SR-22-002

Range Commanders Council
Optical Systems Group

IMAGE COMPRESSION

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 COMPLEX

SPACE LAUNCH DELTA 30
SPACE LAUNCH DELTA 45

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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IMAGE COMPRESSION

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OPTICAL SYSTEMS GROUP

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Preface

This report illustrates the findings of a video compression study and the possible impacts to the generalized test range optical data workflow. This includes examining areas of cost savings, implementation of interoperability standards, workflow use cases, and the accuracy of time-space-position information results from collected optical system data.

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Acronyms

AI	artificial intelligence
CHEETAS	Cloud Hybrid Edge to Enterprise Evaluation and Test Analysis Suite
GB/s	gigabyte per second
GOP	group of pictures
GOSS	government open-source software
HS	high speed
ISO/IEC	International Organization for Standardization/International Electrotechnical Commission
ISOBMFF	ISO Base Media File Format
KLV	key-length-value
KTM	Kineto tracking mount
Mb/s	megabit per second
MISB	Motion Imagery Standards Board
ML	machine learning
MRTFB	Major Range and Test Facility Base
MSE	mean squared error
MWIR	mid-wave infrared
NSG	National System for Geospatial-Intelligence
ODMS	Optical Data Measurement System
OSG	Optical Systems Group
PSNR	peak signal-to-noise ratio
RMS	root-mean-squared
SA	situational awareness
SWIR	short-wave infrared
TRMC	Test Resource Management Center
TSPI	time-space-position information
WSMR	White Sands Missile Range

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1. Introduction

1.1 Background

Digital video compression technology has been advancing at a quick and steady pace for more than two decades. By strategically removing redundant information from either a still image or a sequence of images, modern codecs are capable of accurately representing source imagery with only a fraction of the data requirements of the original uncompressed video.

Test ranges require a methodical and rigorous analysis to ensure retention of measurement accuracy before adopting the use and application of modern codecs on test range imagery. Test ranges use uncompressed video to produce their final time-space-position information (TSPI) data product to ensure the highest level of accuracy. This dictates that uncompressed video is recorded, stored, transferred, and processed through the entire workflow to produce the desired high-quality TSPI data product. To realize efficiency benefits, this study aims to show that current accuracy levels can be retained with the application of an amount of compression that is lighter than what is typically applied when streaming motion imagery.

1.2 Scope

This study examines the effects that standards-compliant video compression may have on the production of a TSPI data product. To decouple the effects of video compression from other known sources of uncertainty, like instrument calibration, this study limits its focus to the errors when determining the measured position of features of interest within the image frames.

2. Projected Labor Cost Savings

The desire to leverage image compression on primary image products at the test ranges is driven by the opportunity for significant savings in storage requirements and transmission/download times. The opportunity for improved post-mission download times of test imagery holds the potential for significant labor savings when operators are required to wait for completion of downloads before shutting down their fielded systems and returning to base.

With current Kineto Tracking Mount (KTM)-based workflows, imagery is typically recorded within high-speed cameras or within uncompressed recorders, such as those provided by IO Industries. Tens or even hundreds of gigabytes are frequently recorded for each camera on a mission. With last mile network speeds currently ranging from a hundred megabits/second (Mb/s) to a gigabit/second, download times for a system with four to six cameras can exceed three hours.

A hypothetical but realistic example involves looking at a typical mission at White Sands Missile Range (WSMR). For a given ground-to-ground scenario, it is not uncommon to have eight KTM tracking systems that are fielded, along with at least 20 fixed (stationary) high-speed (HS) camera systems that cover the launch and impact of an event.

Each KTM is configured with the following sensor payload (Note: The values highlighted in yellow are tunable and were set to represent current camera values and can be adjusted.).

Table 1. High-Speed Visible Camera Configuration

HS Camera Width	2560	Pixels
HS Camera Height	1600	Pixels
HS Camera Bytes/Pixel	2	Bytes/Pixels
HS Camera Frame Size	8192000	Bytes
HS Camera Frame Rate	1000	Hz
HS Camera Data Rate	7.6	Gigabyte/second (GB/s)
HS Camera Memory Capacity	72	GB
HS Camera Data Size	72.0	GB
HS Camera Compressed Data Size	7.2	GB

Table 2. Situational Awareness Visible (4K) Camera Configuration

HS Camera Width	4096	Pixels
HS Camera Height	3072	Pixels
HS Camera Bytes/Pixel	1	Bytes/Pixels
HS Camera Frame Size	12582912	Bytes
HS Camera Frame Rate	120	Hz
HS Camera Data Rate	1.4	GB/s
HS Camera Memory Capacity	1024	GB
HS Camera Data Capture	337.5	GB
HS Camera Compressed Data Size	33.8	GB

Table 3. MWIR Camera Configuration

HS Camera Width	1280	Pixels
HS Camera Height	1024	Pixels
HS Camera Bytes/Pixel	2	Bytes/Pixels
HS Camera Frame Size	2621440	Bytes
HS Camera Frame Rate	120	Hz
HS Camera Data Rate	0.3	GB/s
HS Camera Memory Capacity	512	GB
HS Camera Data Capture	70.3	GB
HS Camera Compressed Data Size	7.0	GB

Table 4. SWIR Camera Configuration

HS Camera Width	1280	Pixels
HS Camera Height	1024	Pixels
HS Camera Bytes/Pixel	2	Bytes/Pixels
HS Camera Frame Size	2621440	Bytes
HS Camera Frame Rate	120	Hz

HS Camera Data Rate	0.3	GB/s
HS Camera Memory Capacity	256	GB
HS Camera Data Capture	21.1	GB
HS Camera Compressed Data Size	2.1	GB

Each of the 20 fixed HS cameras is configured as shown in Table 5.

Table 5. Non-track high-speed camera configuration

HS Camera Width	2560	Pixels
HS Camera Height	1600	Pixels
HS Camera Bytes/Pixel	2	Bytes/Pixels
HS Camera Frame Size	8192000	Bytes
HS Camera Frame Rate	1000	Hz
HS Camera Data Rate	7.6	GB/sec
HS Camera Memory Capacity	72	GB
HS Camera Data Size	72.0	GB
HS Camera Compressed Data Size	7.2	GB

Several assumptions and calculations about the mission configuration are made and listed in Table 6. Included in this is an estimate of running 80 missions per year in this average configuration. With these parameters, an estimate for annual savings that can be realized is calculated to be over $500K when assuming a very modest compression ratio of 10:1.

