Applied Research and Innovation Branch

Non-Destructive Testing and Monitoring of Tunnels with Mobile LIDAR and Thermography (SHRP2 – Project R06G)

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16. Abstract
This research project explored technologies and developed procedures for engaging in Non-Destructive Testing (NDT) and monitoring of the tunnels that CDOT manages and operates. This was done through this Strategic Highway Research Program (SHRP2) project. The project occurred from 2015-2018. This project investigated and recommends high-speed non-destructive testing methods for mapping voids, debonding, delaminations, moisture and other defects behind or within tunnel linings. The study provided a best practices for implementation. The study documented the project and provided a proof of concept and implementation of surveying principles and thermal imaging in various Colorado tunnels and provided by Survey and Mapping Inc. in CDOT projects 21000 and 22553 in survey file directory. Included in report camera technology, survey technology, thermal-loggers for tunnel surface temperatures, and various flat pdf layouts of tunnel liners.

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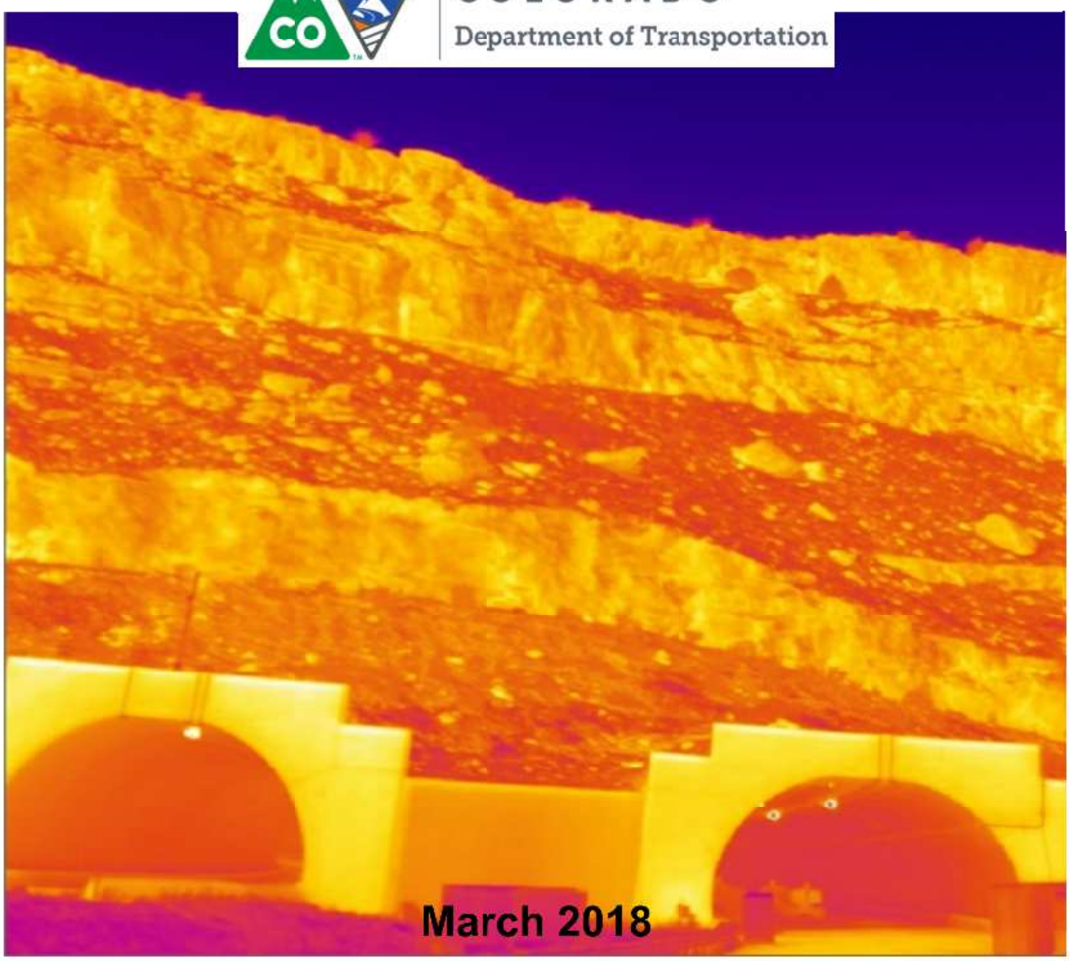
STRATEGIC HIGHWAY RESEARCH PROGRAM (SHRP2)
PROJECT R06G: High-Speed Non-destructive Testing Methods for Mapping Voids, Debonding, Delaminations, Moisture and Other Defects Behind or Within Tunnel Linings

Report on Non-Destructive Testing and Monitoring of Tunnels with Mobile LIDAR and Thermography

Prepared for:

Colorado Department of Transportation



March 2018

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ABBREVIATIONS/ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
CAD	Computer-aided Design
CDOT	Colorado Department of Transportation
CSV	Comma-separated Values File
DOT	U.S. Department of Transportation
F	Fahrenheit
FOV	Field of view
FHWA	Federal Highway Administration
GIS	Geographical Information Systems
GNSS	Global Navigation Satellite System
I-70	Interstate 70
IMU	Inertial Measurement Unit
LIDAR	Light Detection and Ranging
MP	Milepost
MPH	Miles per hour
NDT	Non-destructive Testing
NTI	National Tunnel Inventory
NTIS	National Tunnel Inspection Standards
OEM	Original equipment manufacturer
PennDOT	Pennsylvania Department of Transportation
QA/QC	Quality Assurance/Quality Control
RGB	Red, Green, Blue
ROW	Right of way
SAM	Surveying and Mapping, LLC
SHRP2	Strategic Highway Research Program
SNTI	Specifications for National Tunnel Inventory
SSD	Solid state drive
TB	Terabyte
TIN	Triangulated Irregular Network
TOMIE	Tunnel Operations Maintenance Inspection and Evaluation
TRB	Transportation Research Board
VR	Virtual reality

ACKNOWLEDGEMENTS

Surveying and Mapping, LLC would like to extend its gratitude to those who supported and assisted in this effort for without it the project's success would have been limited.

Tyler Weldon and Dave Tedrow, Colorado Department of Transportation, for their vision and commitment to the traveling public and advancement of technology in the DOT and to the staff of Hanging Lake Tunnels, their willingness to support our schedules and efforts for field collection.

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Eric Huges, FLIR Systems, for sharing his thermal knowledge and experience.

Our sub consultants Nexco USA and Infrasense for creating thermal PDFs and Miniello Consulting for their assistance with assembling the Report.

1.0 EXECUTIVE SUMMARY

The Colorado Department of Transportation (CDOT) selected Surveying and Mapping, LLC (SAM) as a sub-consultant to assist in exploring technologies and developing procedures for engaging in Non-Destructive Testing (NDT) and Monitoring of the tunnels it manages and operates. The work was divided into two Task Orders, Phase 1 and Phase 2.

Phase 1, which focused on Clear Creek Tunnel 4, identified the following objectives:

- Further explore the application of thermography and LIDAR as a NDT
- Create a truly mobile solution
- Create deliverables that are acceptable to the DOT and feed into their workflows

SAM engaged in extensive research into applicable technologies, along with a series of trial and error with cameras and equipment added to its existing mobile LIDAR system. Utilizing a FLIR A6750sc series camera with a 13mm lens, data was collected from the tunnel on June 24 2016. The following deliverables for CDOT were generated from the collection:

- LIDAR point cloud colored by thermal
- LIDAR point cloud with intensities
- Tunnel Triangulated Irregular Network (TIN) from 1 foot contour profiles
- Flattened thermal tunnel image

Although the process was successful, SAM believed there were opportunities for improvement for Phase 2 and identified the following as lessons learned:

- Temperatures and fluctuations should be defined with a scientific gauge to understand the best time to collect and ensure the sensor is capable of detection of thermal separation.
- The angle of the sun caused higher temperatures at the end of the tunnel where it was shining in, while the shaded part of the tunnel was much cooler. The sun warmed the tunnel lining as a whole in that area, lessening the temperature delta between areas where a thermal signature should have appeared. Based on this, SAM determined that collection should occur at night.
- The optimal time of day to collect data should be pre-determined for each tunnel, as a large enough temperature swing is necessary to facilitate temperature change in the tunnel lining. The separation of high and low temperatures at the portal of Tunnel 4 were greatly influenced by the position of the sun. For timing of future collections, it would be helpful to factor in not only the temperature, but the time of sunrise and sunset, as well.
- The use of multiple cameras would require less passes and less image stitching, ultimately reducing project time and increasing the quality of the final product.
- A Red, Green, Blue (RGB) camera should be integrated into data collection at the same time passes are made collecting thermal imagery to offer an additional

perspective and confirm or refute potential areas of concern.
- Improve processes to enhance imagery of 2D tunnel surface

During Phase 2, which focused on Beavertail Tunnel, Hanging Lake Tunnel, and Clear Creek Tunnels 1, 2, 3, 5 and 6, SAM once more explored and experimented with various technologies with the intent of improving, supplementing, and verifying the data collected by the cameras. Thermocouple data loggers proved to be an effective means of determining the best times during which to collect data in tunnels, and they were used in Beavertail and Hanging Lake Tunnels. RGB and HD thermal cameras were also added to the system and incorporated into the mobile LIDAR system with a custom-machined mount. To process and manage the large amount of data gathered during the collection, multiple high-end laptops with high speed solid state drives (SSDs) were utilized.

During August 2017, data from the seven tunnels was collected and generated into the following deliverables to CDOT:

- Point cloud with intensity
- Point cloud with thermal mapped colors
- Contours of tunnel created every 2 feet
- TIN mesh of tunnel
- FLIR self-viewing files
- Flattened image of thermal tunnel surface
- RAW FLIR video on .mp4
- Corresponding RGB images for each thermal image

Although the process was greatly improved from Phase 1, SAM identified the following lessons learned during Phase 2:

- A tunnel's size and shape impacts the number of passes required to capture its entire area and it would be helpful to predefine those camera collection positions
- RGB cameras should capture images in RAW format so they are better quality and can be better manipulated later
- A better exterior light solution with variable settings to adapt to each tunnel's lighting/surfaces should be used
- Use of HD thermal cameras is important
- Owning thermal cameras is crucial for reliability and scheduling
- Thermocouple data loggers are necessary for large tunnels or tunnels located in areas where the environment is unfamiliar to the data collector
- The use of fans had little to no effect on results, as the piston effect created from moving traffic was stronger than the draft generated by fans

Following this experience, SAM recommends that, if at all possible, the DOT should schedule data collection to coincide with any planned shutdowns. Impacts to traffic during SAM's collections were minimal, as the work was performed late at night; although, it was noted that work on minor arterials, where posted speed limits are lower, would not impact the traveling public if performed in a manner similar to SAM's. The quality of the results was directly impacted by the level of technology in use. The cost of scientific grade equipment could be a significant burden if the user has not seriously considered the costs of renting/purchasing/custom fabricating equipment, outfitting survey vehicles, and educating users on all aspects of operations and programs.

Finally, several benefits were identified during the processes, including the development of a workflow from beginning to end for acquiring tunnel data without completely shutting down traffic for an extended period of time. This benefits the DOT, the contractor and the traveling public. Furthermore, the methods advanced by SAM improve safety for those participating in tunnel inspections.

By vetting out the concept of NDT for tunnels maintained by CDOT, numerous technologies were identified, explored, ruled out, and improved. Additionally, SAM utilized equipment in ways that it may have never been intended, and by coupling certain technologies was able to identify best pairings of cameras, lenses, sensors, processing software, and other components.

