WP-22-001

Range Commanders Council
Optical Systems Group

STANDARDS-COMPLIANT ARCHITECTURE FOR RANGE OPTICS

ABERDEEN TEST CENTER
DUGWAY PROVING GROUND
ELECTRONIC PROVING GROUND
REAGAN TEST SITE
REDSTONE TEST CENTER
WHITE SANDS TEST CENTER
YUMA PROVING GROUND

NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION PATUXENT RIVER
NAVAL AIR WARFARE CENTER WEAPONS DIVISION CHINA LAKE
NAVAL AIR WARFARE CENTER WEAPONS DIVISION POINT MUGU
NAVAL SURFACE WARFARE CENTER DAHLGREN DIVISION
NAVAL UNDERSEA WARFARE CENTER DIVISION KEYPORT
NAVAL UNDERSEA WARFARE CENTER DIVISION NEWPORT
PACIFIC MISSILE RANGE FACILITY

96TH TEST WING
412TH TEST WING
ARNOLD ENGINEERING DEVELOPMENT CENTER

SPACE LAUNCH DELTA 30
SPACE LAUNCH DELTA 45

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Preface

The purpose of this task is to document a standards-based architecture for our test range optical systems. The goal is to provide guidance to all stakeholders (operations, development, acquisition, vendors, etc.) on how interfaces and formats need to be implemented to significantly improve interoperability over today's capabilities. This effort will define the primary test range motion imaging use cases, derive the associated motion imaging requirements, and then identify applicable motion imaging standards that address those requirements. With today's range systems, there is a significant amount of proprietary technology and formats that are in daily use. This creates significant inefficiencies with systems and processes that require interfacing with the motion imagery and associated metadata. Initial efforts in this area have been accomplished, but much work still needs to be done. The Optical Systems Group generated MISB ST1606.1,[1] which defines a common motion imagery file format for the test ranges. In addition, the Group has a current task to determine recommendations for the use of motion image compression with TSPI data product motion imagery. Additional areas that require investigation are the adoption and modeling of a common metadata scheme using the DoD Motion Imagery Standards Board (MISB) Motion Imagery Metadata (MIMD) architecture, web and cloud-based motion image content delivery, streaming protocols, security labeling, encryption strategies, graphics overlays, command and control protocols, etc. This effort shall be coordinated with the MISB to ensure compatibility to the maximum extent possible with emerging DoD Modular Open-Systems Approach-based architectures.

The product of this task is the following white paper that identifies range use cases, derives imaging requirements for the test ranges, and identifies standards that address the identified use cases and requirements. This white paper provides a recommended strategy for addressing shortcomings in areas where current standards do not fully address test range needs. The white paper identifies recommended sources of commercial open-source software and government open-source software libraries, tools, applications, and services that implementers can leverage to achieve compliance and interoperability with the architecture. Where significant software infrastructure falls short, the white paper documents software capabilities that can be pursued via modernization efforts.

For questions regarding this white paper, please contact the Range Commanders Council Secretariat.

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[1] Motion Imagery Standards Board. *MXF Profile for High Performance Motion Imagery Applications*. MISB 1606.1. 5 October 2017. May be superseded by update. Retrieved 29 November 2023. Available at https://nsgreg.nga.mil/doc/view?i=4493.

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Acronyms

3G-SDI	3 Gbps – Serial Digital Interface
ABR	Adaptive Bit Rate
AI/ML	artificial intelligence and machine learning
ATO	Authority to Operate
AVC	Advanced Visual Coding
AWS	Amazon Web Services
BNC	Bayonet Neill-Concelman
CDN	content delivery network
CMS	content management system
CRN	Closed Restricted Network
CSP	cloud service provider
CXP	CoaXPress
DAM	digital asset management
EOFFF	Electro-Optical Future File Format
FPS	frames per second
GE	Gigabit Ethernet
GOSS	government open-source software
HD	high definition
HEVC	High Efficiency Video Coding
HS	high speed
HTTP	Hypertext Transfer Protocol
IC	Intelligence Community
IP	Internet Protocol
IR	infrared
ISO	International Organization for Standardization
IT	information technology
JPEG	Joint Photographic Experts Group (format)
KLV	key-length-value
MAM	media asset management
MIMD	Motion Imagery Metadata
MISB	Motion Imagery Standards Board
MISP	Motion Imagery Standards Profile
MPEG	Motion Picture Experts Group (format)
MV	machine vision
NAS	network-attached storage
NIC	network interface card
NSG	National System for Geospatial Intelligence
RAM	random-access memory
RMF	Risk Management Framework
SMPTE	Society of Motion Picture and Television Engineers (format)
SSD	solid state drive
T&E	test and evaluation
TRMC	Test Resource Management Center
TSPI	time-space-position information

UDP	User Datagram Protocol
ULL	ultra-low latency
VDI	virtual desktop infrastructure
VoD	video on demand

1. Introduction

Amazon Web Services (AWS) and TRAX International partnered on the development of a technical whitepaper for a standards-compliant architecture for range optics used at test ranges. With the depth of experience TRAX offers behind test activities and the breadth of experience AWS provides in system modernization, the contract was initiated to engage in analysis of the MI workflows conducted at test ranges. This analysis included two on-site interviews with Yuma Proving Ground and White Sands Missile Range, as well as four virtual sessions held with Naval Air Weapons Station China Lake, Naval Air Station Patuxent River, Eglin Air Force Base, and Vandenberg Space Force Base. One additional interview was conducted with the Test Resource Management Center (TRMC) around topics pertaining to cybersecurity and network connectivity. The goal of the interviews was to examine the end-to-end processes and architectures involved to conduct missions supporting test and evaluation (T&E) activities.

AWS offers a background of not only implementing cloud services and solutions that meet the needs of their customers and partner communities, but also the ability to turn deep analysis of existing technologies and workflows into recommendations that address opportunities for modernization. With an overarching view of how test ranges generate and utilize MI, several challenges were identified relative to systems architecture, standards compliance, and network capabilities. This paper will address these core challenges and strategies that enable ranges to improve workflow efficiency and effectiveness within and across test range locations. AWS teamed with TRAX International to leverage their deep expertise across T&E and the greater MI community, to conduct the discovery and analysis, and to develop a set of recommendations to address the technical and operational challenges discussed.

With respect to standards compliance and architecture considerations, this paper highlights two important factors. As a media-based solution, the first factor is applying alignment with industry standards, established practices, and proven technologies broadly adopted by commercial broadcast, media & entertainment, and industrial imaging industries. The second is overlaying general guidance established by the MISB to achieve interoperability in the communication and functional use of MI. The MISB is an official standards body under the National Geospatial-Intelligence Agency, and is responsible for the review and creation of standards around motion imagery, associated metadata, audio, and other related systems for use within the DoD, Intelligence Community (IC), and National System for Geospatial Intelligence (NSG). The Motion Imagery Standards Profile (MISP) released by the MISB incorporates technical guidance and requirements related to MI systems. The MISP comprises standards from organizations such as International Telecommunication Union, International Organization for Standardization (ISO), Society of Motion Picture and Television Engineers (SMPTE), etc., in addition to non-commercial standards designed to support capability-based needs used by mission systems. Together, the collection of standards and guidance provides a foundational structure that serves the MI community while conforming to requirements defined by the MISP and supporting MISB standards.

2. Summary of Range Modernization Findings

Table 1 provides a summary of recommendations made for test ranges. These recommendations focus on standards compliance, MI processing, cybersecurity, distributed networks, cloud computing, and system-level automation. This table and subsequent sections of the paper highlight challenge areas along with potential resolutions. Refer to the modernization approach in Appendix A, which also highlights major subsections of a multipart modernization strategy. Refer to the reference diagrams in Appendix A for sample workflows.

Table 1. High-level Recommendations

Recommendations	Subsection
Implementation of standard contribution and distribution formats	Signal Acquisition & Processing
Implementation of standardized metadata processing	Signal Acquisition & Processing
Considerations for Electro-Optical Future File Format (EOFFF)	Signal Acquisition & Processing
Network accreditation and Risk Management Framework (RMF)	Security & Network
Obtaining network and cloud Authority to Operate (ATO)	Security & Network
Storage solutions for on-premises, archival, & hybrid use cases	Asset Management
Established data retention policies for content lifecycle	Asset Management
Media delivery strategies and content management systems (CMSs)	Asset Management
Use of artificial intelligence and machine learning (AI/ML) technologies to enhance post-mission analysis activities (e.g. object detection or tip/tail analysis)	Operations & Automation
Application of test and measurement for system health monitoring	Operations & Automation
Implementation of identity and access management for content	Operations & Automation
Automated processing for contribution and distribution formats	Operations & Automation

3. Signal Acquisition and Processing

Test ranges depend on a variety of camera systems (sensor systems) to collect MI and telemetry data around weapon system performance. Sensors range from small form-factor devices that can easily be affixed to a system under test (e.g., track vehicle, howitzer muzzle) up to large trailer-mounted Kineto Tracking Mounts with multiple sensors and advanced optics designed to track fast-moving objects over great distance. Test range sensor systems generally fall into one of four categories: high speed (HS), machine vision (MV), infrared (IR), and broadcast. Table 2 describes differentiating aspects between sensor systems and commonly found device manufacturers.

Table 2. Test Range Sensor Systems

Type	Manufacturers	Bit Depths	Frame Rate	Typical Format
Broadcast Format	IO Industries, Sony, Panasonic, GoPro	8 to 10 bits	30-60 frames per second (FPS)	3G-SDI, 6G-SDI, 12G-SDI
Industrial HS	Vision Research Phantom, Photron	8 to 14 bits	100s to 1000s FPS	CoaXPress, Camera Link, GigE Vision
Industrial MV	Vision Research Phantom, IO	8 to 16 bits	100s to 1000s FPS	CoaXPress, Camera Link, GigE Vision

	Industries, Basler, Imperx, FLIR			
Infrared	FLIR, IRC	14 bits	30-60, 100s FPS	CoaXPress, Camera Link, GigE Vision
Note – This is a sample list based on example range equipment. Some manufacturers may offer products or features in other categories.				

