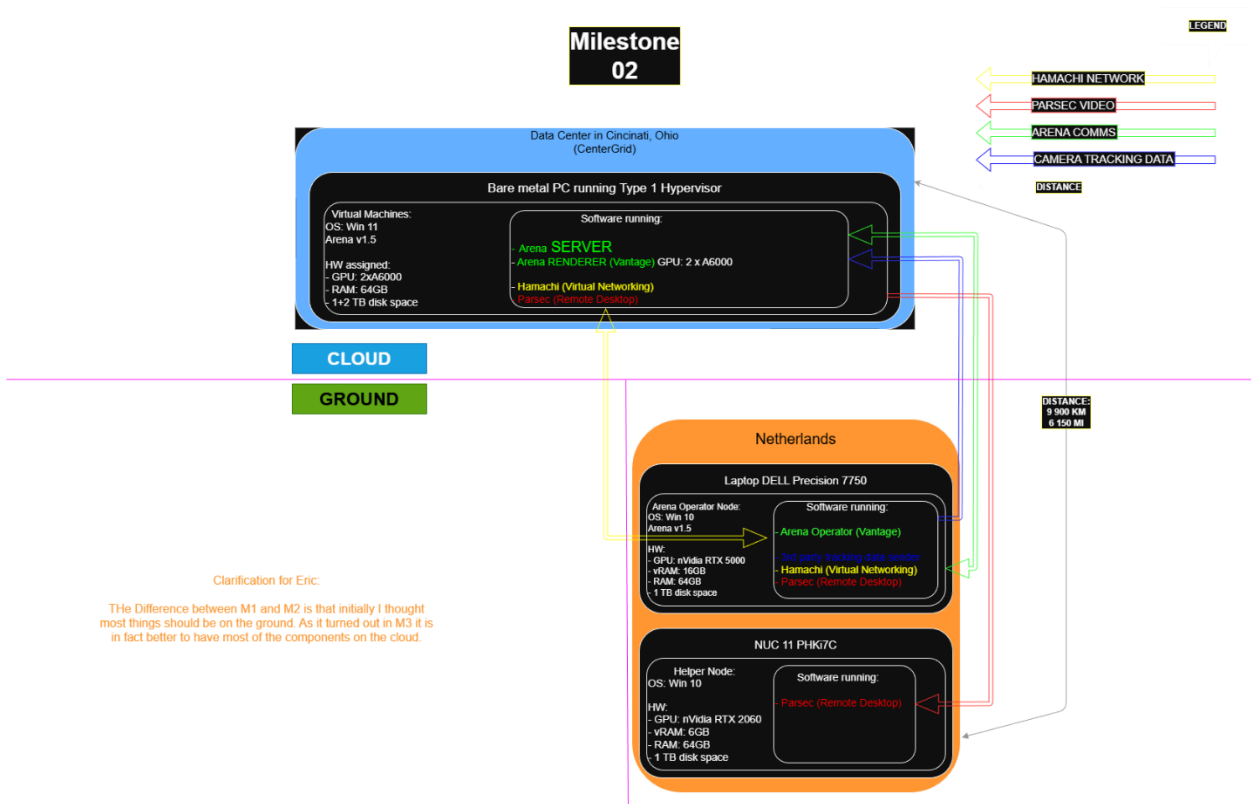


Figure 5. Milestone 02 cloud-server validation architecture. Arena Server was migrated into CenterGrid cloud infrastructure and operated alongside Arena Renderer while operator systems remained in the Netherlands.