The data collected during Phases 1 and 2 is a positive front-end planning tool, as well as a strong quality control component for information determined by inspections conducted manually by professionals. The information serves as a stable reference for DOTs who wish to utilize it for their own tunnel inspection process. Overall, the methods and information gathered by SAM contributed an asset management element to the inspection process.

Phase 3 was used to complete final deliverables for the Clear Creek Tunnel data acquired during Phase 2. Deliverables for Phase 3 included:

- LiDAR with intensity values
- LiDAR colorized by corresponding normalized thermal metadata
- Contours of tunnel created every 2 feet
- Mesh of tunnel liner surface and roadway
- FLIR self-viewing files
- Flattened high resolution normalized thermal tunnel liner PDFs
- RAW FLIR video in .mp4
- Normalized thermal image frames

SAM identified the following lessons learned from Phase 3:

- Further development to improve RGB acquisition to combat variable lighting and high vehicular collection speeds
- Virtual Reality is one example of emerging immersive technologies to analyze post processed data in a controlled environment.

2.0 INTRODUCTION

On July 6, 2012, the Moving Ahead for Progress in the 21st Century Act (MAP-21) was passed by Congress and signed by the President. The Act recognized that the safety and security of the nation's highway tunnels is exceedingly important. As an extension of the principles, the Federal Highway Administration (FHWA) developed the National Tunnel Inspection Standards (NTIS), the Tunnel Operations Maintenance Inspection and Evaluation (TOMIE) Manual, and the Specifications for National Tunnel Inventory (SNTI). In accordance with each, the data produced is maintained in the National Tunnel Inventory (NTI) database, and the conditions of tunnels around the country are tracked.[1]

According to the Federal Register: *The purpose of this final rule is to establish the NTIS for tunnel inspections consistent with the provisions of the Moving Ahead for Progress in the 21st Century Act (MAP-21), which includes requirements for establishing a highway tunnel inspection program, maintaining a tunnel inventory, and reporting to FHWA of inspection results and, in particular, critical findings, which are any structural or safety-related deficiencies that require immediate follow-up inspection or action. The NTIS apply to all structures defined as highway tunnels on all public roads, on and off Federal-aid highways, including tribally and federally owned tunnels. Section 650.511 establishes a minimum inspection frequency of 24 months for routine tunnel inspections. An owner is permitted to increase the frequency of inspection based on a risk analysis approach that considers such factors as tunnel age, traffic characteristics, geotechnical conditions, and known deficiencies. An owner does not need FHWA approval to increase the frequency of inspection. An owner is permitted to decrease the frequency of inspection after a written request that considers tunnel age, time from last major rehabilitation, tunnel complexity, traffic characteristics, geotechnical conditions, functional systems, and known deficiencies has been reviewed and commented on by FHWA.*[2]

The Strategic Highway Research Program (SHRP2) is a national partnership of the FHWA, the American Association of State Highway and Transportation Officials (AASHTO) and the Transportation Research Board (TRB). Under SHRP2, more than 100 research projects were undertaken in order to develop effective solutions to improve the way transportation professionals plan, operate, maintain and ensure safety on America's roadways.[3] The projects were focused on safety, renewal, reliability and capacity. SHRP2 R06G, which fell under the renewal category, focused on High-Speed Non-destructive Testing (NDT) Methods for Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects Behind or Within Tunnel Linings. Tunnels are difficult to

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[1] U.S. Department of Transportation, Federal Highway Administration, *Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual*. Publication No. FHWA-HIF-15-005, July 2015.
[2] Office of the Federal Register, *National Tunnel Inspection Standards* (available from https://www.federalregister.gov/documents/2015/07/14/2015-16896/national-tunnel-inspection-standards), accessed 14 February 2018.
[3] Federal Highway Administration: "SHRP2Solutions" (available from https://www.fhwa.dot.gov/goshrp2/), accessed 10 January 2018.

inspect for maintenance concerns or deficiencies such as leaks, concrete liner cracking, concrete spalling, delamination and other debunking issues. Due to their confinement, heavy use, and typically long detours needed when they are closed to traffic, tunnels pose a unique operational challenge.[4]

By utilizing NDT methods, transportation agencies are able to inspect concrete bridge decks or tunnel linings beyond what the eye can see. The actual extent of deterioration can be defined, meaning improved repairs and real-time solutions. Ultimately, this results in a savings of both time and money.[5]

2.1 PARTIES INVOLVED

2.1.1 CDOT

The evaluations of the tunnels identified under Phase 1 and Phase 2 of this report were conducted under the FHWA's Round 4 Implementation Assistance Program for SHRP2, R06G project. As there are numerous tunnels in their system, CDOT wanted to explore NDT methods that would be effective both time- and budget-wise and assist them in meeting the tunnel inspection schedule in the future.

In addition to the Colorado Department of Transportation (CDOT), a SHRP2 R06G research grant was awarded to the Pennsylvania Department of Transportation (PennDOT). Their efforts were focused on the Liberty and Armstrong Tunnels in Pittsburgh, Pennsylvania. The results can be found in the report, *Condition Assessment of Liberty & Armstrong Tunnels in Pittsburgh, PA using High-Speed Mobile Scanning and Hand-held Non-Destructive Technologies (NDT)* (Mackin Engineering Company, June 2016).

2.1.2 SAM

Surveying and Mapping, LLC (SAM) has an extensive background utilizing cutting edge technology to serve its clients and provides surveying, geospatial, subsurface utility engineering (SUE), utility coordination and construction phase services for a variety of clients throughout the country. SAM is experienced in utilizing information gathering technologies involving digital aerial mapping, terrestrial, mobile and airborne LIDAR services, hydrographic surveying, and geographic information systems (GIS).

As such, CDOT selected SAM because of its history with and understanding of the U.S. Department of Transportation's (DOT) business structure, DOT-friendly deliverables, and project accuracies using traditional survey approaches. SAM was also readily available to mobilize and provide verifiable location information to pair with collected data.

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[4] Ibid. (available from https://www.fhwa.dot.gov/goshrp2/Solutions/Renewal/R06G/Nondestructive_Testing_for_Tunnel_Linings), accessed 15 January 2018.
[5] AASHTO, "SHRP2Solutions" (available from http://shrp2.transportation.org/Pages/R06_NondestructiveTesting.aspx), accessed 15 January 2018.

2.2 OBJECTIVES

The following objectives were identified for this project:

- Further explore the application of thermography and LIDAR as a NDT
- Create a truly mobile solution collecting data at speeds as close to posted speeds as possible
- Create deliverables that are acceptable to the DOT and feed into their workflows

As a sub-consultant to CDOT, SAM's Denver-area office would be responsible for performing all testing, data collection (mobile LIDAR, thermal imaging, and RGB imaging) and management of data processing. Since NDT methods exploration could essentially be considered a new business venture or expansion, the concept of pursuing such work had to be weighed internally. Although SAM already explores research and development of new technologies, considerations such as branching out into NDT, scientific-grade thermal imagery, understanding thermography, integration of additional sensors into the mobile LIDAR system, and creating DOT relevant deliverables were taken into account. Additionally, existing workloads, and the expense of such ventures had to be explored. SAM was already equipped with 15 terrestrial LIDAR scanners, 2 Lynx mobile LIDAR systems, and 6 Unmanned Aerial Vehicles (including a Vapor 55 with LIDAR).

Figure 1: SAM mobile truck in Clear Creek Tunnel #4

Ultimately, SAM was tasked with assisting CDOT and FHWA in finding and implementing technology to better serve the traveling public by being safer and more efficient than traditional means of inspection. The project was divided into two task orders, referred to as Phase 1 and Phase 2 for the purpose of this report. Phase 1 consisted of testing and data collection for one tunnel (Clear Creek Tunnel 4). Any complications identified in Phase 1 would be addressed for Phase 2, which involved seven tunnels (Beavertail Tunnel; Hanging Lake Tunnel; and Clear Creek Tunnels 1, 2, 3, 5, and 6).

3.0 PHASE 1 (FIRST TASK ORDER)

The scope of work identified for Phase 1 involved data collection in one tunnel, Clear Creek Tunnel 4 (Gilpin and Clear Creek Counties). Initially, CDOT reviewed early research from the mid-2000s on different NDT tools and gravitated to the possible applications of LIDAR and thermal imagery. After CDOT shared their thoughts on such technologies, SAM evaluated the options and developed a scope that would realistically meet CDOT's needs and suit their interests. Prior to on-site mobilization, CDOT and SAM engaged in discussions regarding the following:

1.) The viability of such an undertaking within Colorado's tunnels

2.) Each organization's experience with and understanding of LIDAR

3.) Each organization's lack of experience with thermal imaging

4.) An identification of the strengths and weaknesses of the technologies

5.) Determination of the best application for each technology:
- LIDAR would be used to as-built the tunnel from an engineering aspect
- Thermal imagery would be used to evaluate the tunnel from a structural aspect

3.1 RESEARCH

SAM began intensively researching thermal technology in order to best decide how to embrace it for NDT applications in Colorado's tunnels. Understanding emissivity, which is defined as "the relative power of a surface to emit heat by radiation" or "the ratio of the radiant energy emitted by a surface to that emitted by a blackbody at the same temperature"[6] and how it translates to thermal imagery was the starting point. The materials composition of any given tunnel would determine its ability to radiate energy, and those made of materials with low emissivity would clearly present a challenge. If there is little temperature variation between problem areas and those with no issues, it would be harder to accurately pinpoint an area indicating a thermal anomaly. For

[6] Merriam-Webster Dictionary (available from https://www.merriam-webster.com/dictionary/emissivity), accessed 10 January 2018.

example, the interior of a tunnel could be lined with concrete, metal, or glazed tile and differences among even like materials, such as clean tile versus dirty tile, would result in varying, or potentially misleading, outcomes.

Once it had developed a working understanding of thermal technology, SAM began researching equipment available on the market to capture the necessary images. SAM believed it was crucial to seek out a market leader in the field to access the best equipment for the task at hand. They identified FLIR, a company that designs and manufactures thermal imaging infrared cameras. FLIR offers a large variety of cameras, allowing SAM the opportunity for trial and error in order to narrow its selection down to a level of technology and sensor sensitivity that would provide results preferred by CDOT. However, the equipment is expensive, especially considering it would be used for limited jobs, so SAM approached FLIR about renting cameras.

SAM's Denver-area office was already in possession of an Optech Lynx Mobile LIDAR system. This particular vehicle is also equipped with a high rail system allowing for data collection from rail, and the system is regularly used for creating survey grade topographic mapping, civil as-builts, and GIS level mapping. An off-the-shelf camera mount was purchased, and it proved to be secure as well as easy to move. The mount was tested on a few areas of the vehicle before it was decided the most practical location would be on the passenger side, set back approximately two-thirds from the front of the truck. Once the mount was installed, an accurate measurement of the camera was taken into account. In order to provide a spatial reference with which to tie thermal readings to LIDAR data, exceptionally accurate knowledge of the spatial offsets of the thermal sensor to the inertial measurement unit (IMU) was necessary. That way the thermography data could be correlated to the LIDAR later, with each pixel assigned an XYZ coordinate.