Test range workflows fall into two distinct categories: broadcast and scientific. Broadcast workflows leverage highly interoperable commercial off-the-shelf broadcast-grade equipment from a camera sensor through a signal processing chain to viewing devices. These workflows use well-established/well-defined commercial technologies and industry standards. This enables a high degree of system interoperability between vendor equipment. Scientific workflows (e.g., HS, MV, and IR) tend to follow more vendor-specific processes where proprietary systems are more frequent. While there is a handful of standards that help shape scientific workflows, several standards are still emerging or competing. Scientific sensor systems can integrate with broadcast workflows; however, their primary signal formats go beyond traditional broadcast specifications. This gap in standards compliance can lead to unique processing capabilities between vendor equipment that can impact system level interoperability.

Both broadcast and scientific workflows are essential to the test range mission. The broadcast workflow provides clear advantages in situational awareness and safety monitoring during a live testing event. On the other hand, scientific imagery offers unique perspectives into imagery with higher frame rates, bit depth, and dynamic range used to study the performance of ballistics or other fast-moving objects. An important takeaway when comparing the two workflows is that greater levels of standardization are needed across the scientific section to improve system-level interoperability, architecture, metadata handling, efficiency, and imagery format usability. Figure 1, provided by Yuma Proving Ground, provides a representative test range signal acquisition workflow using IR, HS, and broadcast-grade sensors.

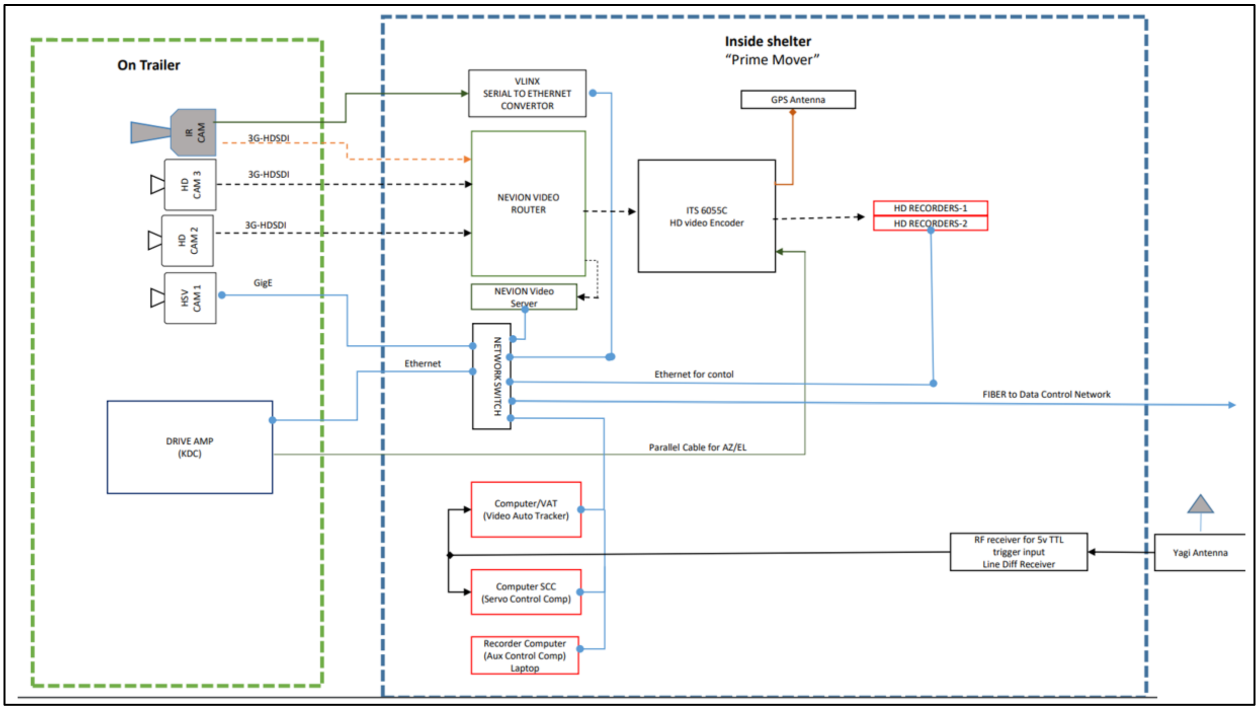

Figure 1. Representative Signal Acquisition Workflow

An important step in defining an architecture is to first identify user groups and use cases involved in a test event. Generally, different users span different functional use cases, each having different requirements around latency, quality, and accessibility. Although most range operations today are designed around real-time observation or post-processing, there are three phases identified below. Refer to the reference diagrams in Appendix A for additional sample workflows. *Note – Each phase may be broken out further into additional user groups and/or use cases as needed.*

3.1 User Groups and Use Cases

Phase 0 (Real-Time) – Users are directly involved with a live test and respective use cases are time-dominant or real-time. Users require MI to be within 150 ms of latency and desire that MI be of high quality (e.g. raw, lossless, or near-lossless) where possible. In this phase MI can be compressed further when bandwidth restrictions apply but is the result of a first-generation encode. This phase best aligns with MISP Class 2 motion imagery.

Phase 1 (Near Real-Time) – Users are involved with a live test but may accept tradeoffs in latency and/or quality in exchange for remote viewing or content accessibility. Motion imagery in this phase is considered near real-time; typically, less than 30 seconds of latency is expected. This phase best aligns with MISP Class 1 motion imagery.

Phase 2 (On-Demand) – Users do not have a specific latency requirement relative to live tests but instead focus on content dominance - accessibility, replay, post-analysis. This phase involves access to MISP Class 2 and/or MISP Class 1 motion imagery.

These user groups and use cases will help identify key architectural decisions with respect to imagery formats, containers, and/or protocols in use. For example, in signal acquisition, live streaming is often associated with the broadcast workflow, whereas capture or video on demand (VoD) is mostly associated with the scientific workflow. While some scientific workflows can integrate with broadcast workflows, the intrinsic value of scientific imagery is derived from high speed/high bit depth/high dynamic range and/or multi-spectral imagery captures that can be replayed. As detailed in Table 2, it is common for scientific imaging devices to capture hundreds or even thousands of frames per second for deep level analysis.

3.2 Broadcast Workflows

Before breaking down potential signal formats used in test range broadcast workflows, it is important to understand the characteristics behind a modern broadcast-style architecture. These systems traditionally separate media workflows into two main categories: *contribution* and *distribution*. This separation helps optimize the flow of media from end-to-end by leveraging the strengths of different protocols for different applications. The term *contribution* generally refers to the point-to-point transport of content between systems or locations (system-to-system). The contribution side of a broadcast video system is focused on the frontend of the media supply chain. Contribution formats are also commonly encountered in live production where high quality and low latency are most critical, similar to Phase 0 use cases. Alternatively, *distribution* workflows are mainly associated with the backend of an architecture and often involve transcoding to formats consumable by end user devices or players (system-to-user). In this model, higher-quality content in contribution sets up high-quality content in distribution. Latency can also be an important aspect in distribution by implementing specific protocols and/or formats that offer granular latency control. The focus in distribution is about serving a distributed user base. While this kind of model is not always implemented, it remains an exemplar approach for end-to-end video delivery systems.

3.2.1 Broadcast Contribution

Test range broadcast workflows closely align with attributes in live video contribution. Broadcast-grade contribution formats can involve several compression technologies such as Joint Photographic Experts Group (JPEG) (e.g., JPEG 2000, JPEG XS) or Motion Picture Experts Group (MPEG) (e.g., High Efficiency Video Coding [HEVC]/H.265, Advanced Video Coding [AVC]/H.264) formats. Setting quality factors aside, deciding which codec to implement in contribution requires careful consideration of end-to-end latency and bandwidth utilization. While JPEG formats provide the lowest latency, they also require the highest bandwidth. Similarly, MPEG formats may allow for lower bandwidth, but often results in the highest latency. This can be attributed to the different styles of compression technologies used by each format. The JPEG compression is based on Wavelet Transform, which uses intra-frame coding (i.e., each frame of motion imagery is individually compressed one picture at a time and transmitted over the network). The MPEG compression uses discrete cosine transform with motion vector tracking, which is far more complex. The MPEG format is often referred to as an inter-frame encoding technique, where instead of single frame compression, video frames reference other video frames to detect changes and encode differences between them. The complexity involved with MPEG compression technologies contributes to the added latency. The additional processing time also leads to higher efficiency, ultimately reducing bandwidth utilization in transmission. Importantly, both JPEG and MPEG technologies can be tuned for different quality and latency parameters. Table 3 provides a general comparison between a few common MPEG and JPEG contribution formats.

Table 3. Contribution Codecs

Contribution Codecs	MPEG		JPEG	
	AVC-Intra 100	AVC-Intra 200	JPEG 2000	JPEG XS
Example Picture Settings	1080P @ 60FPS	1080P @ 60FPS	1080P @ 60FPS	1080P @ 60FPS
Max Chroma Subsampling	4:2:2	4:2:2	4:4:4	4:4:4
Max Bit Depth	10-bit	10-bit	12-bit	12-bit
Standard Compression Ratio	30:1	15:1	20:1	10:1
Bit Rate (Mbps)	100	200	150	300
Resulting Latency	<150 ms	<150 ms	<50 ms	<1 ms
Note – Latency information contained in this table has not been independently verified by this paper, but provides typical performance characteristics within the industry.				