Figure 5. Supplement S5 Hi res image link

https://cgvirtualstudio.com/wp-content/uploads/2026/06/Structure_M2.drawio.png

Table B9. Milestone 02 Infrastructure

Component	Location	Hardware	Software
Cloud Arena Server & Renderer	Hamilton, Ohio USA	2 × NVIDIA RTX A6000, 64 GB RAM, 2 TB Storage	Windows 11, Arena v1.5, Arena Server, Arena Renderer, Chaos Vantage, Hamachi, Parsec
Arena Operator Workstation	Netherlands	Dell Precision 7750, RTX 5000, 16 GB VRAM, 64 GB RAM, 1 TB Storage	Arena Operator, Tracking Data Sender, Hamachi, Parsec

Component	Location	Hardware	Software
Helper Node	Netherlands	Intel NUC 11 PHKi7C, RTX 2060, 6 GB VRAM, 64 GB RAM, 1 TB Storage	Windows 10, Parsec

Table B10. Milestone 02 Network Evolution

Network Path	Milestone 01	Milestone 02
Operator ↔ Arena Server	Local (Netherlands)	Intercontinental
Arena Server ↔ Renderer	Intercontinental	Local (Cloud)
Renderer ↔ Cloud Resources	Local	Local
Tracking Source ↔ Arena Server	Local	Local
Arena Service Traffic	Split Across Continents	Centralized in Cloud

Table B11. summarizes the primary findings of Milestone 02.

Finding	Significance
Initial assumption favored keeping Arena Server on-premises	Original deployment hypothesis
Testing demonstrated Arena Server can operate successfully in the cloud	Hypothesis disproven
Cloud-hosted Arena services reduced network complexity	Improved architecture
Cloud-centralized deployment performed better than expected	Influenced Milestone 03 design
Majority of Arena components were ultimately better suited for cloud deployment	Key research outcome

Table B12. Milestone 02 Validation Summary

Validation Area	Status
Arena Server in Cloud	✓
Cloud-hosted Orchestration	✓

Validation Area	Status
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Remote Operator Communication	✓
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Cloud Service Consolidation	✓
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Operational Stability	✓
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The successful completion of Milestone 02 established that Arena orchestration services could be decoupled from local workstations and successfully operated within cloud infrastructure.

7 MILESTONE 03 — GLOBAL WORKFLOW VALIDATION

Milestone 03 represented the final validation architecture and the most ambitious phase of the Cloud Arena investigation.

For the first time, Arena Renderer, Arena Server, and Arena Operator were deployed as independent cloud-hosted virtual machines while validation activities were conducted simultaneously from multiple countries.

The objective was to determine whether a complete Virtual Production workflow could operate across a globally distributed environment.

7.1 Objective

Milestone 03 sought to validate:

- Independent cloud-hosted Arena services
- Remote operator workflows
- International production validation
- Live camera-tracking integration
- Remote display validation

This milestone moved beyond technical component validation and evaluated a practical production-oriented deployment model.

7.2 Ohio Cloud Infrastructure

CenterGrid cloud infrastructure in Hamilton, Ohio hosted three independent virtual machines:

- VM01 — Arena Renderer
- VM02 — Arena Operator
- VM03 — Arena Server

See Appendix B13. Milestone 03 Infrastructure Matrix for 7.2 – 7.4

Each virtual machine operated independently while communicating through the virtual network environment.

7.3 Netherlands Operations Site

The Netherlands site functioned as the primary remote operations location.

Production personnel accessed cloud-hosted Arena resources through Parsec while monitoring system behavior and workflow functionality.

The site provided realistic validation of remote production workflows.

7.4 Bulgaria Validation Site

Chaos headquarters in Sofia, Bulgaria served as the production-validation location.

A Vive Mars camera-tracking system and Panasonic BGH1 camera supplied position, orientation, and focus metadata. Rendered output was displayed on a 55-inch 4K display for visual validation.

This environment provided a practical approximation of a production-stage deployment.

7.5 Results

Milestone 03 successfully demonstrated operation of a globally distributed Virtual Production workflow spanning North America and Europe.

Arena Server, Arena Renderer, and Arena Operator remained stable while operating as independent cloud-hosted services. Camera-tracking information, operator interactions, and rendered imagery were successfully exchanged between participating locations.

The deployment simultaneously connected infrastructure in Hamilton, Ohio, Enschede, Netherlands, and Sofia, Bulgaria, with communication paths exceeding 10,000 km.

Figure 6. illustrates the final validation architecture.