3.2 TESTING

Before on-site mobilization, SAM tested the equipment they had assembled and conducted calibration acquisitions. First, several cameras from FLIR were gathered in the office. After confirming that file formats, frame rates, and general operation were compatible with SAM's setup, a visit to the abandoned Clear Creek Tunnel 4 was scheduled. SAM staff met CDOT at the tunnel, which is discussed later in detail, where they connected different combinations of cameras and lenses to a laptop in order to collect and review data of specific known flaws in the tunnel lining.

The cameras included uncooled and cooled to gauge the effects on image results and longevity of operations. Starting at the low end of resolution, SAM worked up to higher resolution cameras and HD cameras, coupling each with a variety of lenses. Camera resolution, lens Field of View (FOV), and the distance of the tunnel liner from the sensor were all parts of the equation to consider in deciding which camera/lens combination to use.

The integration time, which refers to a camera's ability to acquire and analyze radiated energy from an object, was an important consideration of camera capability. A camera with a fast integration time allows for higher collection speeds. However, the collection speed must still factor in the frame rate of the camera in comparison to the FOV so as to insure adequate data coverage. SAM also factored in the importance of lens distortion. The wider the FOV, the more lens distortion is created, which can affect the accuracies of the readings and result in issues creating geospatial deliverables.

Finally, pixel size on a tunnel's surface was a major consideration, as a pixel needs to be at least the same size or smaller than the object being identified in order to accurately locate it. This appears in real-time results, as well as in the data that is available for post-processing. Each pixel in the thermal image has its own set of corresponding Meta data representing the thermal energy measured. The pixel count of any camera is fixed, but the surface area represented by a pixel changes with the FOV of the lens and distance from the liner. The larger area a pixel represents on the tunnel liner, the less accurate it becomes due to the fact that it is averaging a larger range of temperatures on the tunnel liner. The smaller the pixel surface area the smaller the potential defect that can be shown (i.e., cracks). For this application, one must decide on the desired level of detail and match that with a camera and lens combination.

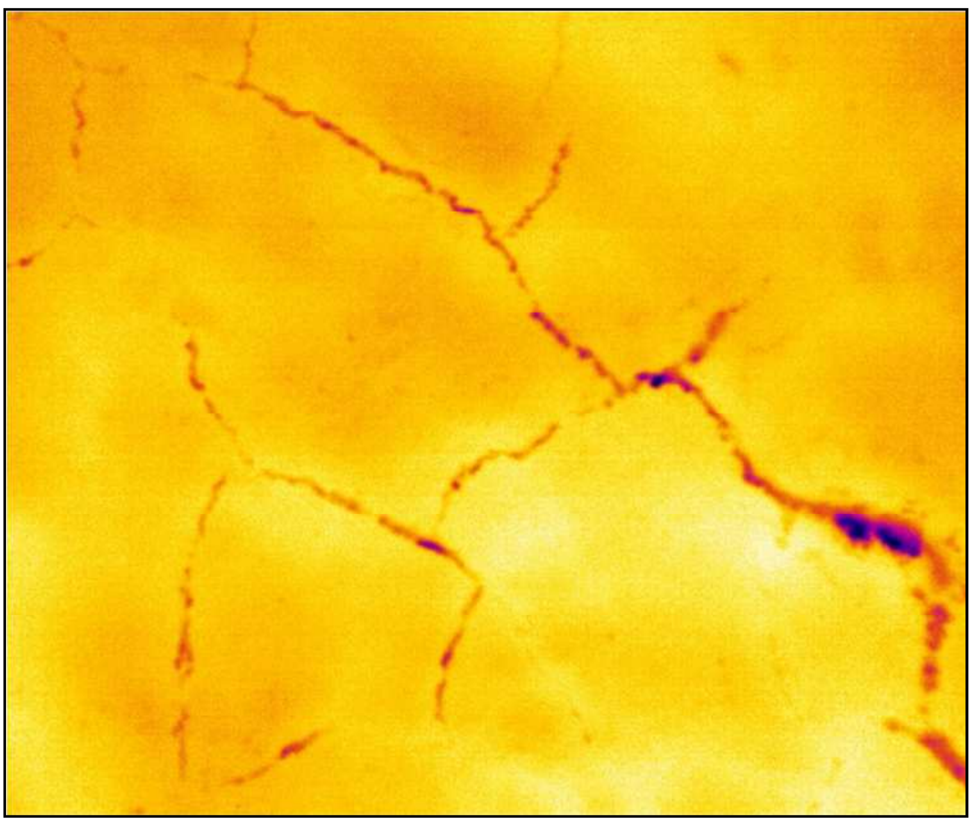

Figure 2: Example of shotcrete with cracking and efflorescence

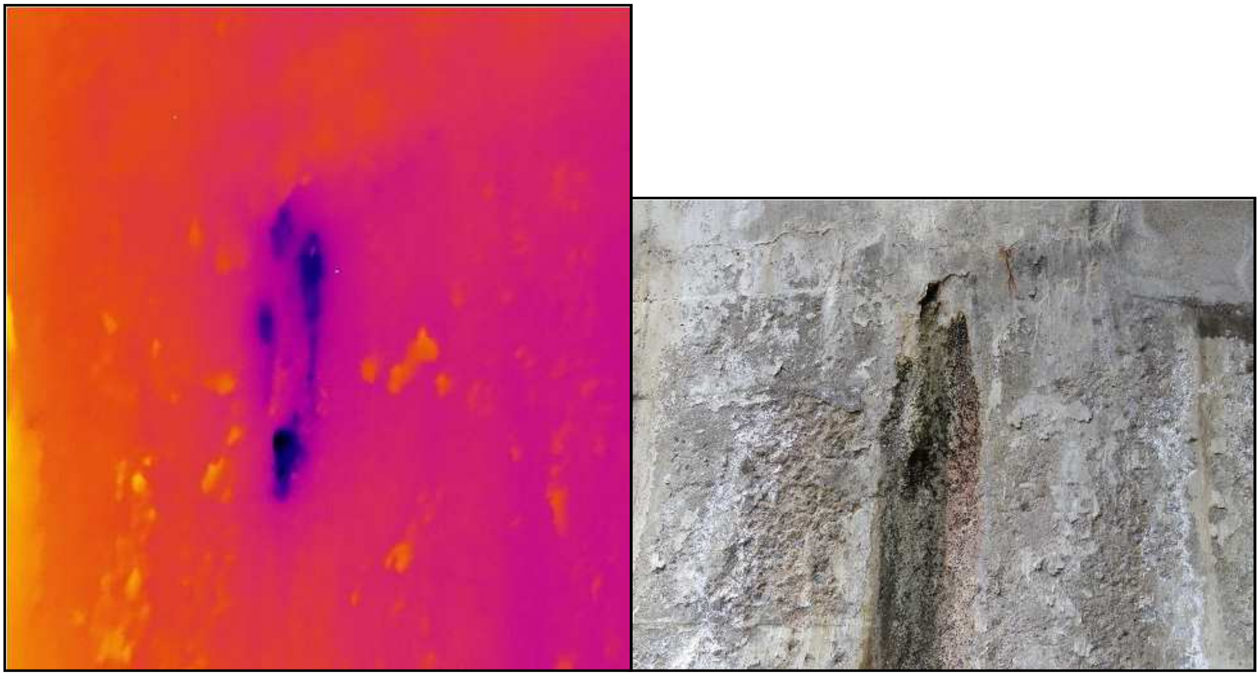

Figure 3: Example of thermal vs RGB active water infiltration.

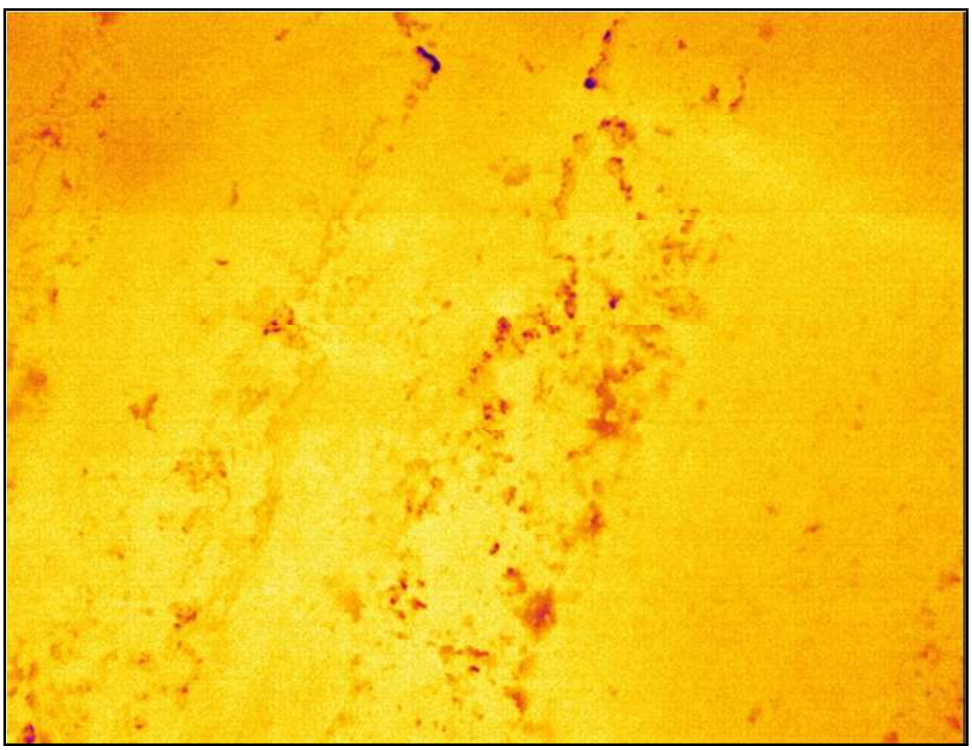

Figure 4: Example of cast in place delamination

Figure 5: RGB image of area with pocket of water behind liner

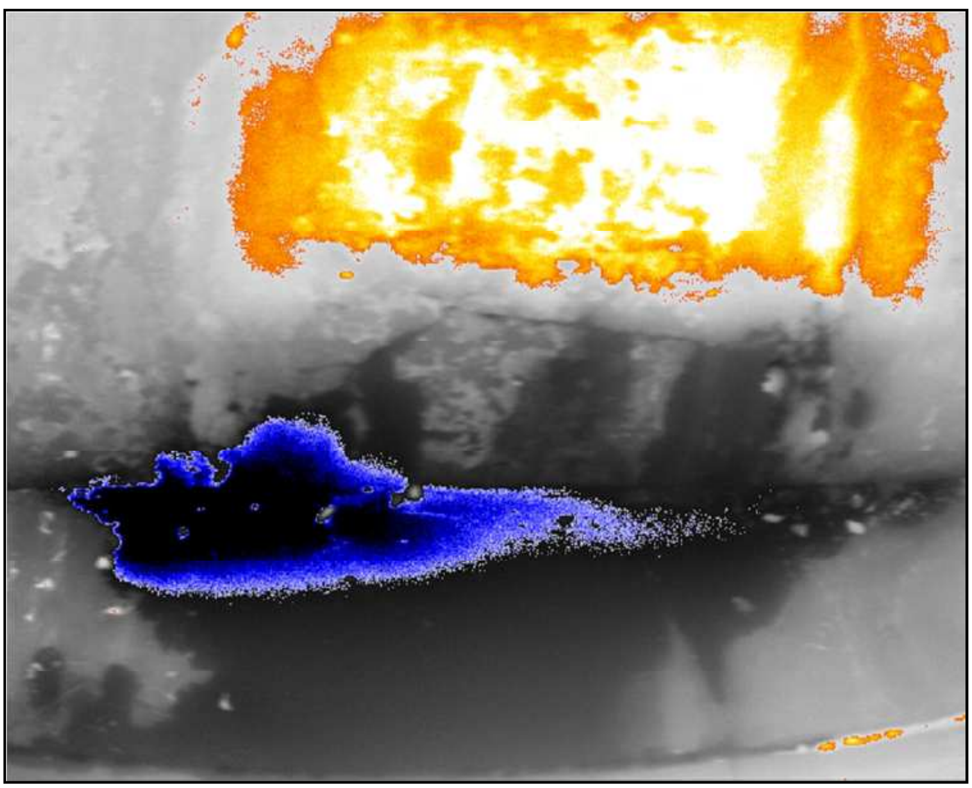

Figure 6: Thermal comparison with above RGB image (Figure 5)