Given the low latency requirements for test range Phase 0 user groups, JPEG XS offers the best performance in terms of latency while meeting functional parameters of a broadcast-grade contribution format. In terms of quality, JPEG XS can be tuned to produce visually lossless or mezzanine compression while preserving multigenerational decode/encode robustness. Mezzanine compression is a technique that lightly compresses frames to slightly reduce the raw video bitrate in transmission. Mezzanine compression typically refers to compression rates that fall between 2:1 – 20:1 of a given format’s uncompressed size. These formats have characteristics that also align with MISP Class 2 motion imagery. Mezzanine compression is analogous to a sponge, where in original condition may be a perfect rectangle, when squeezed can be compressed into a smaller form-factor, and when released returns to its original form with little to no permanent impairment.

Using mezzanine formats for contribution is preferred where possible given the high-performance output and little-to-no picture quality degradation as a result of encode/decode cycles. In many cases, ranges are already using mezzanine formats such as JPEG 2000 in the signal acquisition workflow. For example, one test range explained their use of fiber optics to transport lightly compressed motion imagery from a range test position to the network operations center. At the test position, JPEG 2000 encoders were used to lightly compress 3 Gbps -Serial Digital Interface (3G-SDI) from its original 3 Gbps bitrate to 150 Mbps (20:1 compression) bitrate for transport. As each motion imagery channel is compressed, it would be encapsulated as User Datagram Protocol (UDP)/Internet Protocol (IP), aggregated on an Ethernet network, and transported over fiber optics using 10 Gigabit Ethernet (GE) optical transceivers. At the receiving end, the inverse occurs by terminating the fiber on an Ethernet switch, connecting JPEG 2000 decoders, and de-encapsulating each motion imagery feed back to baseband 3G-SDI.

Deploying high-speed 10GE over fiber allows test ranges to leverage the performance benefits of mezzanine compressed video. Today, 10GE edge switching has become commonplace thanks to the reduction of hardware pricing over the last decade and increased demand for higher throughput capacity on the network (e.g., 25GE/40GE/100GE). The upgrade from 1GE to 10GE edge switching was a notable breakthrough for the broadcast community as well. As mentioned, uncompressed high-definition (HD) video operates at speeds ranging from 1.5 Gbps to 3 Gbps, which would have exceeded earlier 1GE link speeds. Upgrading switches to 10GE allows enough bandwidth to carry one or more HD video signals over IP networks in lieu of using traditional coaxial cable. Fast forward to 2020-2021, the broadcast industry is now embracing the use of mezzanine or even uncompressed video over IP by leveraging newer transport protocols such as SMPTE 2022-6[2], SMPTE 2110[3], and Cloud Digital Interface.[4] Most uncompressed video over IP workflows are performed on-premises where there is ample bandwidth; however, broadcasters are now extending these same high-bandwidth workflows from on-premises to the cloud for processing, storage, and distribution.

In some test range use cases, high-bandwidth contribution formats may not be possible due to bandwidth restrictions on the range. For example, when fiber optics are not present, ranges may need to connect test positions using wireless communication methods (e.g., microwave or multiple input, multiple output), which may not support the full bandwidth requirements for mezzanine or uncompressed video over IP. In these scenarios, the motion imagery contribution format(s) will be shaped by the aggregate number of feeds that need to traverse an RF link and the total bandwidth available on the link. Regardless of transmission medium, contribution would entail the point-to-point transmission of motion imagery from a first-generation encode, serving as the highest quality format producible in a given environment. Contribution formats are most useful on intra-range networks where LANs permit, inter-range relay where wide-area networks permit, and in hybrid range-to-cloud architectures.

3.2.2 **Broadcast Distribution**

In some workflows, broadcast contribution feeds will need to be converted to distribution feeds largely due to bandwidth limitations and the need to optimize formats/protocols for wider network dissemination. In distribution, the original contribution feed is often processed through an additional technique known as transcoding or transrating; these conditioning techniques have some variances. Transcoding involves changing the video format from one to another (e.g., JPEG 2000 to HEVC/H.265). Changing the format can also result in a reduction in bitrate. For example, in contribution where JPEG 2000 is used to preserve high quality with 20:1 compression (150 Mbps), the same feed may be transcoded using HEVC/H.265 up to 1000:1 compression (3 Mbps) for distribution. In transrating, the original video format or codec is preserved, but a reduction in bitrate is applied. In an example where AVC-Intra 100 (100 Mbps) is used in contribution, the underlying video format is AVC/H.264. This format may be preserved in distribution channels by transrating the video to a lower bitrate such as 6 Mbps. The concept in distribution is to optimize video formats, protocols, containers, and bandwidth conditions so they can be shared with users and devices over distributed networks.

The most common distribution codecs in use today are MPEG technologies including AVC/H.264 (standardized in 2003) or its successor HEVC/H.265 (standardized in 2013). Both of these compression formats have been widely adopted by the broadcast industry and have obtained approval by the MISB as supported Class 1 motion imagery formats. Being the latest iteration from MPEG, HEVC/H.265 can offer substantial bandwidth savings (30%-50%) or enhanced picture quality when compared to its predecessor AVC/H.264. Careful consideration

[2] SMPTE. "Transport of High Bit Rate Media Signals over IP Networks (HBRMT)." ST 2022-6:2012. 9 October 2012. May be superseded by update. Retrieved 22 February 2023. Available at https://ieeexplore.ieee.org/document/7289943.

[3] SMPTE. "Professional Media over Managed IP Networks: System Timing and Definitions." ST 2110-10:2022. 28 November 2022. May be superseded by update. Retrieved 22 February 2023. Available at https://ieeexplore.ieee.org/document/9973256.

[4] AWS. "Cloud Digital Interface." Retrieved 22 February 2023. Available at https://aws.amazon.com/media-services/resources/cdi/.

should be given to downstream viewing devices to ensure player compatibility with newer compression standards.

Additionally, a common technique used in distribution processing leverages Adaptive Bit Rate (ABR) encoding. In ABR encoding, a contribution format is transcoded/transrated into several renditions of the same content, with each rendition having different resolutions and bitrates. This is sometimes known as an ABR switching set. Constructing an ABR switching set can be dependent on desired quality settings, user device types, and overall bandwidth considerations. Typically, an ABR switching set includes between 3-8 renditions, ranging from low to high resolutions and bitrates. The typical bitrate stepping ratio between renditions is commonly 1.5x – 2.0x in size. This allows client devices to request a rendition of content that is most suitable for the device and its current bandwidth conditions. As bandwidth fluctuates, the client can request other renditions that are available within the set, effectively adapting to the network. The examples in Table 4 illustrate ABR switching sets when considering HEVC/H.265 or AVC/H.264 for video distribution. One other important consideration in ABR streaming is the transmission protocol uses Transmission Control Protocol, or more specifically Hypertext Transfer Protocol (HTTP), to improve reliability over unmanaged network distribution. While there are several ABR/streaming media formats used in the industry today, the most common formats include HTTP Live Streaming and Dynamic Adaptive Streaming over HTTP.

Table 4. Adaptive Bit Rate Switching Set (2x stepping ratio)

Contribution using JPEG 2000	Distribution using HEVC/H.265	Distribution using AVC/H.264
1080p @ 150 Mbps	1080p @ 14 Mbps	1080p @ 20 Mbps
	1080p @ 7 Mbps	1080p @ 10 Mbps
	720p @ 3.5 Mbps	720p @ 5 Mbps
	540p @ 1.75 Mbps	540p @ 2.5 Mbps
	432p @ 0.875 Mbps	432p @ 1.25 Mbps

In 2020, the MISB formally recognized the use of ABR Content Encoding for motion imagery through the creation of MISB ST 1910.[5] This standard not only highlights and defines the use of ABR for motion imagery workflows, but includes provisions to support key-length-value (KLV) metadata consistent with the MISP. Prior to the release of ST 1910, motion imagery containing KLV metadata would commonly traverse IP networks using MPEG transport streams over UDP/Real-time Transfer Protocol transmission protocols. In this model, motion imagery from a sensor system would often be encoded to satisfy downstream users consuming content in distribution. While this model works, it doesn't fully leverage all of the formats, protocols, and/or containers that may be better optimized to serve contribution or distribution workflows. This is where guidance from MISB ST 1910 helps address motion imagery in distribution. Importantly, ABR supports both live streaming and VoD playback, and is typically aligned to those users who can exchange a few seconds of latency for ease of content accessibility.

Given its flexibility to adapt to the network and native web browser support, ABR works well for distributed users who may need access to content in near-real time or VoD such as in

[5] Motion Imagery Standards Board. *Adaptive Bit Rate Content Encoding*. MISB ST1910.1. 29 October 2020. May be superseded by update. Retrieved 29 November 2023. Available at https://nsgreg.nga.mil/doc/view?i=5097.

post-mission analysis. In terms of live streaming, ABR can be tuned to support newer low-latency modes referred to as ultra-low latency (ULL) streaming that leverage chunked transfer encoding implemented under the Common Media Application Format. With ULL streaming, end-to-end latency of less than two seconds is possible. Standard live streaming workflows typically range from 5-15 seconds end-to-end latency depending on ABR segment sizing and the network distribution model. In either case, traditional network distribution often relies on a geographically distributed network of proxy/reverse-proxy servers that make up a content delivery network (CDN) to connect users to media. While cloud service providers (CSPs) offer vastly dispersed high-speed CDNs as a service, creating a smaller private CDN is possible using a web origination server(s) combined with reverse proxy caching.