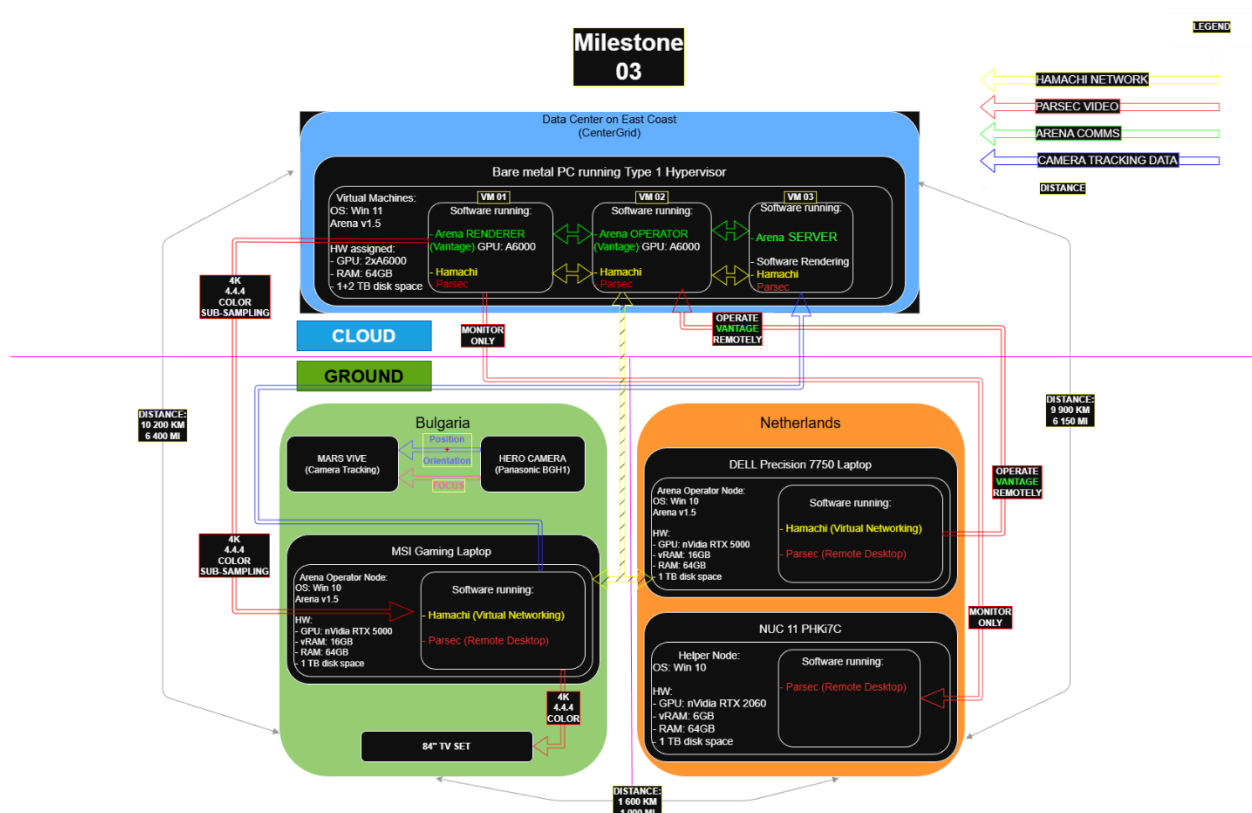


Figure 6. Milestone 03 global workflow validation architecture. Independent cloud-hosted Arena services operated within CenterGrid infrastructure while operator workflows and production validation activities were performed from the Netherlands and Bulgaria.