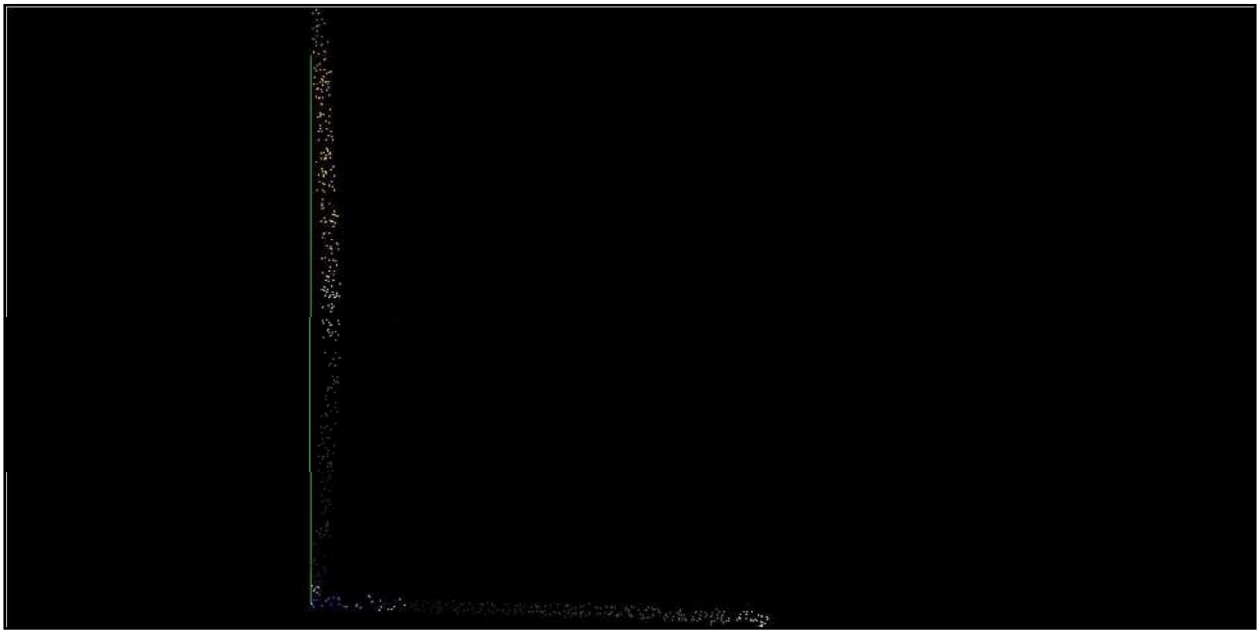

Figure 7: Cross section of LIDAR of the pocket of water in Figures 5 & 6 causing a bulge in the liner

Following a few trials in Tunnel 4, a FLIR A6750sc series camera with a 13mm lens was selected. The camera provides a resolution of 640x512 and utilizes a FLIR-built cro-cooler and InSb detector. With this camera and lens combination SAM was able to pick up sufficient detail of the tunnel liner to meet CDOT's desires, as well as feed into the geospatial deliverable creation.

Figure 8: FLIR A6750 mounted to SAM mobile truck

The next step was to determine camera settings for mobile collection. Several calibration collects were undertaken in order to figure out appropriate angles and the number of passes necessary to collect the entirety of the tunnel's surface, which required an evaluation of the field of vision and size of the tunnel. Due to the varying camera angles and positions of the vehicle, images would need to overlap so they could be stitched together to capture the entire tunnel. Thermal data was also collected during the calibrations to ensure proper alignment before heading to the tunnel for the task order.

Each thermal camera requires a computer to operate and record its collected data. The high resolution images coupled with high frame rates create very large data streams that must have hardware capable of sufficiently handling them. Any weak links in the cabling or laptop solution result in dropped frames, which could translate to data gaps, depending on collection speeds. Higher resolution images require a computer, or computers, powerful enough to record the high data rates.

Although one computer was dedicated to control of the mobile LIDAR system, SAM determined that it would not be able to reliably handle additional information gathered during each pass. In order to address data needs, a second computer was installed. SAM recognized the need for two people to man the mobile LIDAR truck, a driver and a sensor operator. The computers were mounted in a fashion that the sensor operator could manage and monitor them all at the same time in a safe manner while the driver could make the required passes through the tunnel. At this point, SAM had developed what it believed was an effective initial approach for methodology, equipment utilization, mobilization and on-site data gathering.

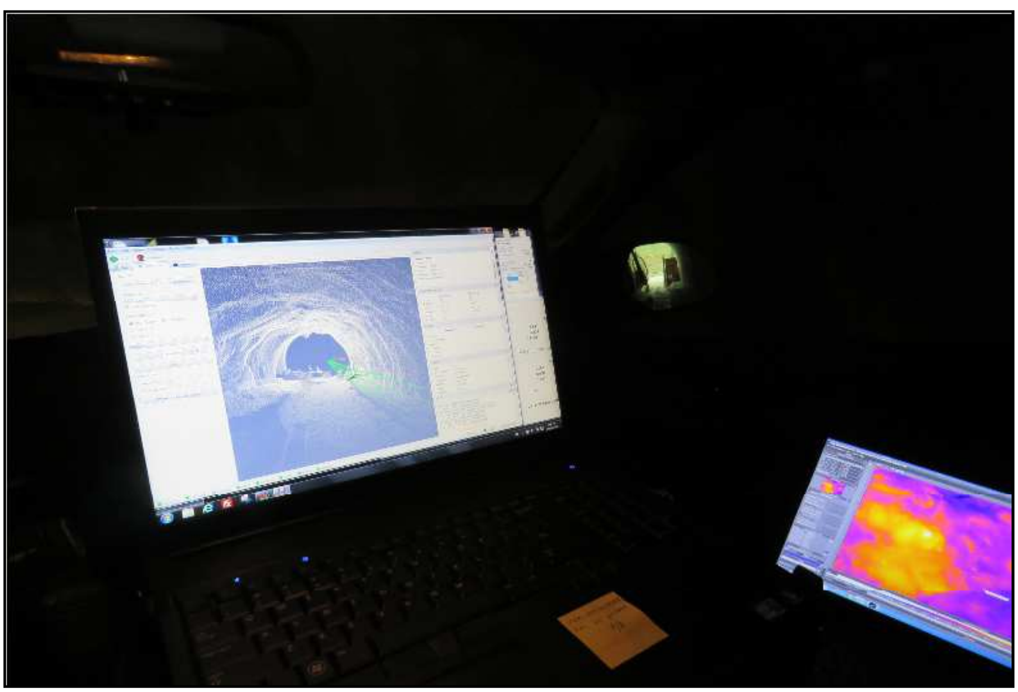

Figure 9: Computers set up in mobile truck in Tunnel 4

3.3 DATA COLLECTION

Phase 1 involved the collection of data from Clear Creek Tunnel 4 (Tunnel 4), which is located within Clear Creek Canyon in Gilpin and Clear Creek Counties, northwest of the current intersection of U.S. Highway 6 and Colorado State Highway 119. Specifically, it is found at 39°44’52.41” N, 105°23’58.72” W, is 6,927 feet above sea level and is oriented on a slight northeast/southwest skew. In 1939, the tunnel was constructed by hard rock drilling and blasting then partially lined with concrete and shotcrete. It measures 191.9 feet in length.

The tunnel was decommissioned and abandoned following the realignment of the intersection of Highway 6 and Colorado State Highway 119 to the south, eliminating the need for the tunnel. Known structural issues associated with the tunnel include spalling, water infiltration and cracks. Rattlesnakes were also reportedly a concern.

Figure 10: Clear Creek Tunnel 4 aerial

Figure 11: Tunnel 4 aerial

Figure 12: Tunnel 4 entrance

On June 24, 2016, there were light winds from the southwest, and it was sunny. SAM approached the tunnel, which was barricaded from traffic, a significant amount of debris and random objects were being stored inside along its north side, so time was needed to move the items to the back and south side. Rain showers moved in, and the weather was overcast with pockets of clearing and an average temperature of 64° Fahrenheit (F) during collection.

SAM made 10 passes through the tunnel with the survey vehicle, each time at a speed of 10 miles per hour (mph). Traveling speed was limited as a result of the narrow gate at the entrance and an inability to drive straight through. SAM determined that 10 mph was easy to maintain and still be able to come to a safe stop.

3.4 DELIVERABLES

Data collected during Phase 1 was converted by SAM into the following deliverables to CDOT:

- LIDAR point cloud colored by thermal, which provides a platform to visualize the thermal signatures in a 3D environment that can be used to measure length or areas of interest
- LIDAR point cloud with intensities, which provides a spatially correct data set of the tunnel in a Computer-aided Design (CAD) environment. From there, it can be

worked on directly or line work can be created off which to model it to provide a more traditional CAD file. Additionally, a 3D line work of tunnel features can be created.

- Tunnel Triangulated Irregular Network (TIN) from 1 foot contour profiles, which provide a 3D surface to analyze and, if needed, aid in repair designs.
- Flattened thermal tunnel image created by NEXCO-West USA (NEXCO), which combines and gives spatial reference to the thermal data in a printable 2D map that can easily be shared among a project team