3.3 Scientific Workflow

Test range scientific workflows involve camera sensors used for the capture of HS, MV, and/or IR motion imagery as described in Table 2. Many of these sensors are capable of generating live broadcast outputs such as HD-SDI, but they are primarily intended for their ability to capture high-speed/high bit depth/high dynamic range imagery over short periods of time. This results in the production of detailed high-speed imagery that can be played back in ultra-slow motion for deeper-level analysis.

As mentioned, many of these sensors have integrated broadcast interfaces such as HD-SDI/3G-SDI, allowing them to connect to an array of broadcast-style infrastructure. In this kind of setup, sensors can follow guidance outlined in the prior section(s) creating a contribution-to-distribution workflow. Aside from feeding motion imagery to the broadcast workflow, these cameras are primarily intended for high speed/high bit depth/high dynamic range content for on-demand playback. Camera manufacturers may offer different modalities of capture based on the duration of a live event. For instance, one type of collection performed is local to the camera. A local collection relies on the onboard random-access memory (RAM) to capture imagery in memory before transferring to long-term disk storage. A second type of capture is streaming where the camera uses specialized protocols to transmit raw imagery to an external recording device. Generally speaking, local collections result in shorter events or smaller sequences of captures, whereas streaming collections may allow for longer-duration events given the higher memory and solid-state drive (SSD) capacity of an external recorder.

Configuration 1 – Local (RAM to Direct Storage): In this configuration, the camera sensor collects motion imagery to on-board RAM, then transfers it to removable storage media (e.g., SSD, memory card). While some camera sensors have implemented commercially available removable storage, others rely on proprietary removable storage to maximize the speed of data to disk.

Configuration 2 – Local (RAM to Network Storage): In this configuration, the camera sensor collects motion imagery to on-board RAM, then transfers it over an Ethernet connection to a computer. Given the volume of data to be transferred, it’s best to establish 10GE link speeds where possible to reduce the amount of time for file transfers over the network. The computer used to collect files should also use a 10GE connection and SSD to improve collection write speed.

Configuration 3 – Streaming Protocols: In this configuration, the camera sensor collects motion imagery and transmits it to an external media recorder using high-performance communication interfaces such as CoaXPress (CXP), Camera Link, or GigE/10GigE Vision.

Realizing the need for more sustainable remote captures and longer duration recordings, the industrial image processing industry came together to develop CXP, a standards-based high data rate streaming protocol for MV/HS/IR imagery. Prior to the release of CXP, the industry had largely standardized on other protocols such as Camera Link and GigE Vision. Setting GigE Vision aside for a moment, CXP and Camera Link are similar peer-to-peer protocols used for real-time HS/MV streaming. More recently, CXP has gained momentum across the industrial image processing segment. Primary reasons for market attraction include the demands for higher bandwidth and simplified/longer cabling between camera and recorder. First standardized in 2011, CXP has now been adopted by dozens of HS/MV/IR camera manufacturers.

Benefits to CXP include high transport bandwidth, simplified cabling infrastructure (75 Ω coaxial cables), common Bayonet Neill-Concelman (BNC)/micro-BNC connectors, and provision for optical transceivers (CXP-over-Fiber). The latest version of CXP, known as CXP 2.0, includes even greater bitrates per channel, further streamlined cabling, micro-BNC connectors, power-over-CXP, and multipath streaming for signal acquisition redundancy. This standard was designed to be scalable ranging from 1.25 Gbps to 12.5 Gbps per connection. Importantly, CXP-equipped devices can be implemented with one or more connections. For example, using CXP 2.0, a properly equipped sensor can connect up to four micro-BNC connections to achieve a maximum data transfer rate of up to 50 Gbps (12.5 Gbps x 4). Most CXP 1.x sensors used by range applications require between 2-4 connections to achieve a desired quality level during a live testing event. Migration to CXP 2.0 can simplify the scientific imagery workflow with fewer connections between equipment and improved bandwidth performances. The CXP 2.0 devices are backwards-compatible with CXP 1.1.1, so older-generation CXP sensors can work with newer CXP 2.0 recorders. Table 5 lists CXP specifications.

Table 5. CoaXPress Specifications

CoaXPress Connection	Standard	Bit Rate per Coax Cable	Connector
CXP-1	1.x	1.250 Gbps	BNC
CXP-2	1.x	2.500 Gbps	BNC
CXP-3	1.x	3.125 Gbps	BNC
CXP-5	1.x	5.000 Gbps	BNC
CXP-6	1.x	6.250 Gbps	BNC
CXP-10	2.x	10.000 Gbps	micro-BNC
CXP-12	2.x	12.500 Gbps	micro-BNC

Both CXP and Camera Link extend real-time HS/MV/IR streaming from a sensor to a recorder. These protocols require a sensor to be cabled to a device called a frame grabber to complete the solution. A frame grabber is an extension of the CXP or Camera Link solution as a hardware capture card commonly integrated into a computer using a Peripheral Component Interconnect Express interface. Frame grabbers have an abundance of on-board memory used to buffer and collect incoming raw imagery from the sensor during a live event. While these protocols provide substantial convenience and extend the capabilities of scientific-grade sensors, they involve a heavy hardware footprint and non-information technology (IT) centric cabling. A third real-time HS/MV/IR streaming protocol is known as GigE Vision or 10GigE Vision. Importantly, GigE Vision is recognized by the MISB as Standard 1608.[6] Some of the benefits behind these IP-based protocols allow HS/MV/IR sensors to stream scientific imagery over standard IT cabling and network infrastructure. As 10GigE Vision emerged, the increased bandwidth placed heavy demands on the receiving computer's CPU. Without the help of a dedicated frame grabber, packets or frames of data would often be dropped. To improve the computer handling of high-bandwidth streams over 10GigE Vision, special network interface cards (NICs) were introduced as 10GigE Vision frame grabbers to buffer and collect incoming raw imagery over IP. While frame grabbers were not originally intended for GigE/10GigE Vision protocols, PC performance is greatly improved when paired with a specialized NIC or network frame grabber.

Camera Link, CXP, and GigE/10GigE Vision are all viable protocol options for HS/MV/IR streaming. 10GigE Vision may offer slight transport advantages by leveraging existing 10GE edge switching equipment. Having said that, IP packets can be subject to network packet jitter resulting in stream instability. This is less likely to occur in peer-to-peer configurations using CXP or Camera Link. Each of these streaming protocols has advantages and disadvantages, although CXP and 10GigE Vision may have the edge in terms of performance, features, and industry adoption. Whereas CSP aligns more with a baseband video infrastructure, 10GigE instead Vision aligns more to IT infrastructure.

Scientific sensor manufacturers often implement proprietary file formats based on differences in digital signal processing. While proprietary file formats can offer performance enhancements, they also limit opportunities for interoperability. As discussed, the transport mechanisms between sensors and capture devices have been standardized using CXP, Camera Link, or GigE Vision technologies. However, the resulting file formats, video players, and video converters are largely proprietary. Many sensor manufacturers offer companion software suites that include player, editor, and converter functions. Range operators often use these tools to view imagery, trim content, and perform conversions to more distributable formats such as AVI, MOV, or MPEG-4. See Table 6 for examples of various scientific file formats.

Table 6. Scientific File Formats

Category	Manufacturer	Format(s)	Convertible
HS	Vision Research/ Phantom	.cine	Yes
MV	Photron	.raw; .mraw	Yes
IR	FLIR	.ats; .seq; .csq	Yes

Given the importance of the scientific imagery workflow used across test ranges, a standards-based file format could lend significant improvements around system interoperability and promote a standards-compliant architecture. Aside from this paper, supplemental research and requirements gathering is being performed within the MISB around the notion of a common imagery format or family of compatible formats that collectively meet the needs of existing and future motion imagery applications. This effort takes into consideration several mission-related use cases where an EOFFF may be positioned to best serve current and future-state architectures

[6] Motion Imagery Standards Board. *Transport of Motion Imagery and Metadata over GigE Vision*. MISB ST1608.1. 5 October 2017. May be superseded by update. Retrieved 29 November 2023. Available at https://nsgreg.nga.mil/doc/view?i=4507.

for the DoD/IC/NSG community. One such use case includes motion imagery products generated by ranges for T&E activities. Current research outlines the ISO base media file format as a potential format that can address the requirements of the EOFFF considering the vast extensibility and broad commercial adoption.

4. Security and Network Requirements

This section addresses the security implications that pertain to a desired future-state architecture for motion imagery systems deployed by test ranges. Figure 2 shows a simplified current-state architecture (left) that is generally more restrictive by design versus a simplified future-state architecture (right) that supports broader, more distributed test range activities. These connectivity improvements can lead to workflow efficiencies that benefit the T&E community through rapid access to range data, support for intra- and inter-range test activities, augmented cloud resources, and wider support for other distributed network events currently constrained by Closed Restricted Networks (CRNs).