Figure 6. Supplement S6 Hi res image link

https://cgvirtualstudio.com/wp-content/uploads/2026/06/Structure_M3.drawio.png

Table B13. Milestone 03 System Configuration

Component	Location	Hardware	Software / Services
Arena Renderer VM01	Hamilton, Ohio, USA (CenterGrid Data Center)	NVIDIA RTX A6000, 64 GB RAM, 1–2 TB Storage	Windows 11, Chaos Arena v1.5, Arena Renderer, Chaos Vantage, Hamachi, Parsec
Arena Operator VM02	Hamilton, Ohio, USA (CenterGrid Data Center)	NVIDIA RTX A6000, 64 GB RAM, 1–2 TB Storage	Windows 11, Chaos Arena v1.5, Arena Operator (Vantage), Hamachi, Parsec
Arena Server VM 03	Hamilton, Ohio, USA (CenterGrid Data Center)	Cloud VM Resources, 64 GB RAM, 1–2 TB Storage	Windows 11, Chaos Arena v1.5, Arena Server, Hamachi, Parsec
Remote Operations Workstation	Enschede, Netherlands	Dell Precision 7750, NVIDIA RTX 5000, 16 GB VRAM, 64 GB RAM, 1 TB Storage	Hamachi, Parsec
Remote Monitoring Node	Enschede, Netherlands	Intel NUC 11 PHKi7C, NVIDIA RTX 2060, 6 GB VRAM, 64 GB RAM, 1 TB Storage	Windows 10, Parsec
Production Validation Workstation	Sofia, Bulgaria	MSI Laptop, NVIDIA RTX 3090, 16 GB VRAM, 64 GB RAM, 1 TB Storage	Windows 11, Hamachi, Parsec
Tracking System	Sofia, Bulgaria	Vive Mars Tracking System	Position and Orientation Tracking
Hero Camera	Sofia, Bulgaria	Panasonic BGH1	Camera Position, Orientation, and Focus Metadata
Display Validation Endpoint	Sofia, Bulgaria	55-inch Display	4K UHD, 4:4:4 Color Validation Output

Table B14. Milestone 03 Functional Roles

System	Primary Function
Arena Renderer VM	Real-time ray-traced rendering using Chaos Vantage

System	Primary Function
Arena Operator VM	Remote scene control and operator interaction
Arena Server VM	System orchestration, synchronization, and communications
Netherlands Operations Site	Remote operation and workflow management
Bulgaria Validation Site	Production-style validation, monitoring, tracking, and display verification
Vive Mars System	Camera tracking data generation
Panasonic BGH1	Camera metadata source
55-inch 4K Display	Final output validation endpoint

Table B15. Milestone 03 validation summary.

Validation Category	Result
Cloud-hosted Arena Renderer	✓ Successful
Cloud-hosted Arena Operator	✓ Successful
Cloud-hosted Arena Server	✓ Successful
Remote Operator Workflow	✓ Successful
International Camera Tracking Integration	✓ Successful
Bulgaria Monitoring Workflow	✓ Successful
4K Display Validation	✓ Successful
Multi-country Deployment	✓ Successful
End-to-End Virtual Production Workflow	✓ Successful
Overall Milestone Status	Milestone 03 Passed

The successful completion of Milestone 03 demonstrated that Virtual Production services traditionally assumed to require physical co-location can instead operate within a geographically distributed cloud infrastructure spanning multiple countries.

8 RESULTS

The Cloud Arena investigation successfully validated all three experimental milestones and demonstrated that a professional Virtual Production platform can operate across geographically distributed cloud infrastructure without modification to the underlying rendering engine.

The results indicate that rendering, orchestration, operator interaction, and production validation activities can be separated geographically while maintaining operational functionality.

8.1 Global Deployment Metrics

The final validation architecture spanned three geographic regions:

- Hamilton, Ohio, USA (CenterGrid Cloud Infrastructure)
- Enschede, Netherlands (Remote Operations)
- Sofia, Bulgaria (Production Validation)

Approximate deployment distances included:

Connection Path Distance

Table B17. Milestone 03 Geographic Deployment

Connection Path	Distance
Hamilton, Ohio ↔ Enschede, Netherlands	9,900 km (6,150 mi)
Hamilton, Ohio ↔ Sofia, Bulgaria	10,200 km (6,400 mi)
Enschede, Netherlands ↔ Sofia, Bulgaria	1,600 km (1,000 mi)

Figure 7 illustrates the geographic distribution of the Cloud Arena deployment.