Table 6. Benefit of Modest Compression

Calculator to compare compression ratio, download times, and labor savings
*Highlighted items can be modified

Tracking Systems Downloads		Non-Track Systems Downloads	
Compression Ratio	10	Compression Ratio	10
Mission Record Time	240 seconds	Mission Record Time	10 Seconds
Uncompressed Data Size	4007.3 GB	Uncompressed Data Size	1440.0 GB
Compressed Data Size	400.7 GB	Compressed Data Size	144.0 GB
Network Download Bandwidth	200 Mb/s	Network Download Bandwidth	200 Mb/s
Network Download Bandwidth	0.025 GB/sec	Network Download Bandwidth	0.025 GB/sec
Uncompressed Download Time	20036.3 Sec	Uncompressed Download Time	2880.0 Sec
Uncompressed Download Time	333.94 Min	Uncompressed Download Time	48.00 Min
Uncompressed Download Time	5.57 Hrs	Uncompressed Download Time	0.80 Hrs
Compressed Download Time	2003.6 Sec	Compressed Download Time	288.0 Sec
Compressed Download Time	33.39 Min	Compressed Download Time	4.800 Min
Compressed Download Time	0.56 Hrs	Compressed Download Time	0.080 Hrs

Number of systems in the field	8 Systems	Number of systems in the field	20 Systems
Operators per system	2 Operators	Operators per system	2 Operators
Operators in the field	16 Operators	Operators in the field	40 Operators
Wage Rate	$75/hr	Wage Rate	$75/hr
Time to travel back to site after mission	0.5 Hrs	Time to travel back to site after mission	0.5 Hrs
Wages during uncompressed download	$6,679	Wages during uncompressed download	$2,400
Wages during compressed download	$668	Wages during compressed download	$1,500
Savings per mission	$6,011	Savings per mission	$900
Missions per year	80	Missions per year	80
Savings per year	$480,870	Savings per year	$72,000
Total Savings	$552,870.00		

While compression ratios of over 100:1 are very common with today's advanced codecs when performing streaming video applications, it is important to recognize that ratios above 10:1 see a diminishing return. As a 10:1 compression removes 90% of a download time or storage capacity, an increased ratio of 100:1, only improves the result by less than an additional 10%. It should also be noted that a ratio of 10:1 is frequently equated to a visually lossless compression, where the average person cannot statistically identify a source image from its compressed counterpart. This is shown in Figure 1.

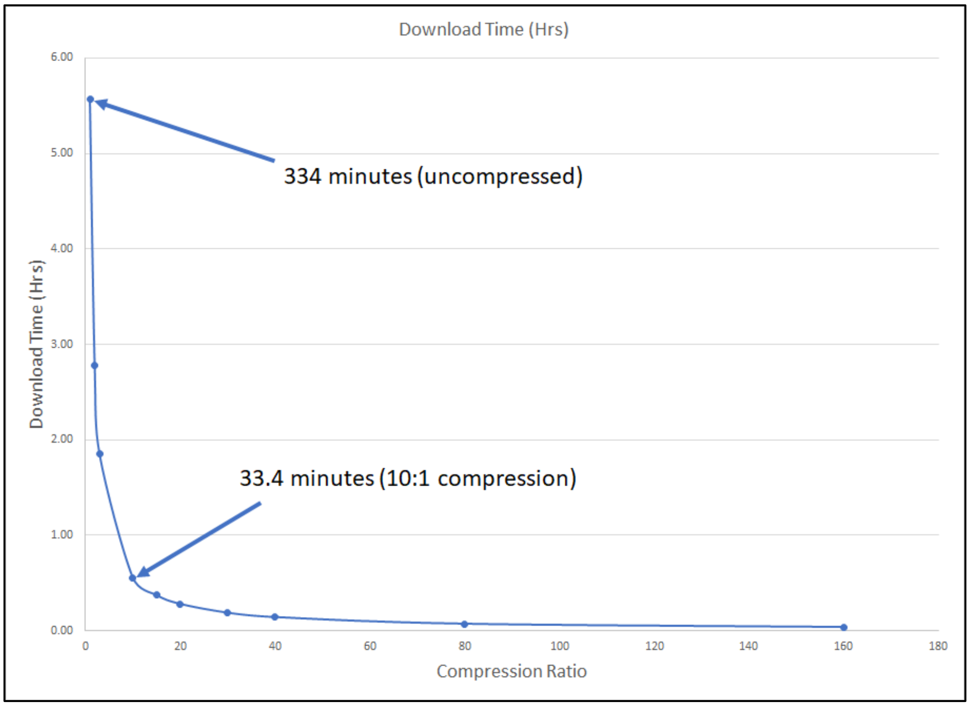

Figure 1. Comparing Compression Ratio Versus Download Times

Converting the savings in download time in Figure 1 to a savings in labor dollars due to operators spending less time in the field during the downloads results in the curve shown in Figure 2 - again, highlighting the diminishing return beyond a 10:1 compression.

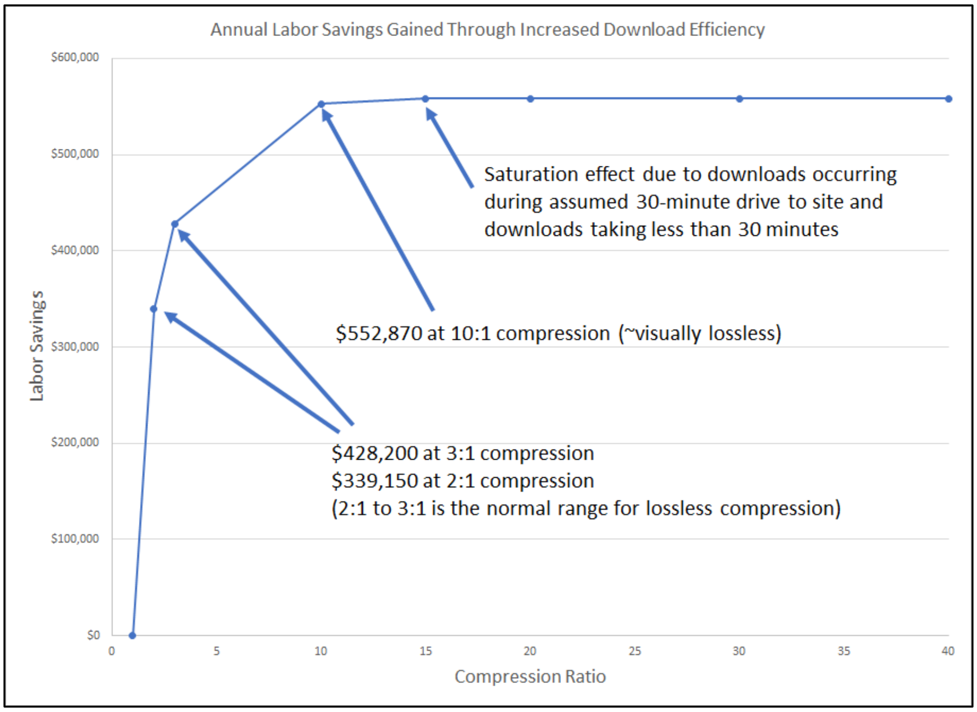

Figure 2. Comparing Compression Ratio Versus Annual Labor Savings

A final observation is that a lossless compression typically achieves a 2:1 to 3:1 level of compression for general imagery. For range imagery with large portions of uniform blue sky, ratios of 6:1 are readily achieved. Significant savings can still be achieved when utilizing lossless compression with no compromise at all in data quality.

3. Motion Imagery Standards Board (MISB) Codecs

At the beginning of this study, it was assumed that H.265 would be the clear choice of codec for the test ranges, since it is based on new technology. A trade space for achieving higher ratios, however, is a significant increase in encoder complexity, which results in a much higher processing requirement. This places a burden on fielded systems, which may create complications that can be avoided, especially since the targeted compression point is only 10:1. It turns out that H.264, in some respects, is a better fit for the test ranges given the different priorities of the consumer video streaming industry. Commercial content producers have the luxury of loading the video encoder with complexity and storing that video for streaming at a later time. Many commercial video decoders need to run within simple browsers or mobile devices, skewing newer technologies to have less complexity at the decoder. Test ranges almost have the inverse challenge when compared to commercial video streaming. That is, test ranges produce large amounts of uncompressed video from distributed sources and have very different network transmission requirements that need to be met. In addition, a desire is to move the image content as quickly as possible via file download versus the commercial model of a streamed playout.