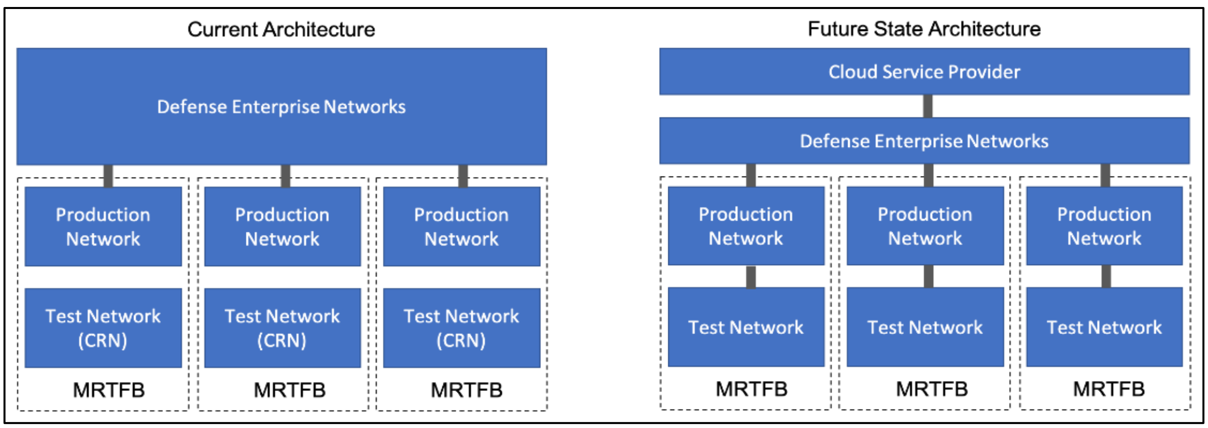

Figure 2. Current and Future State Architectures

One common observation made during site discovery was that most ranges originate test data on isolated CRNs. This is typically done when a network and/or its hardware, software, and services may not meet the strict security requirements imposed on IT systems used by the federal government. While this is one way to control security in a disconnected or stand-alone environment, this mode of operation limits the ability to share test data with those who are authorized to use it. In this case, an RMF may be implemented to help manage information security and privacy risk for participating test ranges.

Data generated by the range community is becoming increasingly time-sensitive and may warrant new participation from remote locations or audiences. While a future-state architecture can enable these kinds of transitional workflows, they also raise important considerations around cybersecurity and risk management. For example, compliance with an RMF is required prior to connecting an isolated network to a distributed defense network. The National Institute of

Standards and Technology Procedure 800-53[7] outlines the RMF as a standardized process that integrates security, privacy, and cyber risk management for federal information systems.

Managing organizational risk is of vital importance in achieving information security. Fortunately, the RMF process can be applied to both new and legacy systems regardless of size and/or sector. This paper identifies key resources within the TRMC supporting the T&E community. The TRMC manages a number of cybersecurity programs and is able to support and/or help conduct an RMF process for any participating test ranges upon request. The TRMC also manages the Joint Mission Environment Test Capability, an established DoD network dedicated to joint distributed testing.

Upon request, cyber-security experts from the TRMC will work with participating ranges to build out an RMF package as well as help generate an overarching cybersecurity strategy. This typically starts with an initial cybersecurity meeting between the TRMC and the range to outline the concept of operations, timelines, and overall strategy for developing the RMF package. As the RMF is defined, security checks are performed across the system/segment to understand security posture. This is often a combination of Defense Information Systems Agency STIGs, Nessus Scans, code scans, network/port scans, and performance of other security checks. As the results are collected, remediation and/or security controls are put in place to improve the security posture. Prior to information system authorization, an assessment of the system/segment is performed to ensure proper compliance has been obtained. After a system/segment has been authorized, ongoing monitoring is conducted on a regular basis to sustain the RMF accreditation.

The average time to obtain an accreditation can be a few months, and typically will not exceed six months in more complicated environments. Some ranges who collaborate with others more frequently may require longer-term connectivity. Other ranges may consider shorter-term connectivity based on limited-duration testing or for working through potential proof of concepts. Obtaining an RMF and ATO can be applied for both short-term and long-term test activities. Further, any advisory or assistance from the TRMC to participating ranges to seek and obtain an RMF comes at no cost to the test range. The TRMC is an available resource and center of excellence that is willing to help ranges requesting support in topics such as cybersecurity, RMF processes, and system accreditation.

5. Asset Management

5.1 Storage Considerations

Test ranges collect large quantities of motion imagery through various tests being performed on a continuous basis. Each range has a slightly different process, but generally involves collecting data onto handheld temporary storage devices and using manual processes to transfer data to more accessible network-attached storage (NAS) systems for users to access. This is partly due to tests taking place on CRNs where there is a lack of broad network connectivity to users who need to process the data. Data collection is a critical step with every mission and the time-sensitive nature of the content further emphasizes the need to improve and modernize the collection process in addition to how the data is transferred and stored.

[7] NIST. "Security and Privacy Controls for Information Systems and Organizations." SP 800-53 Rev. 5. Retrieved 22 February 2023. May be superseded by update. Available at https://csrc.nist.gov/publications/detail/sp/800-53/rev-5/final.

One storage process discovered at several ranges entails manually loading post-mission test data from cameras, computers, or recorders to physical SSDs, then hand-carrying it to a data processing lab. While these tests take place in remote areas, even labs that have direct access to range networks are often throttled by available bandwidth. One option for augmenting on-site storage is through edge storage devices that provide dense storage and compute capacity as a portable, ruggedized device. These devices do not require connectivity to the cloud and may be used to collect data and increase on-premises storage for some operational duration as needed. As cloud storage is considered, edge storage devices can be used as transfer devices moving data to/from the cloud as needed. One example may be using several edge storage devices on-site to collect data on a monthly rotational cadence. Each month, data would be collected and stored on the edge device(s), synchronized with the local NAS, then shipped back to the cloud provider for data ingest with a new device arriving in its place to repeat the same process, creating an op-tempo of content moving to the cloud for longer-term storage. Importantly, edge storage devices provide tamper-evident enclosures, 256-bit encryption, and industry-standard Trusted Platform Modules to ensure security and chain of custody for stored data. Edge storage devices are commonly used in scenarios where customers want to leverage the capabilities of cloud services, but require some portion of temporary storage and/or operations to take place on-premises. These services can help ranges add resources by exchanging capital expenditure equipment for operational expenditure equipment as a managed service offering.

Another type of storage strategy ranges can utilize is hybrid cloud storage, which combines existing on-premises storage systems with cloud storage services. A hybrid approach involves active content migration from storage platforms such as a NAS or storage area network, and migrating portions of content to the cloud for hot, warm, or cold storage. Data migration is an efficient method to transfer infrequently accessed content from local storage systems to the cloud for archiving. Moving content between tiers takes into account how frequently content is being accessed over some period of time, and moves content based on rules defined by the administrator. Content migration can take place manually or through automation with solutions such as intelligent tiering. Once data is moved to the cloud, there are several options to further index, catalog, search, and store based on the scope of the architecture.

5.2 Data Retention Policies

One common challenge across test ranges was the lack of guidance around content retention. Many ranges attempt to keep content indefinitely where other ranges determine timelines based on budget and/or size of local archives. A lack of a well-defined data retention policy can pose issues when trying to restore older data that may be needed for re-use. Ranges that attempt to store content indefinitely may be dependent on the durability of devices such as SSDs, CDs, DVDs, and the overall shelf life expectancy of these devices. Other ranges may elect to store content based on availability of space either physically or virtually. Data collected from these tests is often invaluable and expensive to acquire or re-create. In some scenarios, customers may request new copies of data that can no longer be reproduced. The current data handling challenges are largely based on physical limitations as opposed to structured storage guidelines that can include a more sustainable long-term storage strategy. The table below provides an example around data retention policies that addresses both short-term and long-term requirements for data holding.

Table 7. Storage Types and Sample Data Retention Policy			
Type	**Location**	**Duration**	**Automated Action**
Ultra-Hot	On-premises storage (NAS)	0-90 days after mission	Store mission data
Hot	Cloud storage	91-180 days after mission	Transfer to cloud storage
Warm	Cloud storage - infrequent access	181- 365 days after mission	Transfer to infrequent access
Cold	Cloud archive	1-5 years after mission	Transfer to cloud archive
Ultra-Cold	National archives	5+ years after mission	Migrate mission data to national archives

The criticality of the content collected at test ranges emphasizes the need for established guidelines on data retention and improvements in the ability to store data either on-premises or in the cloud. Automated tiering in conjunction with data retention policies that migrate data between storage tiers can also be utilized to restore content back to hot based on user demand. As content demand cools down, the automated tiering process would start over in accordance with the data retention policy rules. Section 5.3 will discuss the applications of a CMS that can provide users with a method of accessing content available across different storage tiers.

5.3 Content Management Systems

As ranges open opportunities to utilize cloud storage solutions and develop hybrid storage plans, there are additional advantages that can be leveraged in terms of overall content management. Table 7 references the ability to store various degrees of warm or cool content in a tiered storage solution. As data is stored it requires proper indexing and cataloging to keep track of where content is located across various locations. Enterprises today utilize software-based asset tracking tools that provide interfaces and functionality to manage content, including the ability to search, store, view, edit, and deliver to respective users or authorized personnel.

The first type of asset tracking software is commonly known as a media asset management (MAM) or digital asset management (DAM) system. These terms are often used interchangeably, and the goal of both is to search, store, and track digital assets across different storage platforms. The second type is a CMS, which publishes digital content from a MAM/DAM to users through a frontend web interface. This allows the creation of site(s) to manage, view, and deliver media through a distribution network. Nowadays, asset management systems are becoming more unified as an all-encompassing DAM/MAM/CMS that satisfy both contribution and distribution workflows. This paper will refer to the larger asset management solution as a CMS. Below are some of the core capabilities of a CMS for media management.

User Authentication and Content Authorization: A CMS provides administrators and users secure login capability with username and password-protected accounts, some including multifactor authentication for greater security controls. Typically, CMS systems offer integration with existing IT credentialing services (e.g., Lightweight Directory Access Protocol, Security Assertion Markup Language, Single Sign-on). These forms of identity and access management controls also help administer user credentials that help define content rights and permissions.

Asset Tracking and Storage: A CMS is capable of retrieving content across multiple storage locations. This is achieved through metadata on an associated database that maintains location details for all content available within the system. In addition, the database can assist with version tracking or even maintaining organizational structure content.