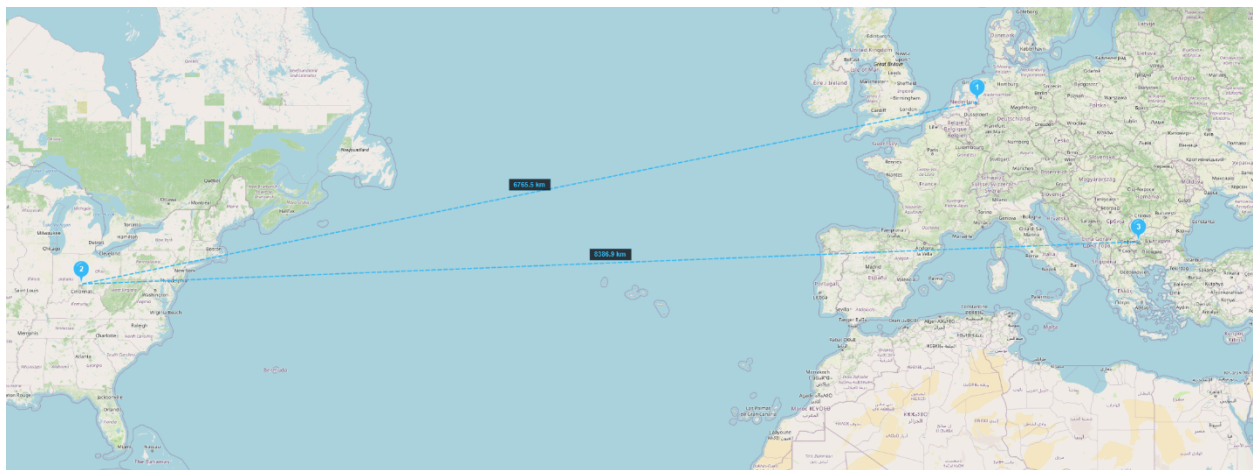


Figure 7. Geographic distribution of the Cloud Arena proof-of-concept. Rendering infrastructure, operator systems, and production-validation endpoints operated across North America and Europe while maintaining real-time functionality.

Figure 7. Supplement S7 Hi res image link

https://cgvirtualstudio.com/wp-content/uploads/2026/06/Enschede_Hamilton_Sofia_DISTANCES-1.png

The deployment demonstrated that Virtual Production services traditionally assumed to require physical co-location can instead operate successfully across international cloud infrastructure.

Table B18 Milestone 03 Functional Validation Matrix

Validation Category	Validation Objective	Test Method	Result	Status
Cloud Rendering	Verify Arena Renderer operation inside cloud-hosted GPU infrastructure	Execute Chaos Vantage rendering workloads on RTX A6000 virtual machines	Stable real-time rendering achieved	✓ Passed
Cloud Orchestration	Verify Arena Server operation within cloud infrastructure	Deploy Arena Server as a dedicated cloud service	Arena Server operated successfully in cloud environment	✓ Passed
Remote Operator Control	Verify remote operation of Arena from a geographically distant location	Control Arena environment from Netherlands operator workstation	Full operator functionality maintained	✓ Passed
Camera Tracking Integration	Verify transport of tracking and camera metadata across distributed infrastructure	Stream tracking data into Arena workflow	Tracking data successfully received and processed	✓ Passed
Multi-Site Connectivity	Verify operation across multiple countries and network domains	Connect Ohio, Netherlands, and Bulgaria sites	Stable intercontinental operation achieved	✓ Passed
Cloud-to-Ground Communications	Verify service communication between cloud-hosted and ground-based systems	Exchange Arena control, tracking, and monitoring data	Reliable communication maintained throughout testing	✓ Passed
Remote Monitoring	Verify remote viewing and monitoring of rendered output	Utilize Parsec-based monitoring workflows	Operators successfully monitored remote render output	✓ Passed
Production Display Validation	Verify rendered imagery on production-style display hardware	Display Arena output on 84-inch 4K monitoring system in Bulgaria	Successful image presentation and validation	✓ Passed
Real-Time Workflow Operation	Verify practical usability of cloud-hosted Arena workflow	Execute complete operational workflow across distributed locations	Workflow remained operational and responsive	✓ Passed