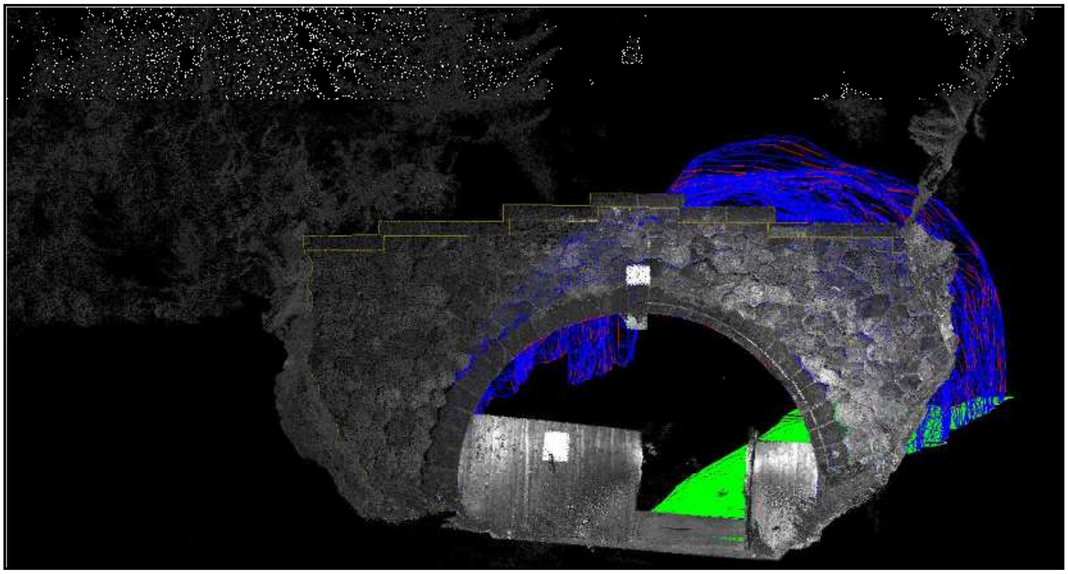

Figure 13: Tunnel 4 LIDAR with intensity and mesh loaded

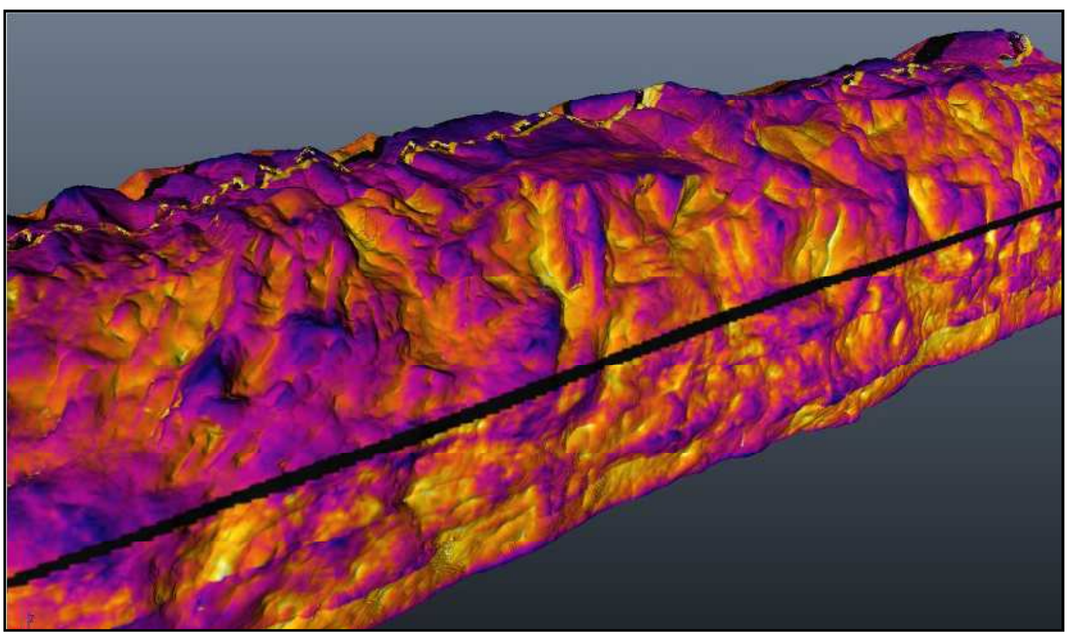

Figure 14: LIDAR colorized with thermal signatures in 3D

The two images below (Figures 15 and 16) illustrate details of the shotcrete with an extremely dense 3D mesh created from the full LIDAR point cloud. While impressive, it proved unmanageable anywhere but on SAM's in-house geospatial machines. As advanced computer hardware becomes more widely available, this could prove to be a meaningful deliverable. One foreseeable application in which this type of deliverable would excel is the Virtual Reality (VR) platform.

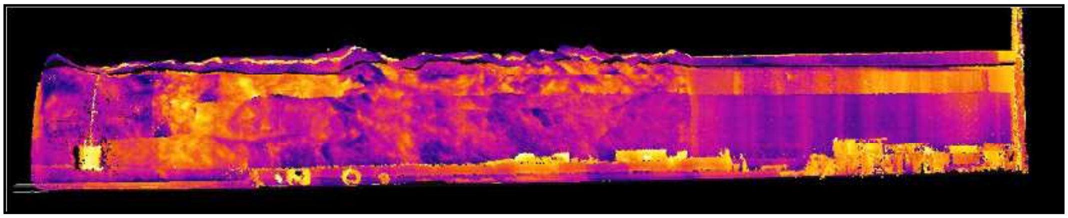

Figure 15: Side view of thermal colorized Tunnel 4 LIDAR

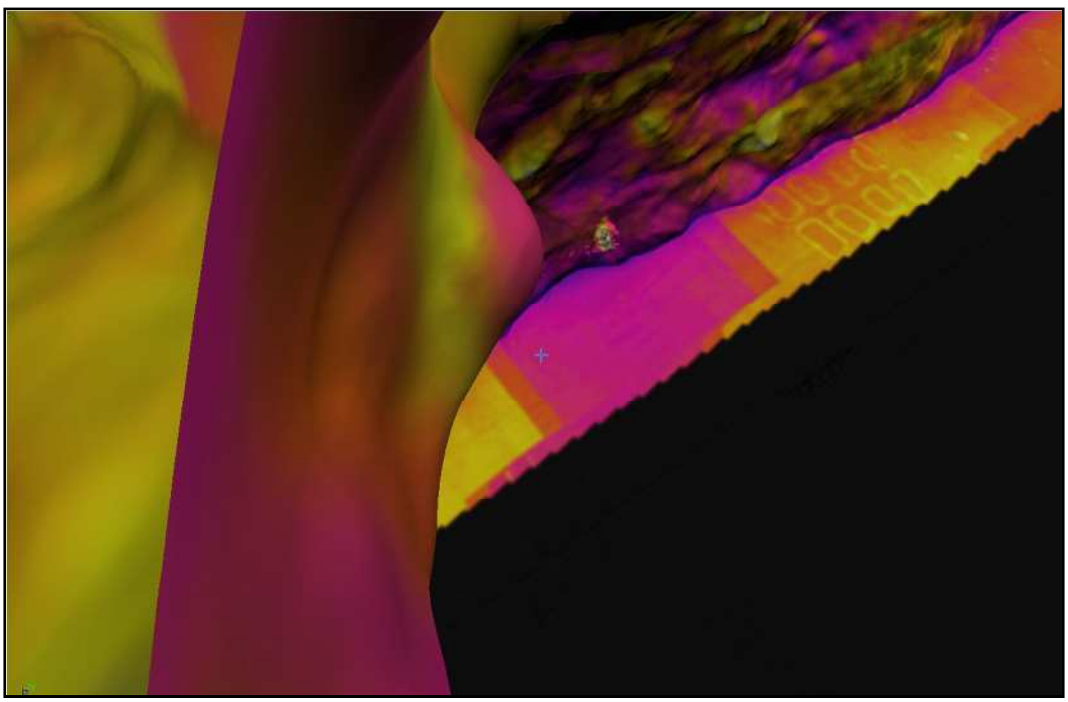

Figure 16: Detail of Tunnel 4 shotcrete

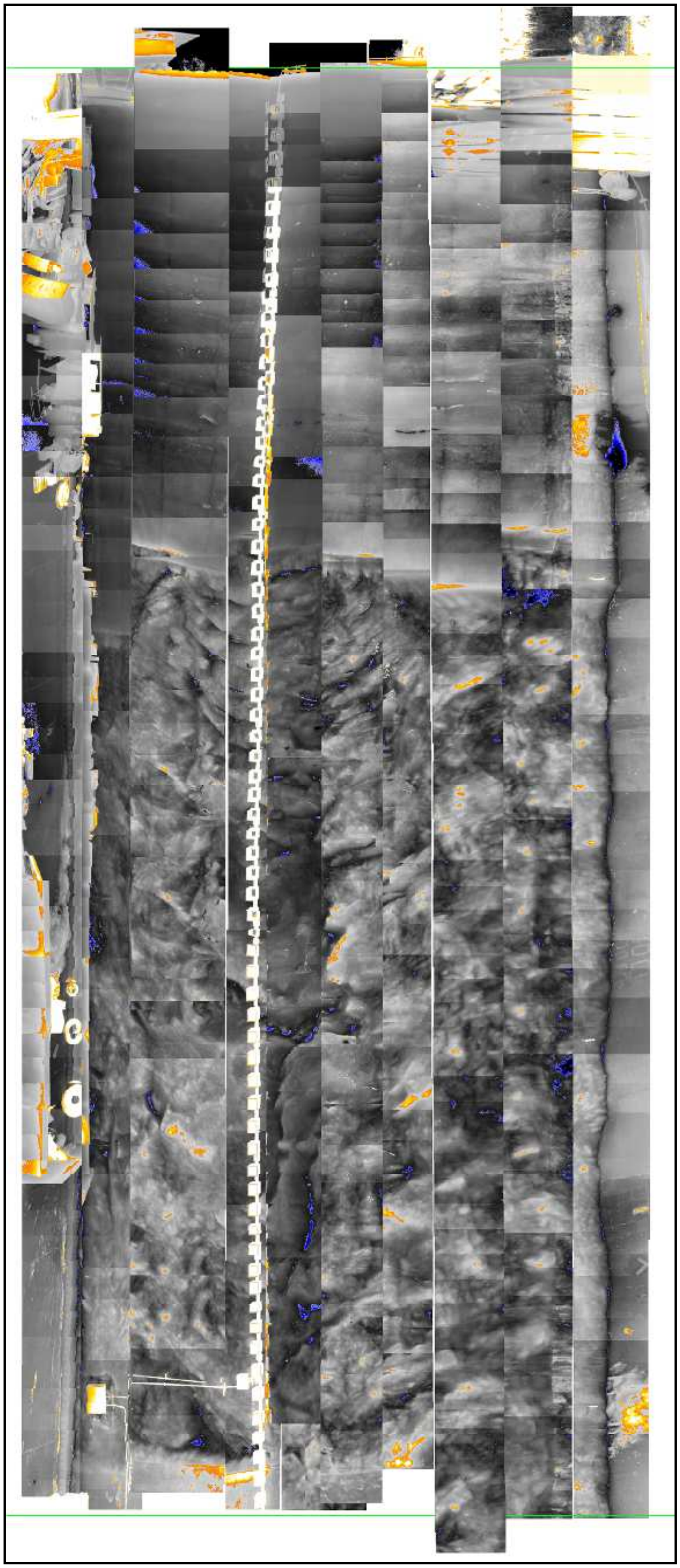

Figure 17: Flattened stitched thermal image of Tunnel 4 by NEXCO-West USA

3.5 LESSONS LEARNED

Overall, SAM believes the task order went well, as they successfully chose and integrated sufficient thermal cameras and collected the project tunnel. Calibration of the LIDAR and deliverables creation were pretty straightforward processes, as SAM interacts with such equipment on a daily basis. A few modifications were necessary, though, for the tunnel environment since a GPS location was denied.

The largest issue they encountered was one that was entirely unanticipated: generation of the stitched flattened thermal pdf requested by CDOT. SAM tried every piece of in-house software from a geospatial aspect and photogrammetry aspect with limited success. Ultimately, the product did not meet SAM's standards. They began to research other software on the market and, after no less than a dozen tries with various products, came to the conclusion that they needed a custom one-off solution.

After talking with their in-house development team, they decided to find a company who had success at generating such products. Following an internet search, SAM ultimately reached out to FLIR, who recommended NEXCO. SAM reached out to NEXCO, who was open to working with them and made it clear they had a working knowledge of what SAM needed, as well as the software to accomplish to job. The Tunnel 4 data was provided to NEXCO, and although it was collected in a manner slightly different from what they were accustomed to, they were able to successfully produce a deliverable for SAM.