Figure 3 shows the encoding times for H.264 and H.265 for two group of pictures (GOP) structures. For the target compression of 10x, it takes H.265 about 12 times as long to compress the same video (for the given PC workstation that was used to perform the test). Assuming a test range instrument is capable of the same compression rate that generated Figure 3, a 10,000-frame video could be compressed with H.264 at 10x in about four minutes. For H.265, the same system would compress the same video in 48 minutes.

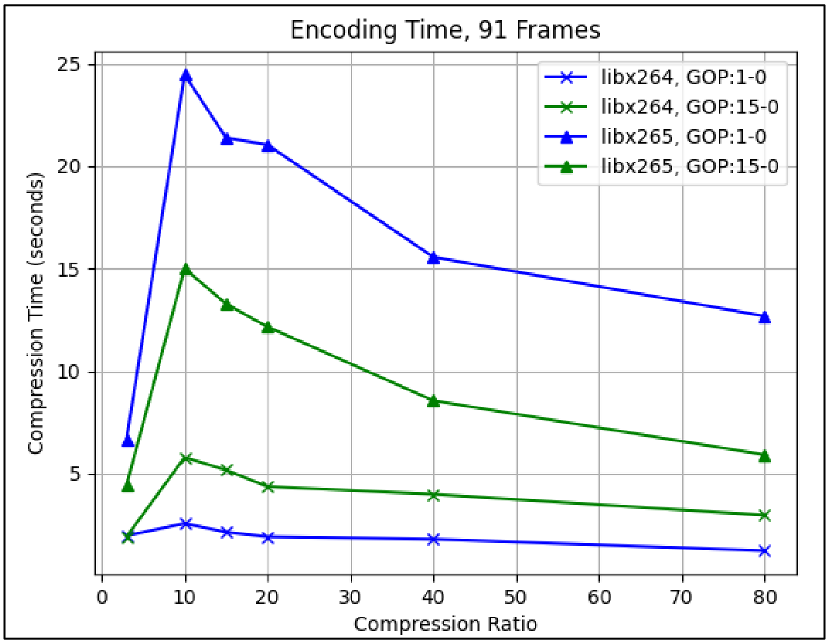

Figure 3. Encoding Time Comparisons

For this reason, this study gathered data only for video compressed with the H.264 codec. If a decision is made to utilize an H.265 codec instead, the quality can be expected to improve by a rough factor of 2:1 and the associated processing time will also go up by an amount that is dependent on available hardware or graphics processing unit acceleration that is available.

The analysis shown in Section 2 shows the importance of targeting the 10x compression ratio. Figure 3 also shows an inverse relationship between the compression ratio and the time required to compress the video.

The video compression ratios used in the testing were configured as below.

- Uncompressed
- Lossless
- 10x
- 20x

Videos were encoded with I-frames only to limit the data-gathering requirement (for range data reduction operators) and to remove any potential issues with respect to using motion vectors in the compression. The measurements from the uncompressed and lossless videos were used to infer a "truth" for the data. These two sets of data are identical, so they allow for characterizing a baseline measurement uncertainty parameter for each operator. The process is described in *Methodology for Testing Metric Zoom Lenses*.[1]

Of note, JPEG2000 was not analyzed in this study due to time and budget constraints, but likely represents a very viable solution for an eventual standards-compliant compression option. JPEG2000 is an intraframe-only codec and has a beneficial feature in that it can compress all the bit-depths in use at the ranges, with future expansion that covers up to 32 bits. An additional codec that shows promise for Major Range and Test Facility Base (MRTFB) specific application is JPEG-XS, which provides low compression ratios, about 10:1, but achieves these with very low computational complexity and very low latency. At the request of the current Optical Systems Group (OSG) Chair, coordination will occur with the MISB to determine the appropriateness and possibility of adopting JPEG-XS as an approved MISB standard. In addition to the MRTFB, Naval Sea Systems Command has use cases that may benefit specifically from the use of this codec.

4. Specific Use Cases

It is important to identify each possible use case scenario when determining the best possible application of compression applied to each video type being produced by optical instrumentation. The below sections cover some of the common use cases identified at test ranges where compression can provide benefit. Some of these are best suited to stream live events in real time with minimum latency and with post-mission data transfer. There is, however, a potential benefit to recording these videos downstream for data reduction purposes to begin the data reduction process while the mission is still being conducted to increase efficiency and provide cost savings.

4.1 Launch

A typical launch scenario can vary depending on the weapon system or test being conducted on the range. When considering this, it is important to look at how these events unfold and the effects that compression can have. One example is when a missile is launched from a tactical vehicle or launch platform and there is a considerable amount of exhaust plume present in each frame. In these cases, the plume can cause a low signal-to-noise ratio in regions of interest, such as where fins are immediately deployed after exiting from the launch tube. Viewing of this deployment process can be critical for determining nominal performance. In many cases, launch video is compressed and live streamed for situational awareness by test officers and mission support personnel. A key constraint in this case is maintaining a latency of lower than 200 milliseconds for any activity that might be required in real time (e.g., a flight safety officer having to make a decision when an anomaly occurs; or an operator that is manning a tracking system that acquires the missile directly from the tube via manual track).

4.2 Intercept Event

Intercept events are considered an important use case as they are common events on some test ranges and involve highly dynamic scenarios where very detailed post-mission analysis may be required. Many intercept events occur at high altitudes, which can induce other detrimental

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[1] Range Commanders Council. *Methodology for Testing Metric Zoom Lenses*. SR-22-003. September 2023. May be superseded by update. Retrieved 25 September 2023. Available at https://www.trmc.osd.mil/wiki/x/YIy8Bg.

distortions that negatively impact analysis and TSPI generation due to atmospheric distortion. During this study, significant atmospheric turbulence was observed in the data. This is common and needs to be recognized as a general source of image degradation that naturally occurs at some level during almost all test range scenarios. For the datasets that were provided, TSPI on the missile tip is a defined measurement requirement. While it is possible that high levels of compression can potentially distort the tip of the missile, it is important to note that the turbulence distortion was a more significant source of error than the video compression, especially with the lighter levels that were implemented within this study.

4.3 Impact Events

Impact use case scenarios involve situations where ground-to-ground and air-to-ground scenarios result in a missile or bomb impacting a target on the ground. In some cases, an air burst above a target may occur by design. In these scenarios, the location of impact on a target or the location of air burst above the target are primary TSPI measurements of interest. In certain cases, the growing fragmentation debris field is of specific interest. The measurement of particle size and velocity may be used to determine lethality. An important area of concern when using compression in these situations is when there is a sudden and dramatic change in scene content due to a large explosion relative to the field of view. With events like this, some projects are interested in effects on targets and some of the potential debris that can be produced. When considering application of compression to these types of videos, it is imperative that these regions of interest are not altered to prevent proper interpretation. The size and the motion of particles are of interest.

4.4 High-Speed Events

Datasets provided for this study did not include any high-speed events. This use case includes events that commonly occur during intercept or impact engagements, at a rocket sled test track, or at a projectile firing. Given the dynamic nature of this use case, cameras are typically configured to record at a high frame rate with short exposure time to satisfy the TSPI data collection requirements. The high frame rates are necessary to ensure that TSPI is collected with sufficient sample rates to determine precise location during highly dynamic and transient events, some of which require very difficult triggering mechanisms to capture. While high-rate video poses an extreme challenge for compressing in real time, it is very much straightforward to compress on download when it is initially recorded in an uncompressed manner and then compressed when the images are extracted from camera memory or from a recorder. Test ranges expect that the benefits of compressing high frame rate video during high-speed events will follow the trend laid out in this study. It is important to note that the usage of short exposure times generally results in an image with a lower signal content as not as many photons are captured during a short exposure. This results in a general case where the signal-to-noise ratio will be lower, which can potentially affect the compression results. Utilization of higher bit depths with range cameras can improve this situation because the lower amount of signal level is captured with a finer granularity of gray levels. Increased noise content can result in making imagery more difficult to compress in general. Our test results in this effort, however, indicate the light compression that is being suggested did not impact the quality of the TSPI results.