Validation Category	Validation Objective	Test Method	Result	Status
Geographically Distributed Deployment	Verify end-to-end functionality across international locations	Operate system across North America and Europe	Global deployment successfully demonstrated	✓ Passed
Cloud-Native Architecture Feasibility	Determine whether core Arena services can operate primarily in cloud infrastructure	Progressively migrate Arena components into cloud environment	Architecture validated as operationally viable	✓ Passed
Synchronization Assessment	Evaluate suitability for future multi-node synchronized rendering	Analyze frame delivery and distributed rendering behavior	Synchronization identified as primary future challenge	✓ Identified Limitation

Table B18. Functional validation matrix summarizing the principal objectives evaluated during Milestone 03. All primary operational goals were successfully achieved, demonstrating the viability of geographically distributed cloud-hosted Virtual Production workflows. The only significant limitation identified was deterministic synchronization across distributed rendering nodes, which became the principal area for future research and development.

Table B19. Milestone 03 Functional validation summary.

Validation Area	Status
Cloud-hosted Rendering	✓
GPU Passthrough Operation	✓
Cloud-hosted Arena Server	✓
Remote Operator Workflows	✓
Live Tracking Integration	✓
International Deployment	✓
Remote Display Validation	✓

8.3 Operational Observations

Several observations emerged consistently throughout the investigation.

First, cloud-hosted GPU resources proved capable of supporting real-time ray-traced rendering workloads without modification to Chaos Vantage or Arena Renderer.

Second, cloud-hosted orchestration services remained stable throughout deployment and successfully coordinated remote operator interactions and rendering activities.

Third, the deployment demonstrated that production-oriented workflows could be performed across multiple countries using commercially available networking and remote-access technologies.

Collectively, these findings indicate that cloud infrastructure can support a substantially larger portion of Virtual Production workflows than traditionally assumed.

Please see Appendix B16 for Operational Metrics Matrix

8.4 Key Findings

The most significant finding of the investigation was that rendering performance did not emerge as the primary obstacle to cloud-native Virtual Production.

Instead, as deployment complexity increased and future multi-render-node scenarios were evaluated, synchronization and deterministic frame alignment became the dominant technical challenge.

This observation fundamentally shifted the focus of the investigation.

Rather than asking whether cloud rendering is possible, the results suggest that future research should focus on how independently rendered outputs can be synchronized and presented deterministically across distributed systems.

9 DISCUSSION

The Cloud Arena investigation began with the assumption that network latency would represent the principal limitation of cloud-hosted Virtual Production.

The experimental results suggest a different conclusion.

9.1 Why Latency Was Not the Problem

Latency is frequently cited as the primary reason Virtual Production systems remain dependent upon local infrastructure.

However, throughout the investigation, operator interaction, scene management, cloud rendering, and tracking-data transport remained functional despite geographic separations exceeding 10,000 km.

While latency was present, it remained comparable to other remote-production workflows already utilized within the media and entertainment industry.

Most importantly, latency alone did not prevent successful operation of the platform.

This finding suggests that cloud-hosted Virtual Production should not be dismissed solely on the basis of geographic distance.

9.2 Synchronization Became the Bottleneck

As the investigation evolved toward larger-scale deployment scenarios, a different limitation emerged.

Future Virtual Production environments frequently require multiple synchronized render nodes to drive segmented LED-wall displays. In such systems, independent renderers must generate and present imagery simultaneously.

When rendering nodes operate across distributed infrastructure, transport latency becomes only one component of a larger synchronization problem.

Frames generated by different renderers may arrive at different times, experience varying network conditions, or become misaligned during presentation.

The resulting issue is not rendering performance but deterministic frame assembly.

In practical terms, cloud-native Virtual Production systems require mechanisms capable of ensuring that all display segments present the correct frame at precisely the correct moment.

9.3 Implications for Cloud-Native Virtual Production

The findings suggest that future Virtual Production architectures may differ significantly from traditional local deployments.

Historically, synchronization has been achieved through hardware solutions operating within tightly controlled local environments.