Following data collection during Phase 1, SAM gained a better understanding of the process and noted several areas for improvement:

- Temperatures and fluctuations should be defined with a scientific gauge to understand the best time to collect and ensure the sensor is capable of detection of thermal separation.
- The angle of the sun caused higher temperatures at the end of the tunnel where it was shining in, while the shaded part of the tunnel was much cooler. The sun warmed the tunnel lining as a whole in that area, lessening the temperature delta between areas where a thermal signature should have appeared. Based on this, SAM determined that collection should occur at night.
- The optimal time of day to collect data should be pre-determined for each tunnel, as a large enough temperature swing is necessary to facilitate temperature change in the tunnel lining. The separation of high and low temperatures at the portal of Tunnel 4 were greatly influenced by the position of the sun. For timing of future collections, it would be helpful to factor in not only the temperature, but the time of sunrise and sunset, as well.
- The use of multiple cameras would require less passes and less image stitching, ultimately reducing project time and increasing the quality of the final product.
- A Red, Green, Blue (RGB) camera should be integrated into data collection at the same time passes are made collecting thermal imagery to offer an additional perspective and confirm or refute potential areas of concern.

- Improve processes to enhance imagery of 2D tunnel surface

Finally, SAM staff attended and presented information from the first Task Order at the 2017 PennDOT showcase. Other attending contractors who had explored similar NDT testing and methods cited multiple reasons that thermal failed for them. SAM observed the technology they had implemented and, coupled with their own experience on Tunnel 4, identified opportunities for improvement. After convincing CDOT that such hurdles could be overcome, the objectives for Phase 2 (Second Task Order) were established.

4.0 PHASE 2 (SECOND TASK ORDER)

Phase 2 included data collection in seven tunnels during August 2017: Beavertail Tunnel (BT) in Mesa County, Hanging Lake Tunnel (HLT) in Garfield County; and Clear Creek Tunnels (CCT) 1, 2, 3, 5 and 6 in Jefferson and Clear Creek Counties.

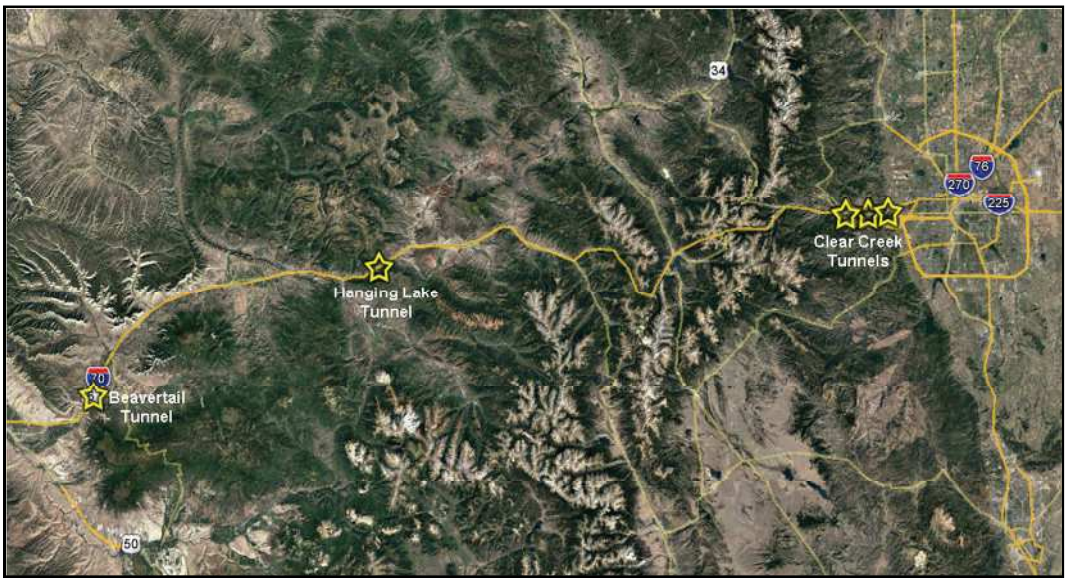

Figure 18: Overall project aerial map

4.1 RESEARCH & EQUIPMENT

SAM researched the following additional equipment to pair with the thermal cameras and took advantage of the opportunities for improvement identified in Phase 1.

4.1.1 THERMOCOUPLE DATA LOGGER

After attending the PennDOT showcase, SAM wanted to make sure they addressed the thermography concerns that other contractors had expressed, as well as explore solutions to a question that was posed regarding the use of tunnel exhaust fans to induce thermal swings within the tunnels. It was stated in the PennDOT report results that there were no thermal swings in a long tunnel, due to the fact that the ambient air temperature would mean out by the time it would push through. SAM felt there were thermal swings in a long tunnel, and that perhaps different equipment or sensors would be able to measure what was likely a negligible difference. Exploring this opportunity meant installing thermocouple data loggers, which could be an inexpensive way to see if there was a swing, measure it, and record when it would occur. Adding such equipment to NDT methods would mean SAM needed to explore and test another area (trial and error) before pursuing the next level of technology.

To accurately account for temperature shifts during Phase 2 and identify prime thermal data collection times, SAM researched thermocouple data loggers and their applications. Understanding the tunnel environment and how the tunnel liner responds to ambient temperature changes outside the tunnel is very important for a couple of reasons. First, one wants to confirm there are thermal variants at compromised liner locations. Second, there should be assurance that those variants, if they exist, fall within the sensitivity of the selected sensor.

A thermocouple data logger is a device that monitors temperatures in a location over time. The data can be transmitted remotely, downloaded and reviewed later. A data logger typically has two wires attached to one end and is placed in or on an area of interest. The unattached ends of the wires have probes of dissimilar metals, one of which is heated.

Figure 19: Thermocouple data logger installed in a custom waterproof box

SAM chose to implement the Supco DVT4 for the purposes of studying the environment and temperature of each tunnel in relation to the tunnel surface and its defects prior to mobilizing. The DVT4 records up to four temperatures using one internal and three external sensors. The DVT4 was selected because of the number of channels, battery life, storage size (87,040 data points), and its operating system. Most loggers on the market record one or two channels, but SAM needed three, at a minimum, with one measuring ambient temperature, one in a sound location, and one in a compromised location.

One problem with the selected model was that it was not waterproof and could not be installed in a condensing environment. SAM determined that the solution was to create a waterproof enclosure for the DVT4 and attach it to the tunnel wall using industrial strength Velcro and epoxy. By securing it that way, the device would be fixed for an extended period of time, stand up to the exposure of live traffic, and be easy to remove and reinstall.

Since the DVT4 records four different temperatures, SAM intended to place four identical devices at intervals on the walls of each tunnel. One would be placed at each end of the tunnel, and the other two would be located somewhere in the middle at a problem area in order to monitor the delta of a good versus a bad spot. With the device itself recording ambient temperature, two sensors with nickel-plated copper probes were attached to a deficient area with thermally conductive silicone and the remaining sensor was attached in an identical manner to an area with no deficiencies.

Figure 20: Example of logger installed at Hanging Lake Tunnel monitoring tile delamination with water and good tile surface on either side

The data from the device could be exported to a comma-separated values file (CSV) and contained its own software. Once the data was gathered, it could be plotted and analyzed either specific to one device or in relation to the other devices. After comparing the data gathered from the center devices with those at the tunnel ends, the optimal time for thermal data collection could be determined. Initially, SAM decided to log data points from the DVT4 every five minutes over a period of 15 days. An evaluation of the data would reveal temperature intervals and could offer another means of supporting or refuting findings recorded with the other equipment. Additionally, it might identify inconsistencies in those other methods.

HLT would prove to be the most challenging for thermography analysis due to its length and tile lining, so SAM chose to install the loggers there first. Four were attached in the westbound bore and one was attached in the middle of the eastbound bore. Taking into account a question posed at the PennDOT showcase about tunnel exhaust fans changing the temperature in a tunnel, SAM did an additional test with the loggers before removing them. HLT is equipped with eight fans, and each is capable of moving 250 cubic feet of air per minute at full speed. The tunnel's power is supplied by two different power companies for redundancy and demand if needed. After SAM spoke with the operations manager and explained what they wanted to test, he expressed concern that if all of the fans were turned on at full speed the large amount of power they consume would result in a significant surcharge.

The operations manager offered to turn on two fans to a level that would not incur a surcharge, with each supplied by a different power company. Located in the middle of the tunnel, the fans pulled in air from throttled louvers in the ceiling for 30 minutes. SAM monitored ambient tunnel temperature and wind speed/direction from the command center. Surprisingly, they observed that the piston effect from traffic moving through the tunnel was stronger than the draft created by the fan on the exiting portal side, as the fans were pulling air in the opposite direction of traffic on that side of the tunnel. On the entrance half of the tunnel, the wind speed was increased by the fans but varied greatly with traffic flow. This suggested that the added pull was not significant. In the end, the fans were unable to influence the tunnel's ambient temperature and, therefore, unable to create a thermal swing in the tunnel liner.

The graph on the following page (Figure 21) shows the ambient temperatures of each logger installed in HLT, the ambient temperature outside for comparison, and the sunrise and sunset times (greatly influencing the temperatures).