4.5 Color vs Monochrome

Different mission scenarios require the use of either monochrome or color imagery. Monochrome imagery is used with infrared motion imagery and for visible imagery where the increase in camera sensor sensitivity is important to the mission and data collection. While infrared imagery can be colorized through pseudo-coloring algorithms, color imagery is native to the visible band, which roughly covers the 400-700 nm spectral region. Image sensors leverage red, green, and blue filters to generate images that are representative of what we normally see.

Compression algorithms rarely compress the color images in this form. To take advantage of human physiological interpretation of the images, the images are converted into a color space that consists of an intensity band and two color difference bands. The YCbCr is the dominant color space that is used by today's codecs. When the imagery is converted into this space, the color difference information is typically averaged across neighboring pixels in the horizontal direction (4:2:2 format) for lighter compression, and then in the vertical direction also (4:2:0 format) for higher levels of compression. This is important because for metric image analysis, a certain amount of information is being lost when these conversions take place. This happens automatically when broadcast format cameras utilize HD-SDI signals to output uncompressed 4:2:2 imagery.

Initial testing was conducted on monochrome video to compare immediately noticeable effects of compression on monochrome versus color video. No significant differences were detected. All measurements for this study were obtained from color video provided by the test ranges, since this is the current primary source of imagery that is used for generating TSPI. It is important to note that compression codecs are available that support the retention of higher bit depths than the standard eight bits that are used in normal codecs. This allows for the retention of full dynamic range when compressing datasets. For current high-speed visible cameras, this involves 12-bit samples (in a native Bayer format), and with monochrome infrared, this involves 14-bit 4:0:0 format source imagery.

5. Results

This study limited its in-depth focus to two uses cases: non-track impact and tracking impact using mission data from a Guided Multiple Launch Rocket System ground-to-ground mission at WSMR.

5.1 Non-Track Impact

The uncompressed video for this scenario was generated by a Phantom v711 camera on a fixed tripod. The target was focused well, and there was minimal distortion due to atmospherics. Figure 4 shows a representative sample of this video.

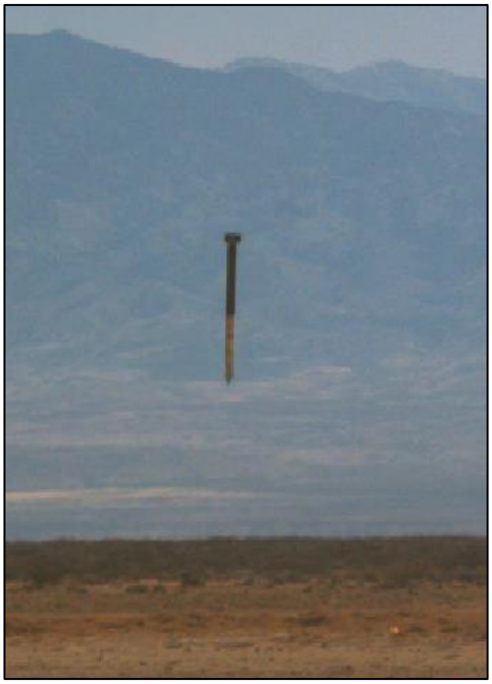


Figure 4. Example Imagery of Non-Track Video Sample

Figure 5 shows the resultant "truth" after measurements were analyzed from the uncompressed and lossless videos. Each solid curve represents the mean of all "truth" measurements, and the shaded area depicts three standard deviations from the mean.

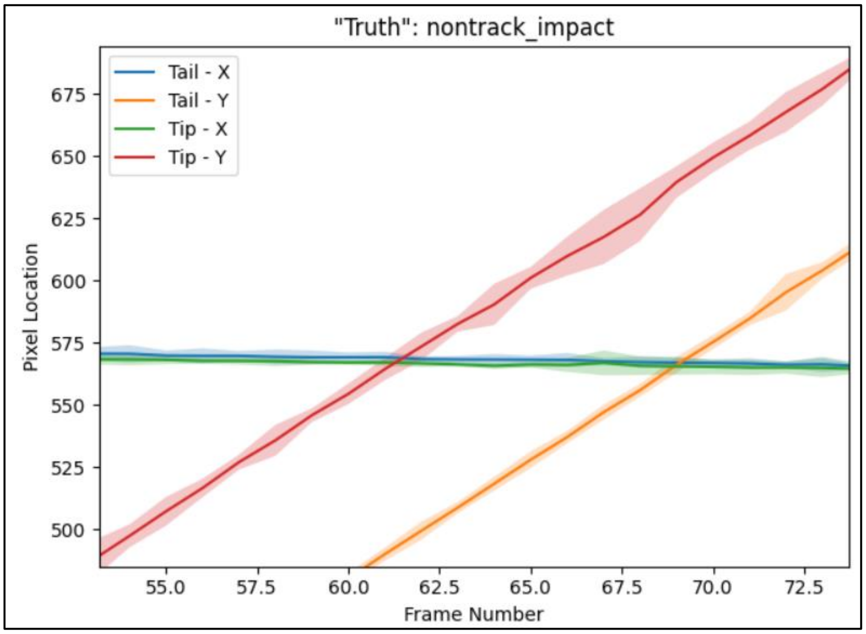


Figure 5. Calculated "Truth" for Non-Track Video

The collection of measurements is a non-stationary process; it is not guaranteed that any two frames share identical statistics. Figure 6 plots the uncertainty in the "truth" for each frame, precisely three standard deviations. The X-dimension for both tip and tail shows less variability than the Y-dimension for the same features. This is likely due to the vertical motion present in the video and a human component of having to physically move a mouse cursor onto the perceived tip of the missile. There is also increased variability after frame 64. Figure 7 shows uncompressed video frames 64 and 67, where the tip feature is particularly difficult to discern due to background clutter.