Cloud-native deployments introduce additional requirements including:

- Frame identification
- Metadata preservation
- WAN transport
- Frame buffering
- Deterministic release mechanisms
- Distributed synchronization

These requirements indicate that future development efforts should focus on synchronization frameworks rather than rendering performance alone.

Figure 8. Summarizes the principal findings of the Cloud Arena investigation.

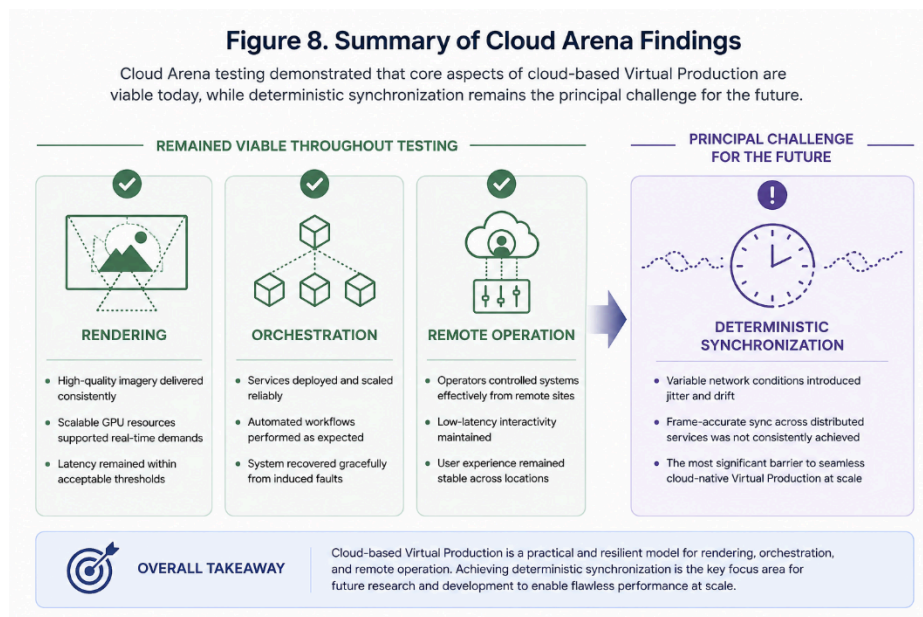


Figure 8. Summary of Cloud Arena findings. Rendering, orchestration, and remote operation remained viable throughout testing, while deterministic synchronization emerged as the principal challenge for future cloud-native Virtual Production deployments.

Supplement S8 Hi res image link

<https://cgvirtualstudio.com/wp-content/uploads/2026/06/Fig-8i.png>

10 FUTURE DEV FOR CLOUD-NATIVE SYNCHRONIZATION ARCHITECTURE

The results of the Cloud Arena investigation motivated development of a conceptual reference architecture designed to address the synchronization challenges identified during testing.

The proposed architecture is not presented as a production implementation. Rather, it represents a potential framework for future cloud-native Virtual Production systems.

10.1 Native NDI Output Module

The proposed architecture begins with direct frame capture from the Arena rendering pipeline.

Upon completion of rendering, each frame would be passed to a native NDI output module capable of generating standards-compliant NDI streams.

The module would additionally embed synchronization metadata associated with each rendered frame.

Potential metadata includes:

- Frame number
- Timestamp
- Render-node identifier
- Synchronization state
- Timecode

10.2 NDI Bridge WAN Transport

The generated NDI streams would be transported across wide-area networks using NDI Bridge.

Unlike conventional streaming solutions, NDI Bridge preserves the underlying NDI protocol and associated metadata while providing WAN connectivity between geographically separated locations.

This capability allows synchronization information to remain attached to individual frames throughout transport.

Importantly, NDI Bridge serves solely as a transport mechanism and does not perform synchronization.

10.3 Frame Alignment Engine

Synchronization occurs at the receiving site through a dedicated frame-alignment engine.

The engine performs five primary functions:

1. Receive incoming NDI streams.
2. Extract synchronization metadata.

3. Compare frame identifiers.
4. Buffer frames as necessary.
5. Release synchronized frames for presentation.

Under this model, frames are presented only after all participating render nodes have reached an identical frame state.