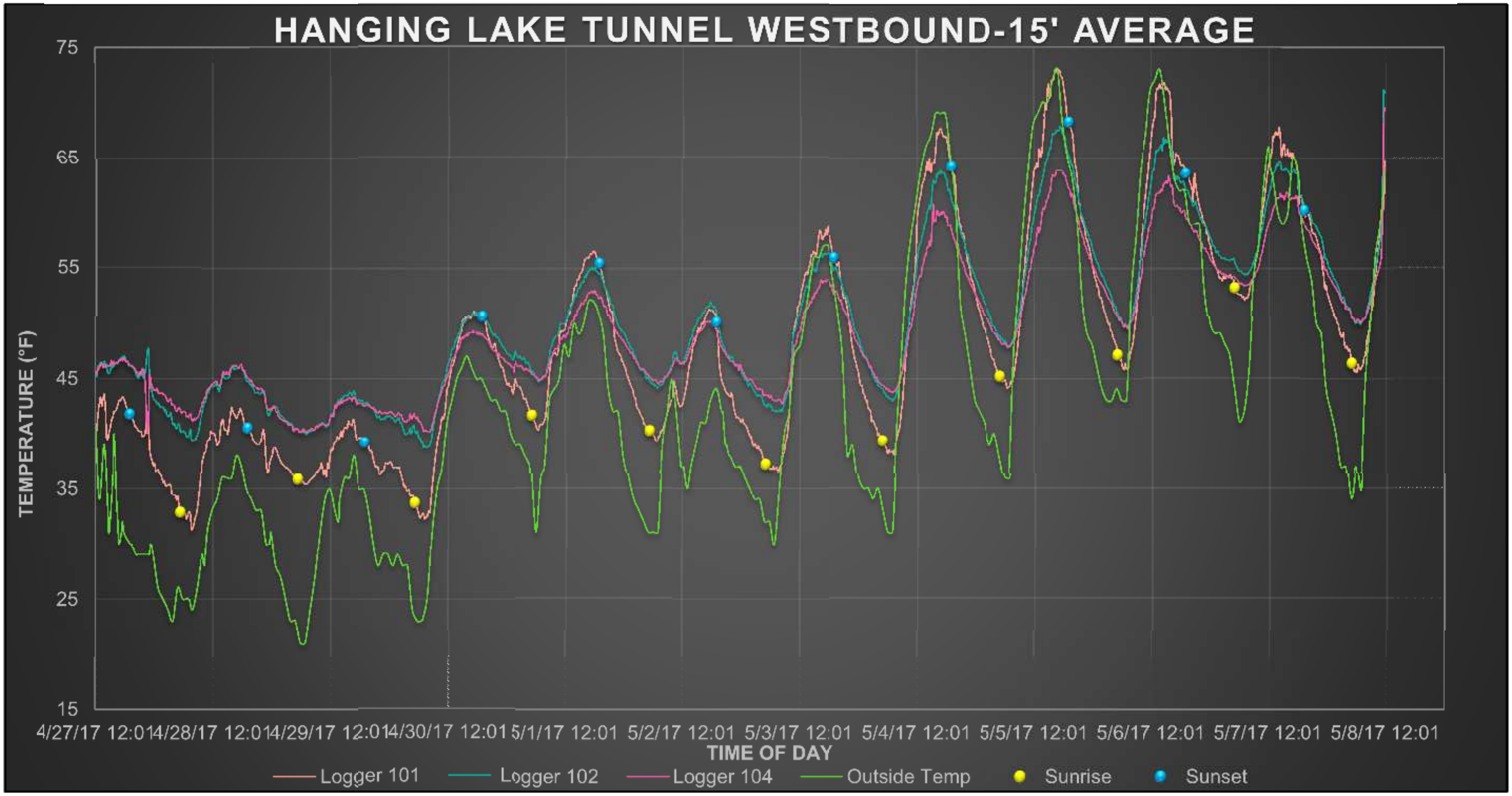

Figure 21: Ambient trends in HLT

On the following pages, Figures 22-26 depict how the sun and outside temperature swings affect the defects in the tunnel lining. The first three days of logger data were tracked during a snow storm that resulted in a narrow change in temperature highs and lows, showing little to no detectable separation. Toward the end of the logger data, the separation of the daily high and low was significant and created a differential in the tunnel liner defect being monitored. It is also noteworthy that the largest and longest liner deltas happened shortly after sunset before narrowing back down. This data illustrates that with thermal sensors, the user can verify before mobilizing to the site that the collection will be successful.