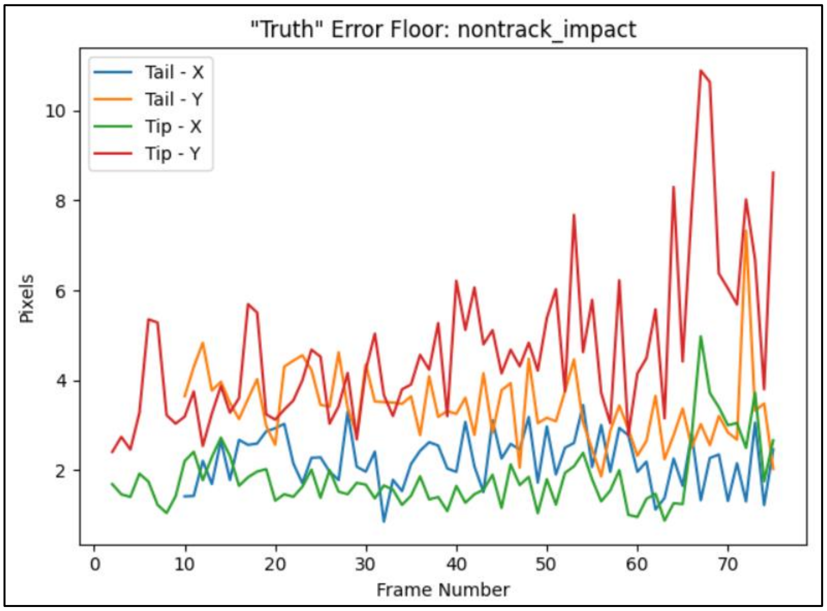


Figure 6. Error Floor for Non-Track Video

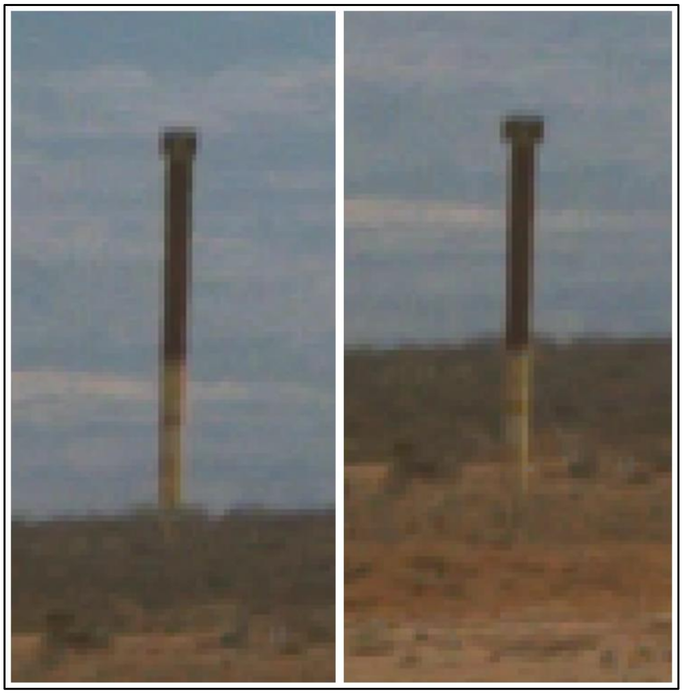


Figure 7. Challenging Video Frames for Tip on Non-Track Video

It is possible to get a single error metric of an entire video by taking the root-mean-squared (RMS) error over each compression ratio. Figure 8 shows essentially a flat line between uncompressed and 20x compression for RMS error. The slight variability in the graph can be attributed to the limited collected sample size. This shows there is no change in error between each of the compression ratios selected.

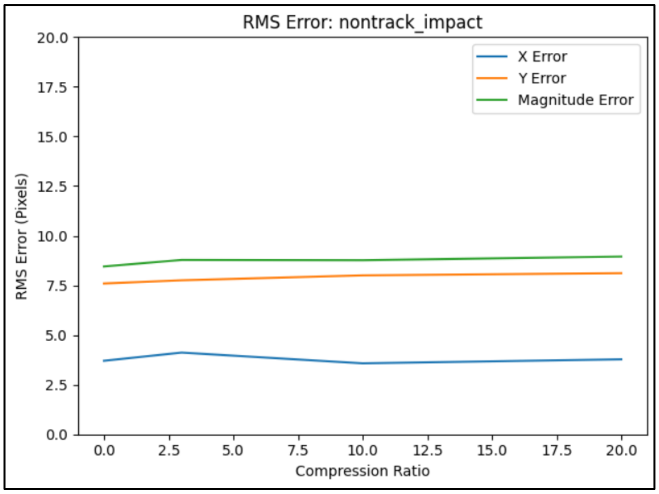


Figure 8. RMS Error for Non-Track Video

5.1.1 Sources of Error

For this scenario, the dominant source of error was human. Figure 9 shows the RMS error for each of the participants. One of the readers introduced an error of ±12 pixels, which would be uncharacteristic of even the most aggressive video compression settings.

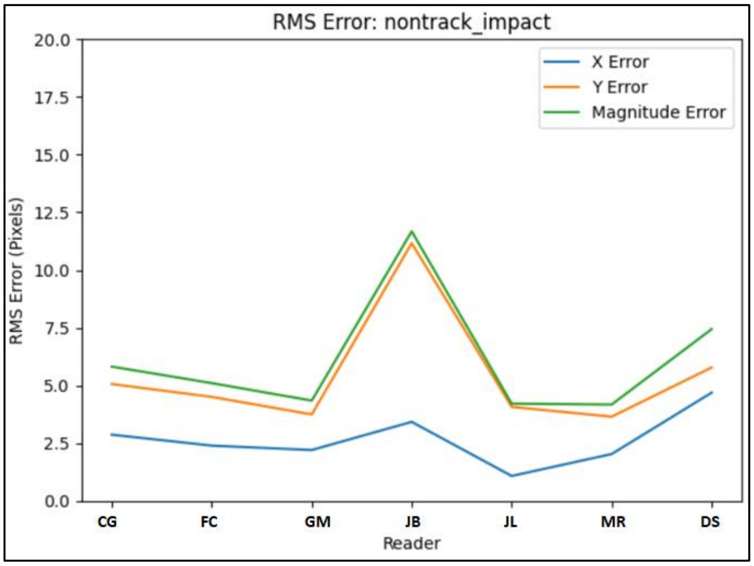


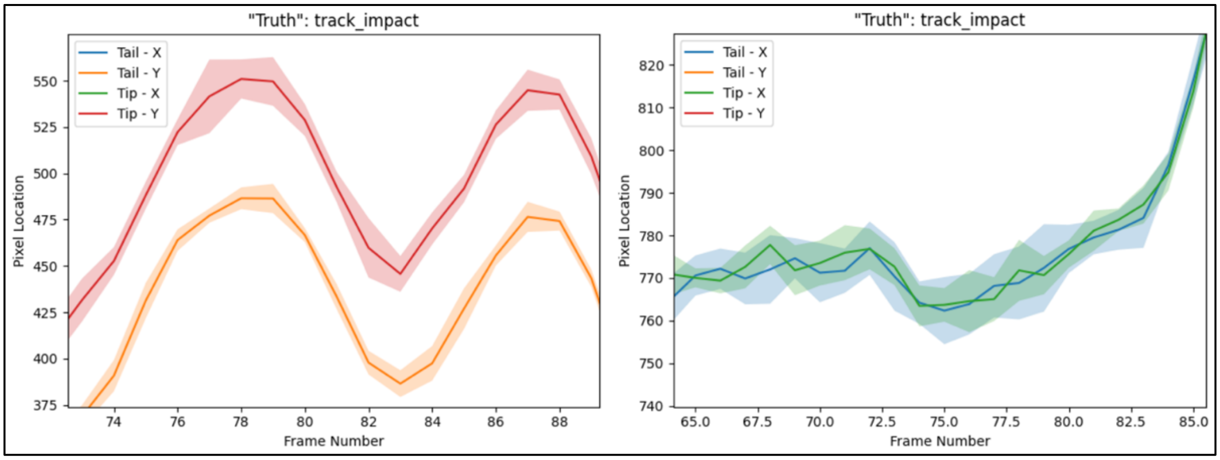
Figure 9. Sources of Error for Non-Track Video

5.2 Tracking Impact

The uncompressed video for this scenario was generated by a Phantom VEO 340L camera on a KTM. It is difficult to determine if the focus was set properly for the target, or if the image quality was degraded due to atmospherics. Figure 10 shows a representative sample of this video.