Media Analysis: A CMS can generate metadata from content, or "essence information", through media compression details, audio-to-text translations, and AI/ML processing. Essence information may include attributes such as format, resolution, frame rate, bit depth, etc. The AI/ML detections may use image recognition to assign descriptive information about a frame. A CMS may be capable of extracting other forms of metadata such as KLV data or time-space-position information (TSPI) data to provide time and location information about the content.

Search and Discovery: A CMS is capable of automated metadata tagging, which provides methods to use metadata for search expressions beyond file name such as geospatial or date/time. Additionally, some CMSs can manage complex queries such as Boolean or search builders to discover content.

Content Editing (Image and Video Manipulation): Some CMSs offer integrated content editors while others have integrations with third-party tools to perform functions such as video clipping, scaling, and resizing. Still imagery editing may include adjustments in color, rotation, orientation, and format conversions.

Metadata Enrichment: A CMS can be capable of adding or extracting metadata to enhance content search capabilities. Types of metadata formats can include KLV data, TSPI data, descriptive metadata (e.g., title, track), technical metadata (pixel pitch, camera types), and tagging (e.g. keywords, phrases). Tagging compliant with MIMD can facilitate further capabilities such as predictive maintenance and fleet performance tracking.

Media Playback and Distribution: A CMS can also serve end users in distribution by integrating web portals for users to access streaming content. These portals offer a view into available content with tools that allow users to select those files for playback. Media players or web-enabled players are often integrated and expose controls such as play, pause, rewind, fast-forward, step-frames, etc. Many CMSs operate in a web-centric environment, allowing easy browsing and access to content in both live and on-demand use cases.

6. Operations & Automation

Enterprise organizations today have embraced the opportunities for incorporating automation to enhance their day-to-day operations. This includes utilizing AI/ML to address and replace some of the manual processes that comprise traditional workflows. Similarly, test ranges can leverage automation to promote efficiencies by reducing the potential for error and the overall time it takes to conduct an end-to-end test mission. Besides reducing manual processes, automation can help integrate segregated systems. With a holistic view of activities that encompass the motion imagery workflow, a particular set of use cases has been identified to introduce enhanced capabilities that provide immediate and long-term value to ranges.

Use Case 1: Test Event Planning

A typical test range mission plan entails numerous requirements for determining the appropriate number of cameras, available land/naval/air space, equipment concerns, safety precautions, and so on. Currently, mission planners that receive information about a test will generate documentation outlining range requirements that produce an appropriate scenario for capturing the full mission. This process is currently almost completely manual and lacks structure for future missions that may have similar requirements.

To modernize the approach in test event planning, one step may be to develop an online form-based approach that allows test range planners to input requirements for a test and automatically translate these requirements to a documented test plan and reservation system. While implementing this type of automation typically requires a large amount of requirements gathering, AI/ML or recommendation engines can be implemented to analyze user input and provide possible output selections.

Use Case 2: Contribution/Distribution Processing

While test ranges currently have methods of processing local content for contribution and distribution, cloud services provide options to process both live streams and VoD for different workflows. Cloud native media services may be used to ingest contribution feeds for fan out and delivery to other contribution locations. Additionally, contribution feeds may be transcoded into distribution feeds to serve remote users using streaming technologies and CDNs.

Use Case 3: Scientific Metadata Alignment

To provide detail around a test event, post-mission metadata requires manipulation from proprietary formats to a format that can be attached to a final delivered product. This can be TSPI, KLV information, or other metadata that is made available from sensor systems. The process at most ranges noted highly manual metadata-to-imagery alignment, requiring translating and appending scientific metadata to the desired final format. Here, AI can pose advantages in being able to automate the scientific metadata generation process without the need for human intervention.

To achieve this, formulaic translations and trigger criteria can be pre-defined to allow generation of the final product(s) as soon as the relevant content is available to operate against. For example, once the raw HS or IR metadata is available, the matching conversions can be automatically applied and made readily available for customer delivery. With MIMD/MISP compliant formats and metadata, the required translations would be further simplified and can be repurposed for use across all ranges. Through this form of automation, deeper analysis will help determine the translations required to compile a workflow of operations that AI can automate.

Use Case 4: Object & Path Detection

Post-mission analysis consists of a large effort in providing object location and orientation. This process requires manually detecting points of interest on a frame-by-frame basis. With up to thousands of frames being captured per second, this results in a large amount of manual labor that needs to be conducted for each test. Here, AI/ML can be implemented to identify objects or points of interest and predict object path to minimize measurement uncertainty and error. This is accomplished by “training” a model based on the particular object(s) that require identification, such as the tip and tail of an airborne projectile.

This form of ML training can take place during the same analysis currently being performed and involves simple steps of confirming or correcting the ML output to obtain greater levels of accuracy in future analysis. Predictive paths can also be implemented, which mitigates instances where the object may be distorted due to conditions such as atmospheric turbulence that causes objects to appear as they are split or duplicated within a frame. Here, path analysis predicts where an object is headed and makes more reliable assessments on object location.

Use Case 5: Access Management

As referenced in prior sections, CMSs provide the ability to store, search, review, and distribute content to system administrators in addition to remote users. A CMS sits at the core of the media solution as an overarching management system for content and users. These systems typically have two levels of authentication to consider: the first being identify, access, and management used to control access to the underlying infrastructure or cloud services in use; and the second being about rights or privileges associated to content within a system.

While customers can build CMS solutions using cloud services, CSPs also leverage vast partner communities capable of providing turnkey CMS solutions that leverage cloud services. Many solutions are fully cloud native and have the ability to be deployed into a customer account using infrastructure as code. While some CSPs operate fully in the cloud, other platforms can offer a hybrid on-premises/cloud model.

Use Case 6: System Monitoring & Health Checks

Test ranges conduct mission-critical operations and do not typically come with an option to repeat a test given time constraints, range availability, and products conforming to one-time usage. During the analysis conducted with test ranges, there was a significant concern over the inability to validate all components of a motion imagery workflow before a test is about to occur. System automation can assist with predictive maintenance or the ability to identify system issues as soon as they arise. To accomplish this, test ranges may consider the use of network management systems where all systems can communicate/report status information.

System alerts can be put in place to regularly monitor the system and notify respective users when a problem arises. This involves identifying each system component and the responsible parties and developing a plan to address issues as soon as they arise to ensure gaps preventing the motion imagery workflow are mitigated prior to conduction of any tests. This can be expanded to other portions of the system such as notifying respective users of asset expiry based on retention policies or general health checks of the entire infrastructure. In addition to alerts, dashboards allow for visualized logging/analytics into the system's current state, health, and activities, either current or historic.

An option for further modernization involves utilizing automation to address when a component has failed. While this may not always be an applicable solution, certain steps can be implemented to redirect an alternate path if an error is identified. For example, if a recording/streaming node is unavailable, a mechanism is established to restore, replace, or redirect a stream so it does not impact in-flight operations. This recommendation is impactful for organizations with critical workflows in place that cannot stand for disruptions due to the nature of their operations.

Use Case 7: Remote Access

With the intersection of technology modernization and real-world circumstances, approaches such as remote operations have become more commonplace. Several test ranges currently utilize remote controls to operate machinery from safe distances, but this is often hosted within relatively close proximity to the test site. For increased safety, remote operations can extend to larger radii for mission deployment. Remote operability can also extend to all types of users involved in the motion imagery workflow through virtual desktop infrastructures (VDIs) that allow access from on-premises or remote environments to a secure, virtual machine with connectivity to the services or functionality the particular user needs.

Enterprises often benefit from persistent desktops or a virtual desktop where a user can log in and access their own personalized machine akin to a physical computer. This type of virtual machine would consist of all security settings, software applications, etc. required for the user's regular day-to-day-operations, but with permissible user customizations. Organizations looking for heightened security in their VDIs can benefit from non-persistent desktops, which provide a fresh, pre-designed machine once a user logs in and terminate machines completely once logged out. These "master" machines that supply the new desktop can be created based on user persona, allowing the ability to log in to a secure workstation with the applications, software, and integrations required for their line of business.

Use Case 8: Automated Data Backups

Section 5.1 describes a variety of storage options between on-premises, cloud, or hybrid approaches to secure data management. Many test ranges do not retain raw test data long after a test has been completed, and typically only two copies of the final customer product will be produced: one for delivery to the customer and another for storing/archiving the test within the respective range. While there will be two source locations for the mission content, this design is not built around redundancy and durability within ranges. Data backups are cost-effective solutions that can be automated through the lifecycle policies referenced when discussing data retention. These are highly efficient measures that can help organizations meet their recovery time/point objectives. In addition, these can be centrally managed by the Defense Enterprise Networks instead of by individual ranges.

In addition to automated database backups, users can initiate their own backups where they will have full control of storing, using, deleting, copying, and sharing that backup. This can lead to additional capabilities such as improved reliability and redundancy. In addition, if user-accessible content editing features are provided within a CMS, content version history backups can be applied to allow restoration of any version from original master to a recent clip.

7. Multipart Modernization

This paper focuses on promoting optimization and collaboration within and between test ranges. There is high value in resolving the current technical and operational challenges and adopting a phased approach towards achieving a desired future-state architecture. The paper has been outlined to address order of significance by macro area and the most beneficial outcomes achieved for motion imagery operations, but does not dive into implementation strategy for accomplishing technology modernization. A visual representation of this modernization approach is available in Appendix A.

Phase 1 of the approach entails working towards intra-range compliance via security and network accreditation, and a parallel initiative to format standardization. These first two initiatives involve working with external parties such as the TRMC to achieve distributed network and cloud ATOs, and collaboration with sensor manufacturers/government open-source software (GOSS) developers to standardize the formats being used for scientific imagery/metadata. During this phase, format standardization can also be implemented by moving towards highly capable media protocols such as JPEG XS for local contribution. As soon as cloud ATO is achieved, ranges can begin leveraging storage as a service for hybrid and cloud archiving. In Phase 1.5, scientific imagery/metadata standardization can begin to take place in parallel to further enable inter-range distribution capabilities and allow processing of scientific metadata.