10.4 Genlocked LED Output

Following frame alignment, synchronized imagery enters a traditional genlocked display pipeline.

This stage provides hardware-level synchronization between display outputs and LED processors.

By separating rendering synchronization from display synchronization, the architecture introduces additional flexibility for cloud-native deployments.

10.5 End-to-End Workflow

The proposed workflow consists of four independent synchronization layers:

1. Deterministic frame generation.
2. Metadata-preserving transport.
3. Frame alignment and barrier synchronization.
4. Genlocked display presentation.

Figure 9 Illustrates the complete architecture.

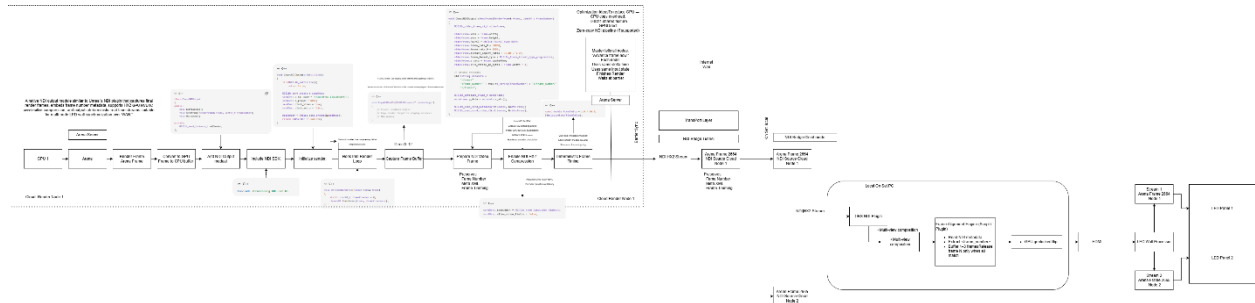


Figure 9. Proposed cloud-native synchronization architecture. Rendered frames are transmitted through metadata-preserving NDI transport, aligned through a local synchronization engine, and released through a genlocked display pipeline for deterministic multi-node presentation.

Supplement S91 Hi res image link

https://cgvirtualstudio.com/wp-content/uploads/2026/06/Arean_Cloud_drawio_200dpi-scaled.png

Table B20. Proposed synchronization architecture components.

Layer	Function
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Deterministic Frame Generation	Generates identical frame sequences across distributed render nodes using fixed-timestep simulation and rendering.
Metadata-Aware Transport	Preserves frame numbers, timestamps, and synchronization metadata during transmission.
Frame Alignment Engine	Buffers and aligns incoming frames before presentation.
Genlocked Display Presentation	Ensures synchronized output timing across L

Table B20. summarizes the proposed synchronization workflow. Detailed architectural tables are provided in **Appendix B21–B31**.

11 CONCLUSION

11.1 Research Summary

Cloud Arena investigated whether a professional real-time ray-traced Virtual Production platform could successfully operate across geographically distributed cloud infrastructure without modification to its core rendering system.

Using a milestone-based methodology, rendering services, orchestration services, operator systems, and production-validation environments were progressively deployed across cloud infrastructure spanning North America and Europe.

All primary validation objectives were successfully achieved.

11.2 Primary Finding

The most important finding of the investigation is that latency did not emerge as the principal obstacle to cloud-native Virtual Production.

Instead, deterministic synchronization and frame alignment became the dominant technical challenge as deployment complexity increased.

This observation reframes the discussion surrounding cloud-native Virtual Production. The critical problem is no longer whether rendering can occur remotely, but how independently rendered outputs can be synchronized and presented deterministically.

11.3 Future Work

Future investigations should focus on:

- Native NDI integration
- Deterministic frame numbering
- Metadata-aware transport
- Frame-alignment services
- Multi-node cloud rendering
- LED-wall synchronization frameworks
- Cloud-native orchestration systems

The findings presented in this paper establish a foundation for future research into globally distributed Virtual Production architectures capable of supporting collaborative creative teams, cloud-rendering resources, and large-scale LED-volume environments.

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