Figure 10. Example Imagery of Track Video Sample

Figure 11 shows the resultant "truth" after measurements were analyzed from the uncompressed and lossless videos. As for the previous video, each solid curve represents the mean of all "truth" measurements, and the shaded area depicts three standard deviations from the mean.



"Truth": track_impact

"Truth": track_impact

Figure 11. Calculated "Truth" for Track Video

Figure 12 shows the non-stationary behavior for the measurement process by plotting the uncertainty in the "truth" for each frame, three standard deviations. Like the previous scenario, the X-dimension for both tip and tail shows less variability than the Y-dimension for the same features. This is likely due to the vertical motion present in the video. The quality of the source video is quite poor, especially around frame 77, which corresponds to the spike in Figure 12. Figure 13 shows an example of what the target looks like for much of the video.

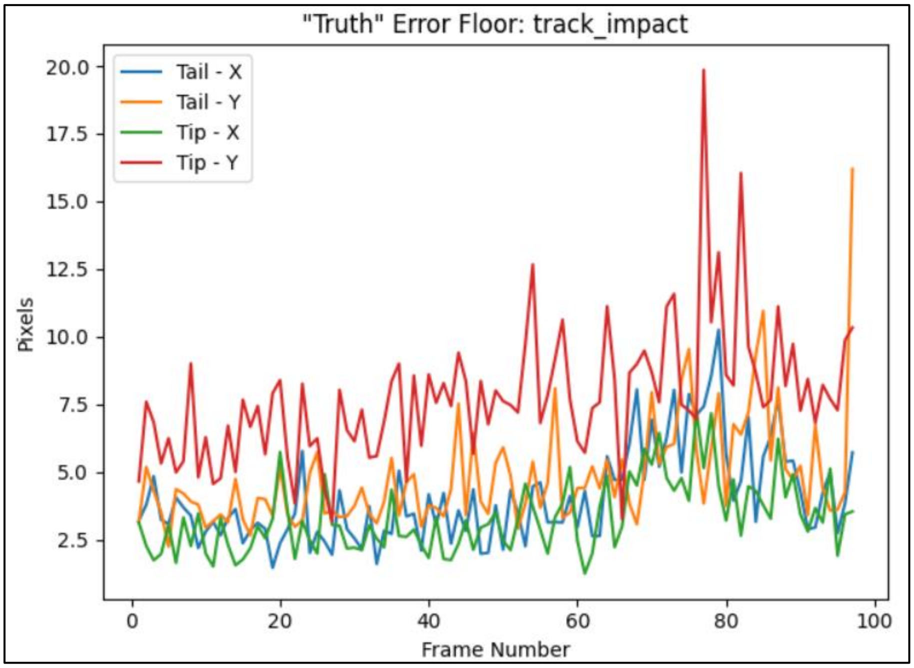


Figure 12. Error Floor for Non-Track Video

Figure 13. Challenging Video Frame for Track Video

As in the previous scenario, the RMS error was calculated over each compression ratio. Figure 14 shows an effective flat line between uncompressed and 20x compression for RMS error. The change in RMS error from uncompressed to lossless, which are binary equivalent videos, points to the limited sample size collected for this study. Figure 14 shows there is no significant change in error between each of the compression ratios selected.

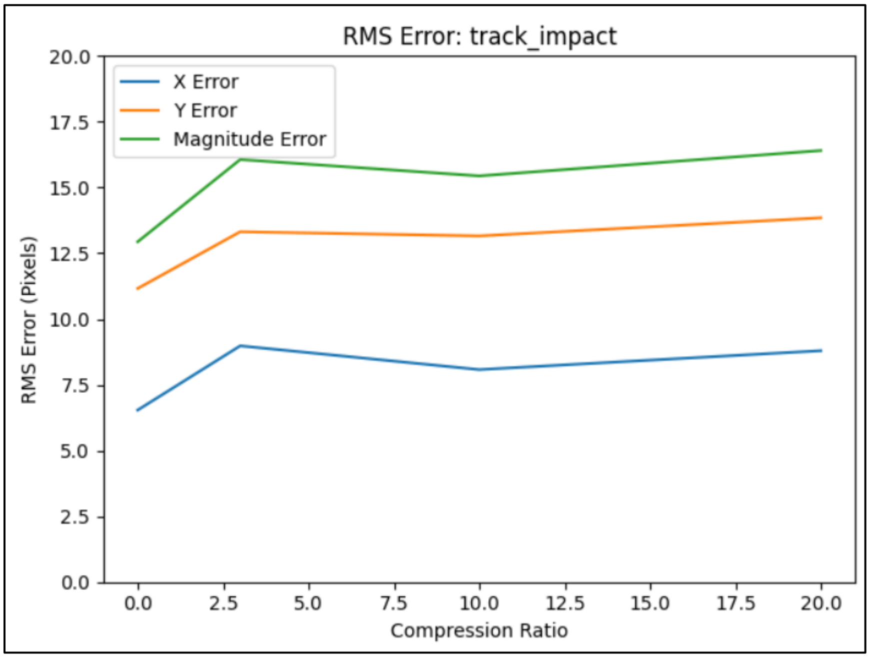


Figure 14. RMS Error for Track Video

5.2.1 Sources of Error

For this scenario, the dominant source of error was video quality. Figure 15 shows that the RMS error did vary across the participants, just like in the previous scenario, but the elevated RMS (about 16 pixels) is likely attributed to the quality of the imagery.

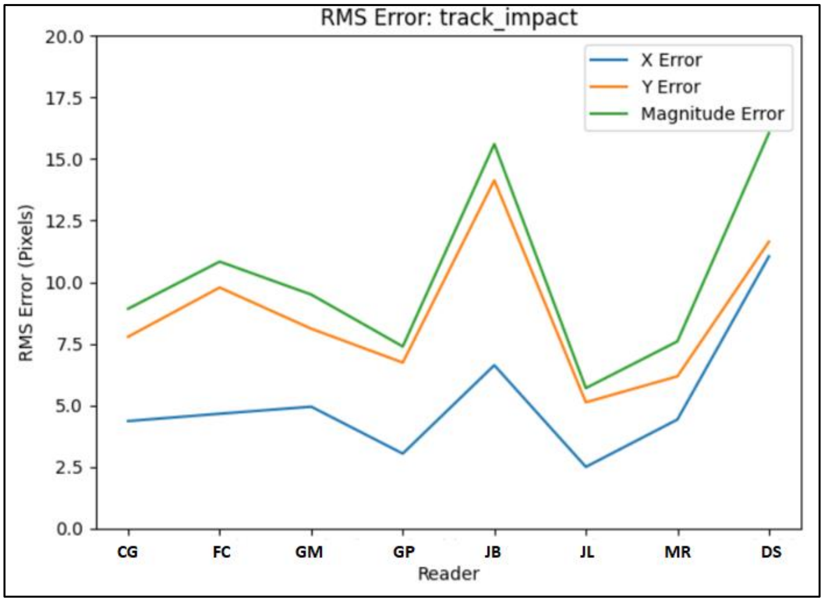


Figure 15. Sources of Error for Track Video

Figure 16 shows uncompressed video frames 51 and 52. The target in the frames is a rigid object, unable to flex as it appears by the frames below.