Once these initial steps to work towards inter-range connectivity are in place, Phase 2 can begin the focus on broadcast-grade distribution of range motion imagery to a distributed user community. Newer distribution techniques such as ABR streaming over CDNs can be leveraged to better serve the enterprise with both live and on-demand media information. A hybrid cloud storage solution can also be implemented within this phase, allowing for the migration of data between various storage tiers and further leveraging the breadth of commercial cloud capabilities.

The final phase addresses the implementation of enterprise services to leverage cloud processing. This includes capabilities such as implementation of automated lifecycle/retention policies, operational efficiencies from system health, test planning, AI/ML, and the ability to utilize a CMS. The intent of a multi-phased approach is to optimize and modernize the motion imagery workflows in a systematic, methodical approach while continuously improving range operations and test capabilities.

8. Conclusion

As a result of the analysis conducted with test ranges, this paper provides a media and technology background/perspective to the sequences that compose the motion imagery workflow. It also highlights the opportunities ranges have in modernizing their operations and shares high-level recommendations for consideration or implementation of these optimization opportunities. These recommendations are outlined in the paper with priority based on the desired goal of inter-range operability, improvement of the mechanisms currently in place, and the need to implement strict security requirements that adhere to DoD specifications.

The gap analysis performed showed that at a high-level overview, ranges perform nearly identical activities within their motion imagery workflows with slightly modified use cases depending on the range's expertise. To further unify all test ranges, a first step is to drive standardization on the formats, codecs, containers, and protocols being used to enable common architectures. This standardization effort can be achieved through collaboration with sensor manufacturers/GOSS developers, while ensuring future formats adhere to MISB recommendations. Standardization enables further unification within ranges by removing the need to convert proprietary formats if/when sharing data.

Obtaining inter-range connectivity will require cybersecurity evaluations and RMF accreditations, which the TRMC can help support. During this step, cloud ATO can allow test ranges to take advantage of cloud services such as storage, media processing, analysis, AI/ML, and more that will further improve the agility at which ranges operate. Additional benefits include but are not limited to enhanced security, reduction of manual error, increased performance and efficiency, and most importantly, range-to-range connectivity for a variety of use cases across data sharing and test collaboration.

While costs are common drivers for governments and enterprise organizations to begin conversations around these types of technologies and cloud solutions, modernization can lead to significant improvement in range operations and test capabilities. Common challenges in accelerating cloud adoption can be organizationally driven, which otherwise eases and expedites cloud capabilities. As these solutions have been presented, it remains important to continue collaboration within the T&E community, including members from the TRMC, OSG, RCC, and test ranges on achieving a standards compliant architecture for range optics. An important finding is that the TRMC serves as a key resource and center of excellence in helping ranges implement RMF packages at no cost to ranges, which further enables pathways to connective networks and cloud computing resources. Through a phased approach such as the one highlighted in this paper, test ranges can independently reach a state that enables cross-range collaboration and continue to optimize any of the processes that make up the motion imagery workflow. While the paper has included suggestions on where to optimize, there are several opportunities to dive deeper from a high-level overview of various ranges and further guide the implementation process.