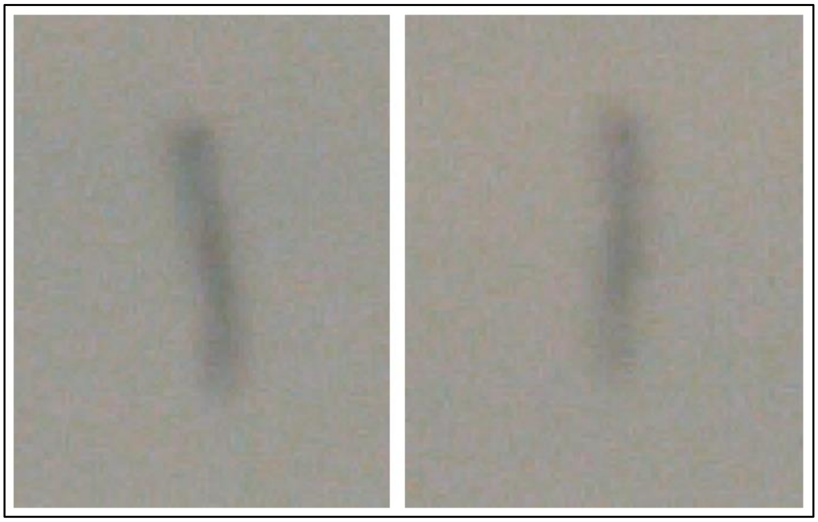


Figure 16. Frames 51 (left) and 52 (right) of Track Video

Figure 17 shows uncompressed video frames 96 and 97. The target is centered in both frames, but barely discernable in frame 97.

Figure 17. Frames 96 (left) and 97 (right) of Track Video

In these situations, where the tip of the missile is not discernable or highly distorted, an operator is left with no option but to make a best guess for where the tip resides.

6. PSNR

The peak signal-to-noise ratio (PSNR) was calculated for each of the two scenarios described in the previous section. Figure 18 shows the PSNR versus compression ratio for non-track and track impact videos.

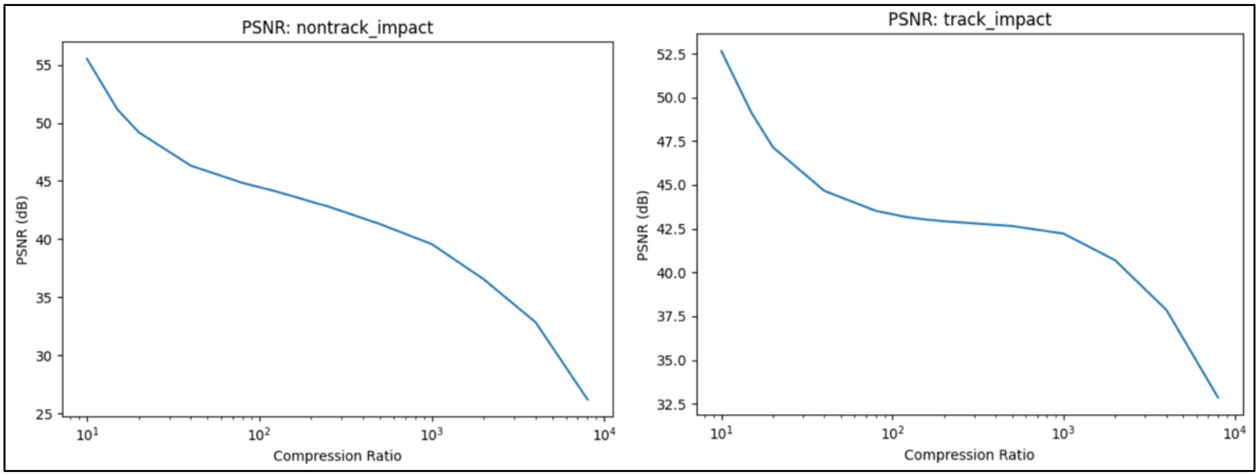


Figure 18. PSNR Curves for Non-Track (left) and Track (right) Videos

The PSNR is calculated using equation 1.

$$PSNR = 10 \cdot log_{10}\left(\frac{MAX_I^2}{MSE}\right) \qquad \text{Equation 1}$$

Where MAX_I is the maximum possible pixel value of an image (255 for an 8-bit image), and MSE is the mean squared error between the uncompressed image and its compressed counterpart. If the MSE is equal to or less than one, the PSNR will be equal to or greater than 48.13 dB. This situation indicates that on average, each pixel has a deviation of one gray level value or less. This indicates a near identical reproduction of the source imagery and points to our conclusion of 10x and 20x compression as being within the range of “visually lossless”, given the current setup and configuration of range equipment for this process. Mr. Pankaj Topiwala, of FastVDO, reported at a recent MISB meeting that broadcast companies target a PSNR of at least 38 dB as being acceptable for high-end commercial streaming applications. While this is a different application and market, it provides a general confirmation that PSNR values in the mid- to high- 40s result is very high-quality reproductions. As a side note, the PSNR level of 38 dB can be considered a very reasonable benchmark for live-streaming applications at the ranges.

The PSNR is commonly used to relate an objective metric to a subjective observation; that is, to determine how much an image can be compressed before a human is able to detect distortion in the compressed image. Typically, this happens at some point in the knee of the PSNR curve. For the curves in Figure 18, the knee happens around 1000x compression. It is important to emphasize that the compression ratios of 10x and 20x are near or above the maximum useful value of 48 dB, indicating near perfect reproduction. One final observation is that range imagery can frequently contain large areas of uniform sky when tracking aircraft, missiles, and bombs.

This uniformity makes for images that are easier to compress. The images that we were provided with were of this nature. When evaluating solutions for generalized cases, imagery that contains broad structure and clutter across the entire image will provide for a more conservative result.

7. Verification of Compression Parameters

Videos were compressed using FFmpeg, a leading open-source framework for manipulating multimedia. In addition to compressing the videos, ffprobe was used to verify the parameters set during encoding. The parameters verified were:

Compression codec;
GOP structure;
Compression ratio.

The compression and verification of the source uncompressed video was executed by a collection of Python scripts available at the Test Resource Management Center (TRMC) repository:

https://www.trmc.osd.mil/bitbucket/scm/rccosg/video-compression-analysis.git

Access to the TRMC-hosted OSG repository can be requested through the site, with approval from the OSG.

8. Conclusions and Recommendations

Recommendation 1: Adoption of Image Compression within the TSPI Workflow

A primary recommendation from this study is that the ranges should move forward in implementing standards-based compression on range motion imagery that is used for TSPI data product generation. Initially, the software that downloads imagery from the uncompressed recorders will need to be modified to support the compression and downloads. Open-source software is readily available to meet the compression and file generation needs at the library level. For all cases, the MISB recommends that the compressed imagery be written into files that are compliant with the International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) 14496-12[2] Base Media File Format (ISOBMFF). The DoD, Intelligence Community, and National System for Geospatial-Intelligence (NSG) community is currently in the process of defining a profile of ISOBMFF as a standard format for all primary Geospatial Intelligence Enterprise Community applications. The H.264, H.265, and JPEG2000 codecs are all compatible with this format. In addition, an ISO committee is currently adding support for carrying uncompressed motion imagery, along with key-length-value (KLV) metadata and time stamps within ISOBMFF files. This set of capabilities will meet the needs of the MRTFB and will provide for a standard solution for the entire range motion imagery workflow. This will provide a significant improvement with the interoperability of test range motion imagery and associated metadata.

Recommendation 2: Implementation Strategy

The results of this study conclude that efforts can and should be initiated to implement compression with test range imagery. Given this, it will be prudent to proceed in a methodical, incremental manner. An approach recommended by the authors of this study is to implement software solutions that allow for initially compressing imagery in software at a conservative 10x ratio and process for TSPI results in parallel with the uncompressed source imagery. Over time,

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[2] ISO/IEC. *Information Technology – Coding of Audio-visual Objects- Part 12: ISO Base Media File Format*. ISO/IEC 14496-12:2022. Geneva: ISO/IEC, 2022.

the amount of compression and the choice of codec can be varied to optimize the solution. Eventually, when confidence is achieved, a full transition to compressed imagery can be implemented. For missions where uncompressed imagery is deemed an essential requirement, that capability can be maintained and implemented as needed. The authors of this study recommend the transition be accomplished while maintaining compliance with DoD Motion Imagery Standards Profile standards. This will help facilitate integration with common software and automated processing capabilities.

Recommendation 3: Compression Settings

Considering the circumstances unique to the test range community, we recommend the compression settings in Table 7 for source video compression on motion imagery that is intended to be processed for the extraction of TSPI information.

Table 7. Recommended Compression Settings

Codec	H.264
Compression Ratio	20x
GOP Structure	I-frame only

As seen in Section 2, test ranges have inverse challenges for video compression when compared to many common commercial applications. While labor cost savings begin to taper at 10x compression, there are other benefits to higher compression ratios. One of them is a slightly faster compression speed. Since this study did not detect any significant difference in error between 10x and 20x, the study recommends 20x compression with H.264.

As an additional observation, only the simplest GOP structure was considered for this study, which is I-frame only. More complicated GOP structures will allow for higher compression ratios with comparable video quality when compared to I-frame only. One tradeoff for this is a higher processing requirement for implementing interframe compression, such as P and B frames. In addition, seeking to a specific frame of interest with common viewing software is more cumbersome due to the interframe compression and its reliance on key frames at GOP boundaries to facilitate search and access. While this study has shown the viability of achieving 20x compression using intraframe compression, the study's authors recommend that consideration be given to analyzing the use of GOP structures and their effect on TSPI as a future effort. As a general best practice, for a given compression ratio, the use of P and B frames will generate a compressed image with higher quality.

Recommendation 4: Investigation and Implementation of Automated Processing

It is useful to define the ability of trained operators to delineate the number of gray levels that can be reliably detected with typical room lighting and displays that are used when performing data reduction activities. This is because the data reduction process currently relies on human recognition for feature location determination and measurement. Unless special care is taken to control these specific variables, human operators are typically capable of discerning between 64 and 128 distinct gray levels. When very special care is taken to control lighting and calibrated high dynamic range monitors are utilized (which represents the best possible scenario) between 700 and 900 gray levels have been shown to be reliably detectable using monitors designed for medical use.[3] This represents 9 to 10 bits of dynamic range, which is the best-case scenario for human operators discerning thresholding information. It is likely that these levels are never achieved in practice as current data reduction systems are not truly configured to optimize display and lighting for operators. In addition to gray level detection limitations, human operators also suffer from fatigue and other aspects that can increase measurement uncertainty. These aspects go into the levels of uncertainty that were measured as part of this investigation.

Automated systems, on the other hand, hold promise for generating results in a timelier manner as they do not need to move a physical mouse and do not suffer from fatigue, eye strain, etc. In addition, automated systems can leverage the full dynamic range that T&E optical systems are able to provide. Current T&E camera systems can capture 12- and 14-bit dynamic range. When automated processes are developed for performing these data reduction activities, additional dynamic range and higher PSNR values will prove to be beneficial and improve results. This was proven to be true when the WSMR Universal Video Tracker was upgraded from 8-bit processing to 14-bit processing. Segmentation performance and target discrimination significantly improved when this modification was implemented approximately ten years ago.

While the ranges have traditionally relied on 8-bit uncompressed imagery to perform analysis, this study has shown that lightly compressed imagery can achieve results with similar TSPI measurement uncertainty values. It is important to note, however, that in many cases, especially short exposure, low light imaging, lightly compressed 12- or 14-bit imagery will contain more information than an uncompressed 8-bit version of the same imagery. This holds significant promise for the combination of automated processing systems, such as artificial intelligence/machine learning (AI/ML) algorithms, and lightly compressed high dynamic range imagery. The technologies that are needed to achieve this capability are readily available and just need to be assembled, configured, and tuned. High dynamic range codecs are readily available to process 12- and 14-bit imagery. These include standards-compliant solutions H.264 (AVC), H.265 (HEVC), and JPEG2000. In addition, JPEG-XS might be a viable solution for this application due to its very efficient processing requirement and support for up to 16-bit pixels.

For AI/ML capabilities, the Cloud Hybrid Edge to Enterprise Evaluation and Test Analysis Suite (CHEETAS) platform provides a mature hosting environment for these types of T&E solutions. This is a likely viable path to a successful automated solution. The results from this effort provide some insight into the current baseline measurement uncertainty of the TSPI measurement process. Results showed the human variability in the process that is to be expected. An automated processing system that achieves a similar or better measurement uncertainty is the benchmark for being able to replace the current labor-intensive process.

Recommendation 5: Implementation of Turbulence Mitigation Capabilities

Atmospheric turbulence was a primary source of measurement uncertainty error that was experienced in this study. This is not a new problem at the ranges. Multiple development efforts over the years have attempted to solve the challenges associated with this ever-present phenomenon. While efforts to implement solutions over a decade ago showed significant promise, they suffered from low technology readiness level. Today, there are off-the-shelf solutions to help mitigate the detrimental effects of atmospheric turbulence. There are commercial software and embedded hardware solutions readily available that have shown great

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[3] Kimpe, Tom and Tom Tuytschaever. “Increasing the Number of Gray Shades in Medical Display Systems—How Much is Enough?” Journal of digital imaging vol. 20 no. 4 (2007): 422-32.

results. The ability to preprocess imagery, improve contrast, and reduce distortion will benefit not only human-based measurement but also those performed by automated systems, such as AI/ML solutions based on CHEETAS.

Recommendation 6: Implementation via Standardized Solutions and Government Open-Source Software (GOSS)

When implementing solutions, the authors of this study recommend that the government adopt solutions that are compliant with DoD/IC/NSG standards defined by the Motion Imagery Standards Board. In addition, software implementation can benefit greatly when implemented as GOSS solutions. This allows multiple test ranges the ability to leverage each other's development and implementation efforts.

The software used in this study to collect the human mouse clicks is built on the *Luxon* framework, which is GOSS and available on the TRMC-hosted OSG repository. The decision to create a new software application for data collection in this effort was influenced by the limited access to and availability of the existing data reduction software packages, such as *TrackEye* and *Optical Data Measurement System*. The analysis of the collected measurements was achieved using a collection of Python scripts available at the TRMC repository:

https://www.trmc.osd.mil/bitbucket/scm/rccosg/video-compression-analysis.git

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APPENDIX A

Citations

International Organization for Standardization/International Electrotechnical Commission. *Information Technology – Coding of Audio-visual Objects- Part 12: ISO Base Media File Format*. ISO/IEC 14496-12:2022. Geneva: ISO/IEC, 2022.

Kimpe, Tom, and Tom Tuytschaever. "Increasing the Number of Gray Shades in Medical Display Systems—How Much is Enough?" Journal of Digital Imaging vol. 20 no. 4 (2007): 422-32.

Range Commanders Council. *Methodology for Testing Metric Zoom Lenses*. SR-22-003. September 2023. May be superseded by update. Retrieved 25 September 2023. Available at https://www.trmc.osd.mil/wiki/x/YIy8Bg.