APPENDIX A

Reference Diagrams

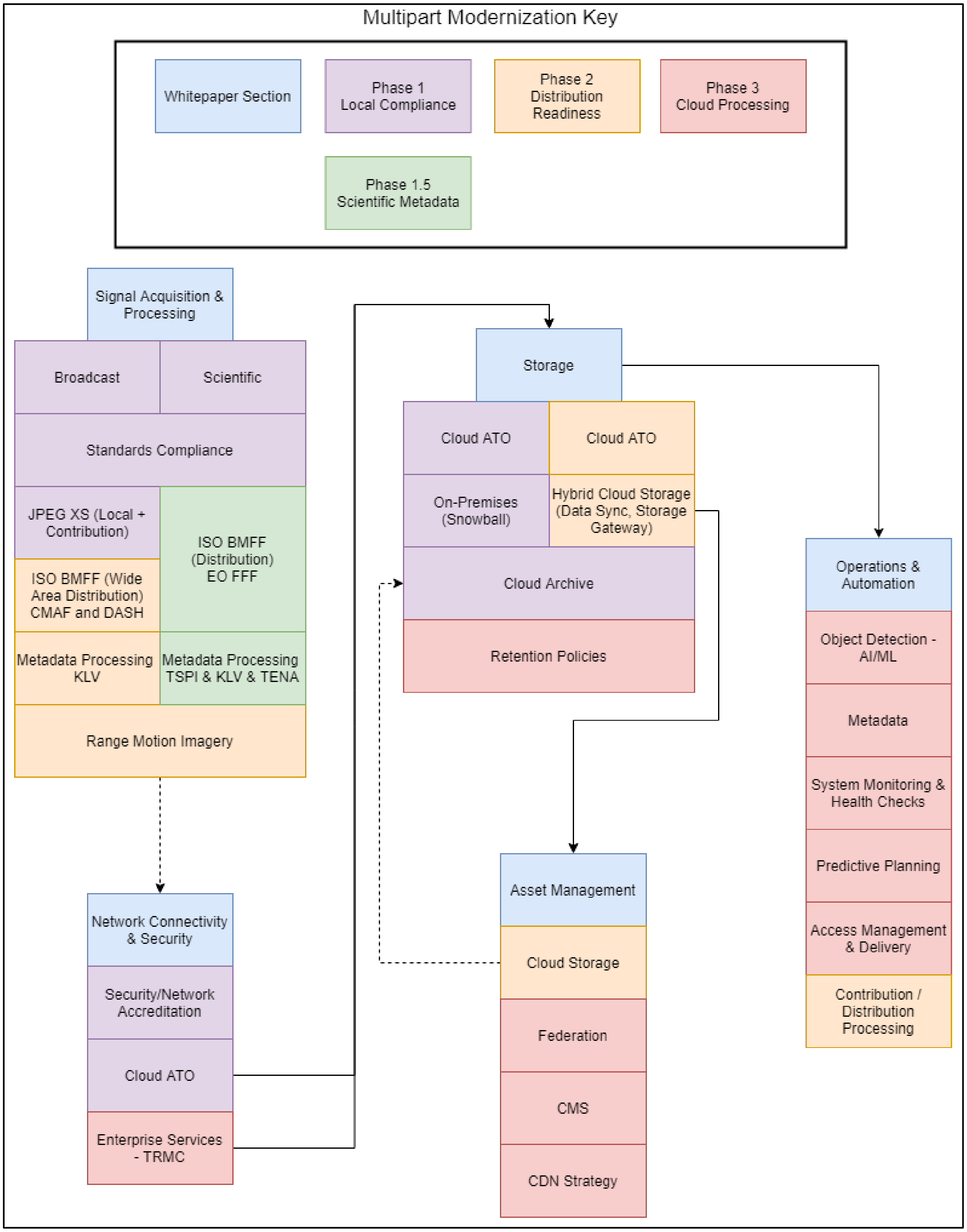

Figure A-1. Modernization Approach

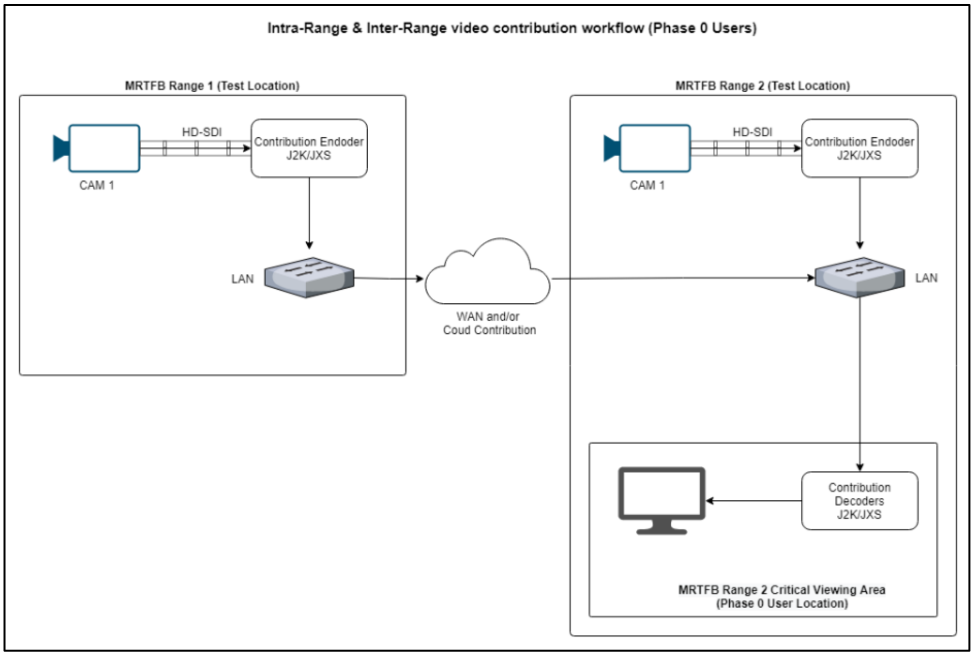

Figure A-2. Phase 0 Users – Contribution Workflow

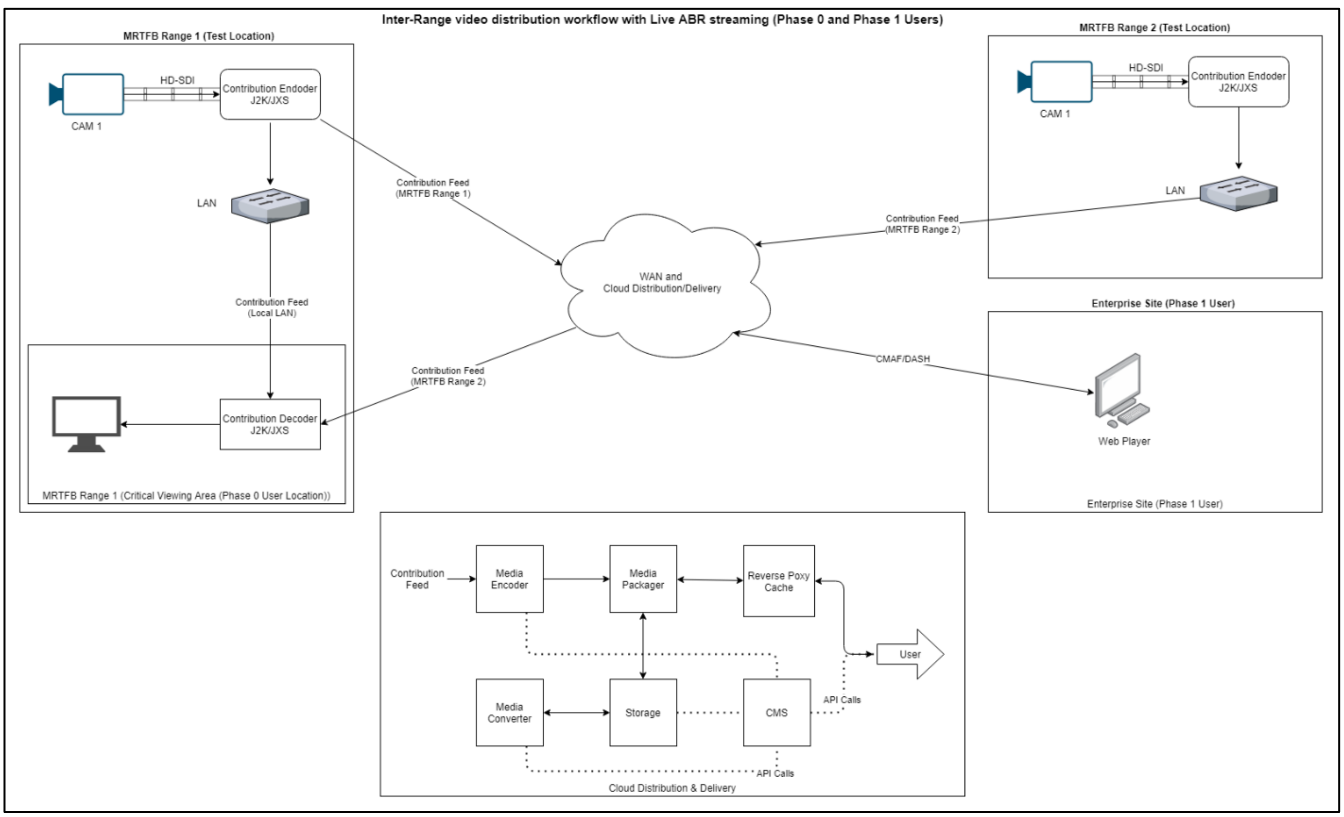

Figure A-3. Phase 0 & 1 Users – Contribution & Distribution Workflow 1

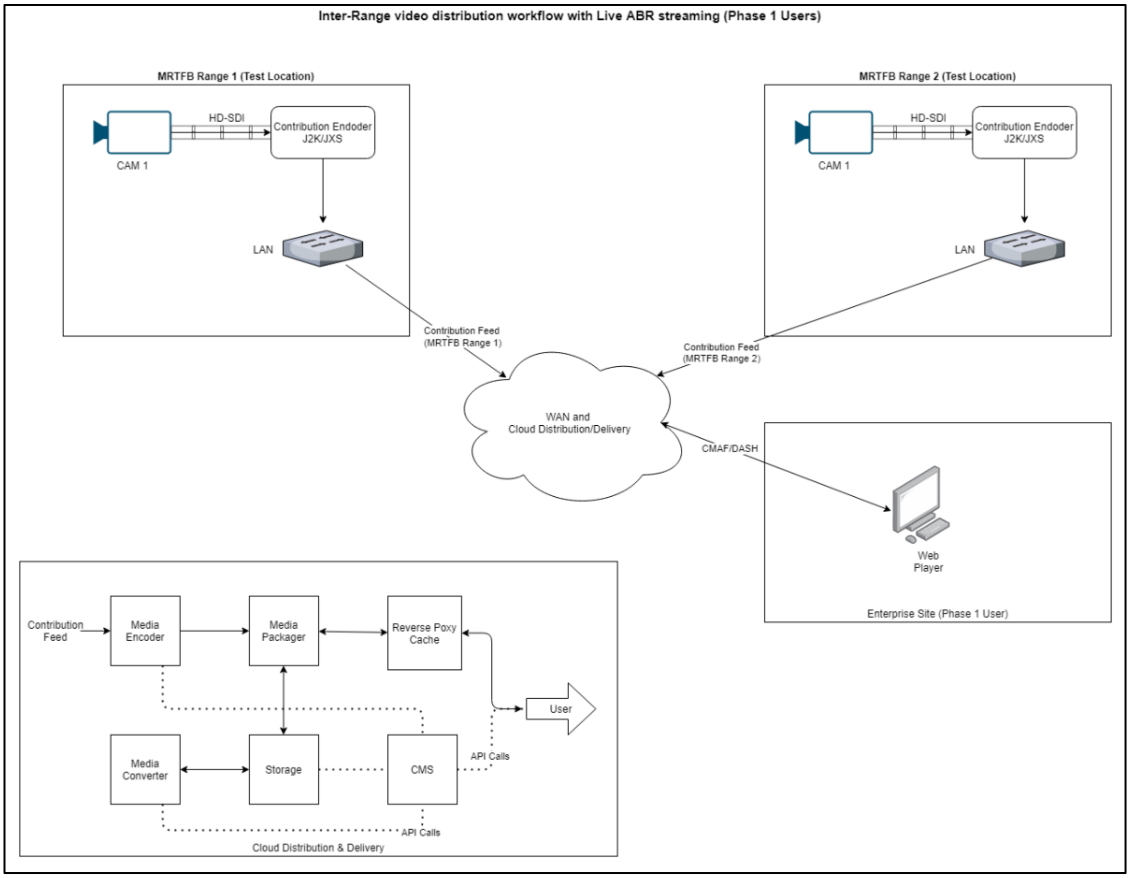

Figure A-4. Phase 1 Users – Contribution & Distribution Workflow 2

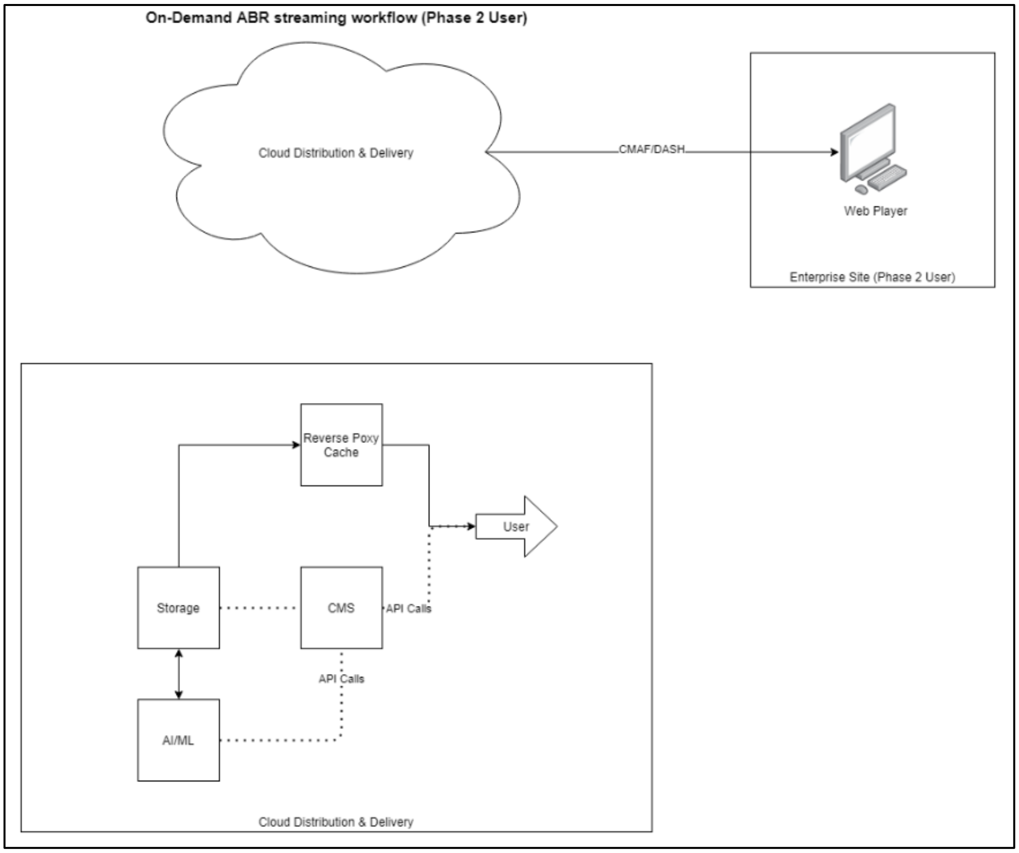

Figure A-5. Phase 2 Users – Distribution Workflow

APPENDIX B

Citations

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