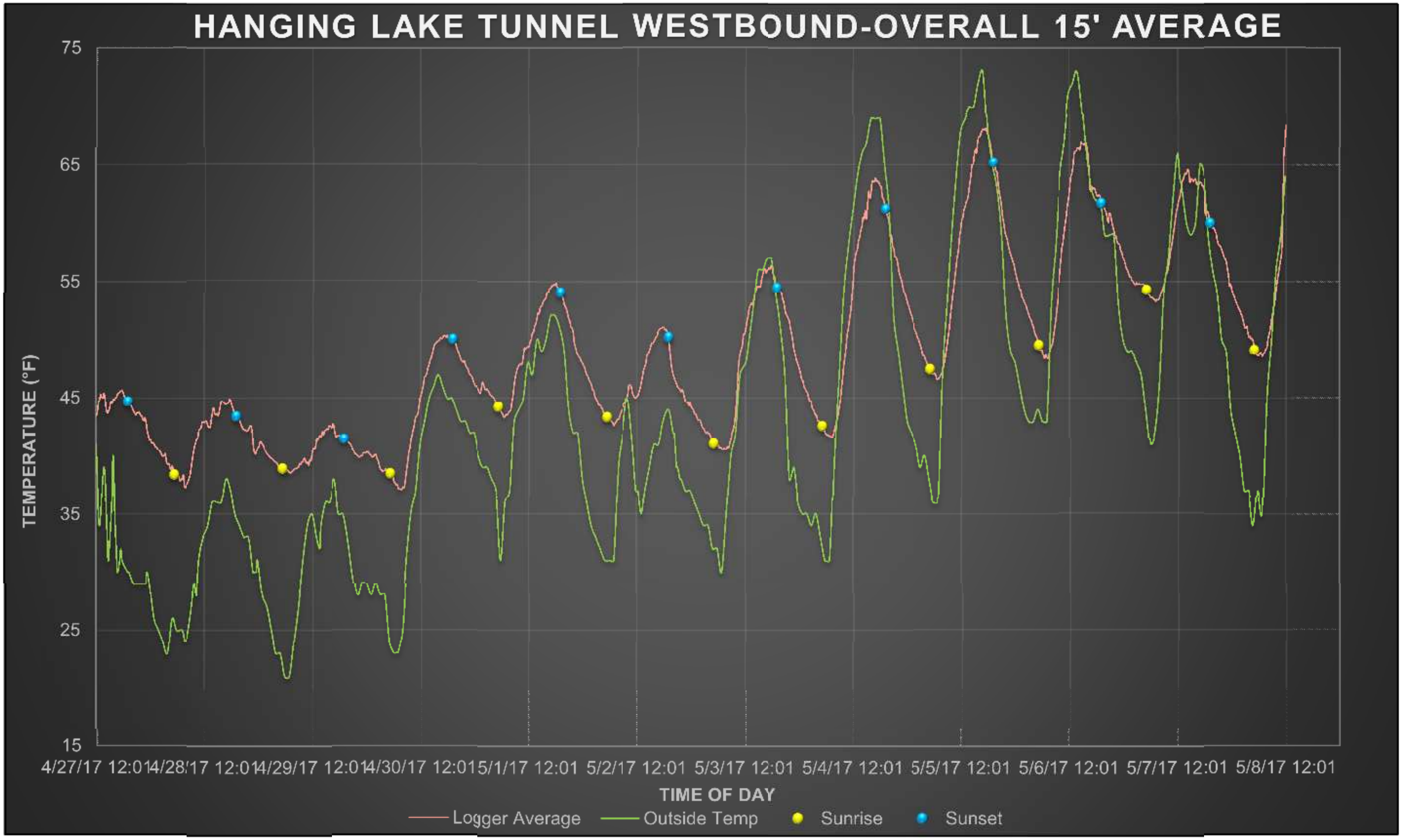

Figure 22: Ambient averages from loggers inside HLT vs. outside temperatures

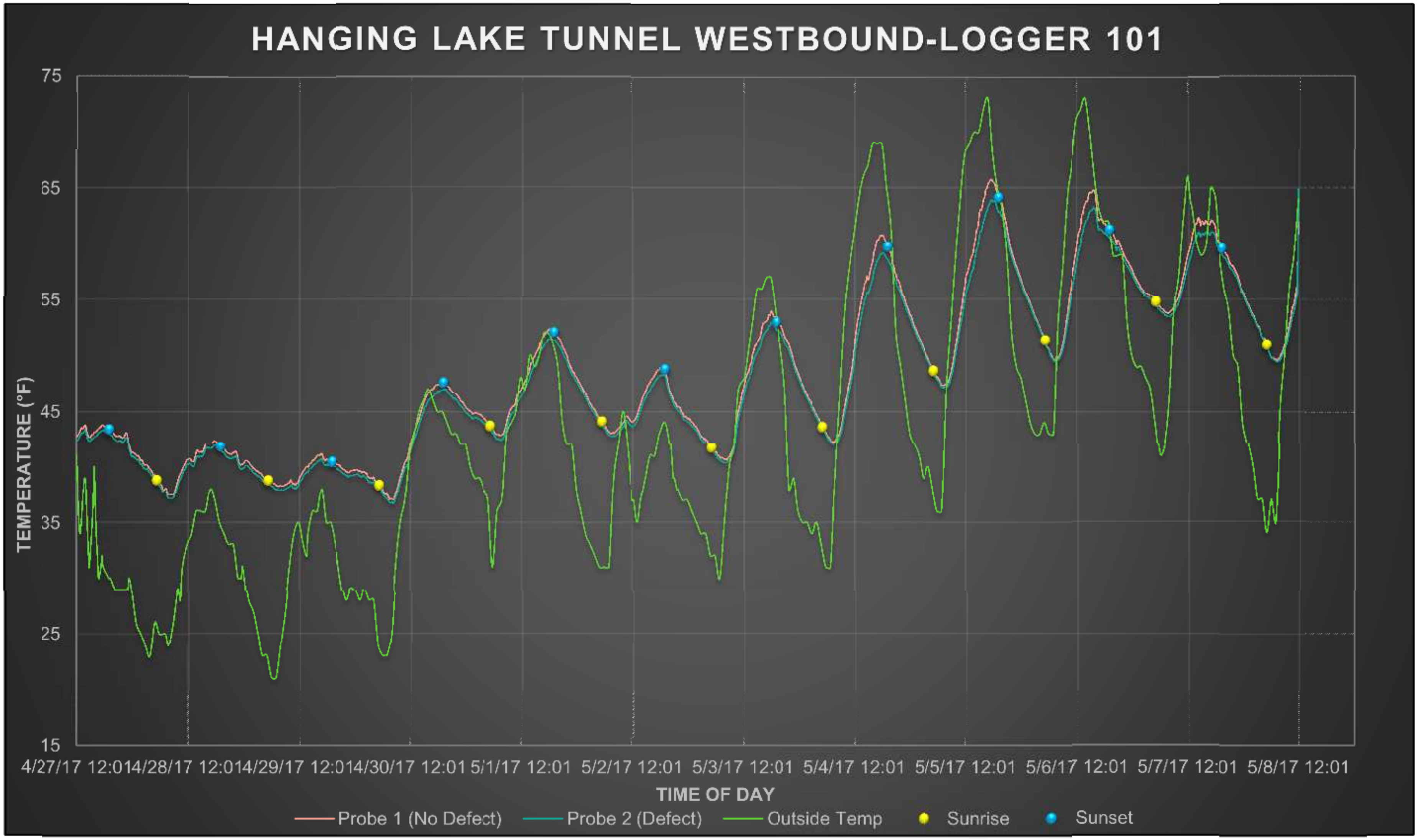

Figure 23: Results from logger installed at HLT's east portal

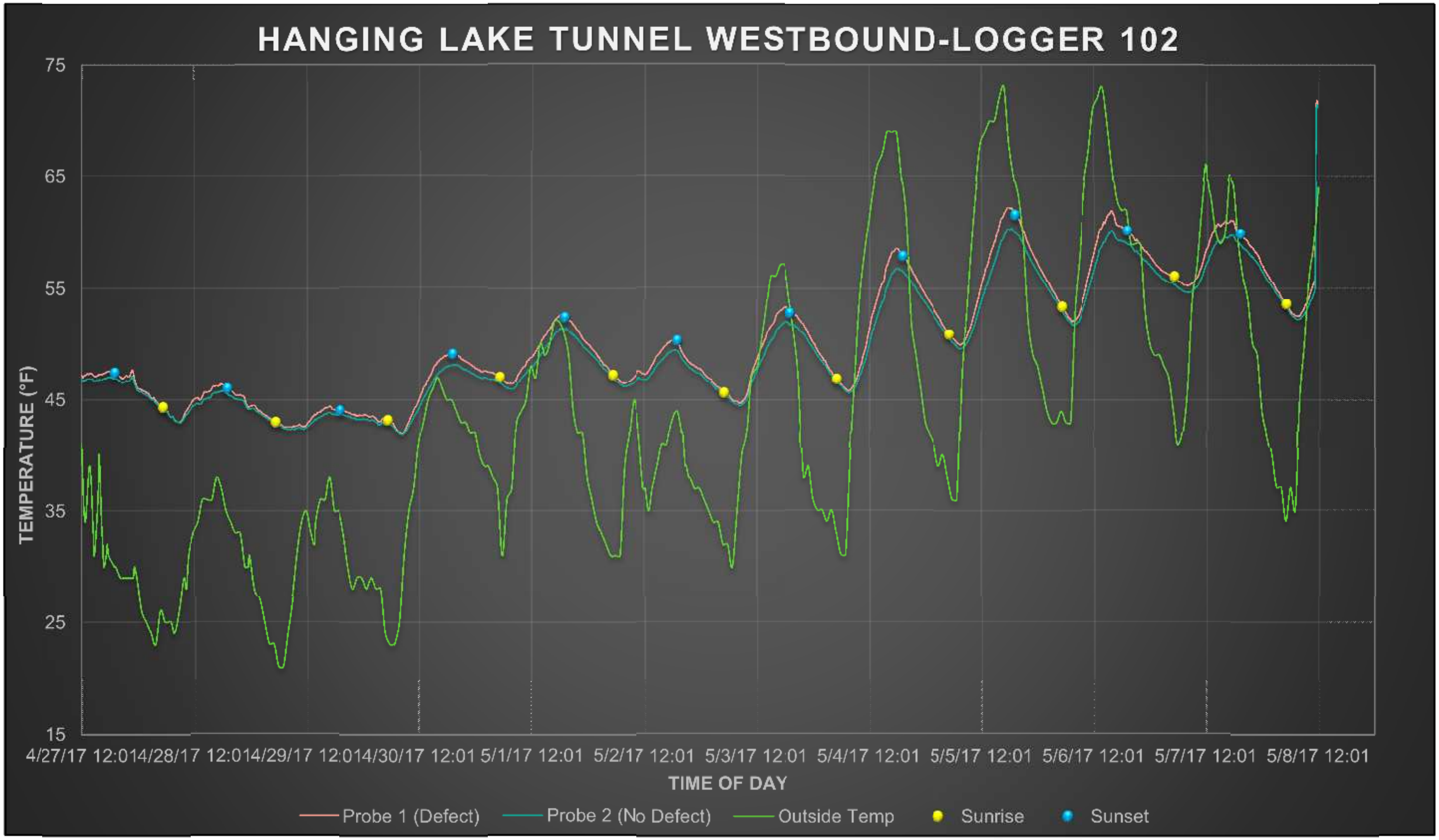

Figure 24: Results from logger installed in the middle of HLT

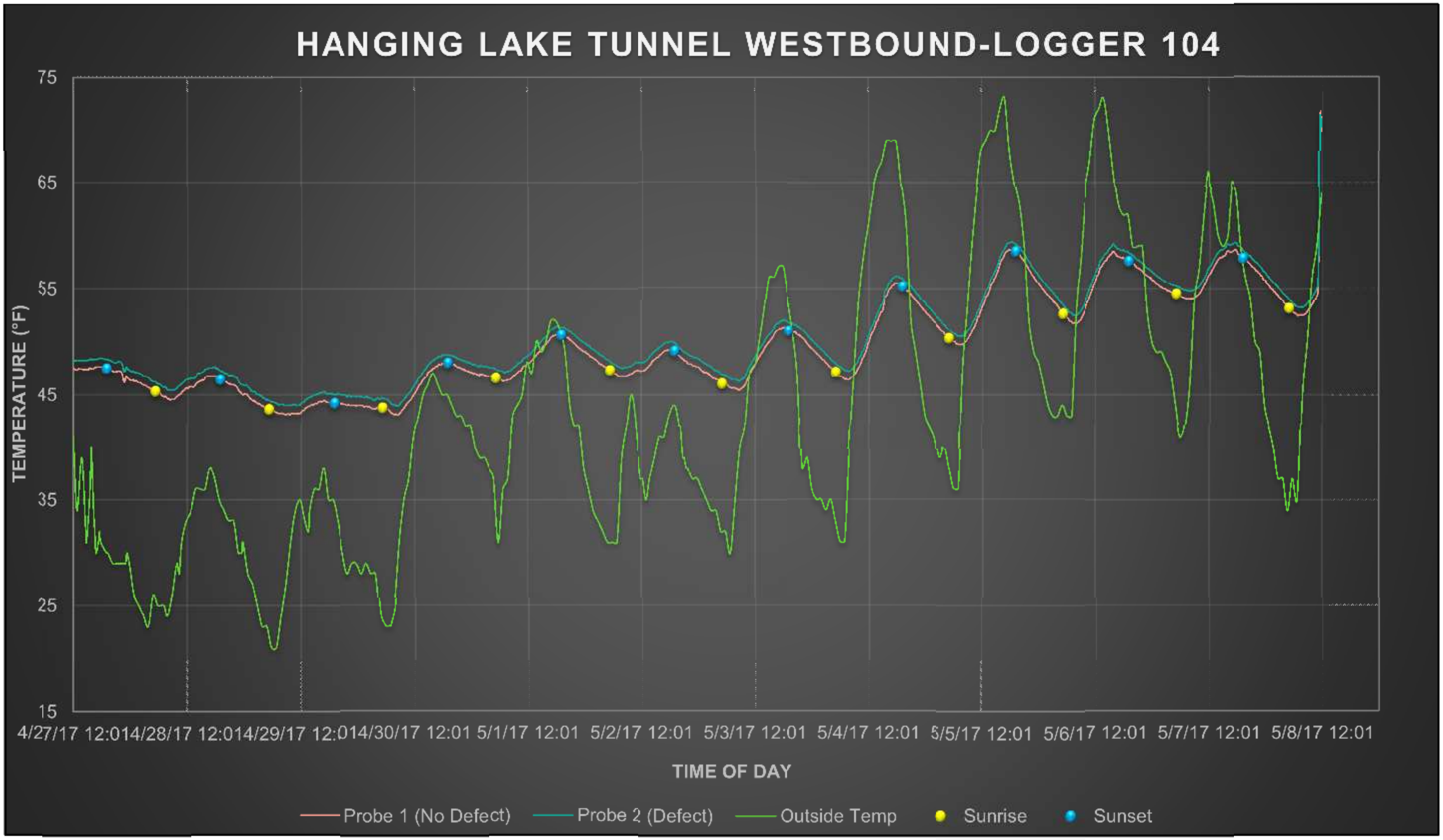

Figure 25: Results from logger installed at HLT's west portal

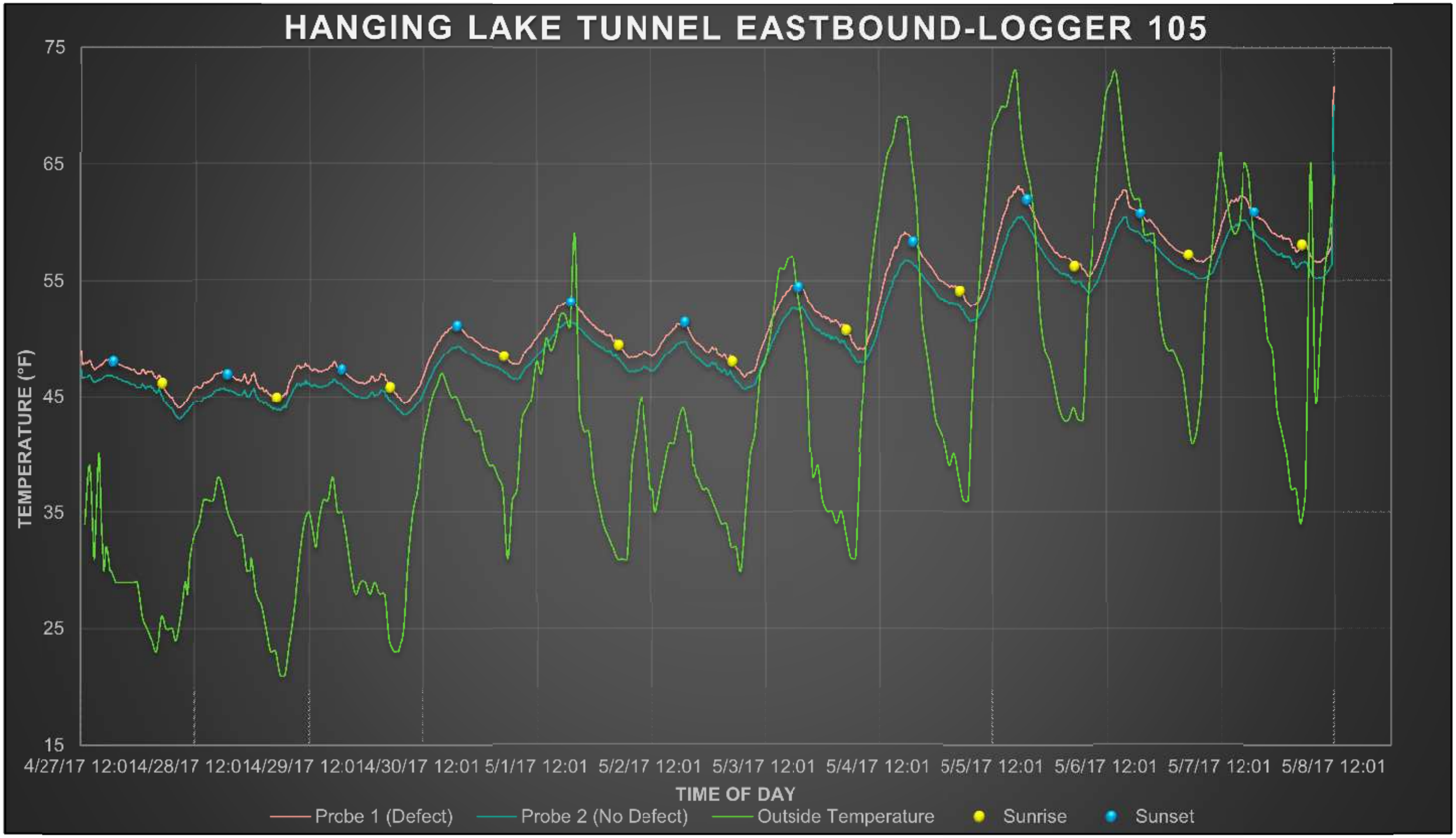

Figure 26: Results from logger installed in the middle of the eastbound tunnel (historically trends slightly cooler than the westbound bore)

Figures 27-29 on the following pages depict data gathered from BT, which is noteworthy for the ways in which it varied from HLT data. Comparatively, BT's cast-in-place tunnel liner is new. Given its age and construction, along with previous rehabilitation work, it was difficult to find significantly compromised areas. The original plan was to collect data from the eastbound bore before and after previously scheduled repairs were conducted, so four loggers were installed in the eastbound bore. As the project progressed, SAM was unable to coordinate its schedule with CDOT's, so survey work and collection were conducted in the westbound bore.

All of the loggers were placed on the largest cracks within an ideal defined area. While BT is shorter than HLT, its closure meant there was no piston effect caused by air movement from traffic. Any swings were reliant on the natural air flow through the canyon. In the end, SAM was still able to detect thermal swings in the tunnel liner but believes the limited results were due to a lack of textbook delamination or water intrusion. There were also some arterial swings created by the tunnel contractors using gas powered lifts and other equipment near some of the loggers but that data was easily identified by comparing the loggers nearest and ruling out the spike.

After evaluating all of the logger data and charting it for visual analysis, SAM is confident in predicting the most opportune times to collect data in any tunnel in the Mountain West region of the United States without the need to gather further information with thermocouple data loggers. It appears that anytime the separation of the daily high and low temperatures exceeds 20°F, and preferably with a difference of 30°F, a successful collection of thermal data in a tunnel can occur. With regard to data collection in tunnels on the East Coast or in the Midwest, it would be prudent to utilize the thermocouple data loggers in advance since those areas do not typically see the large swings in highs and lows. Additionally, those regions have higher relative humidity compared to the arid climate where this study was conducted.

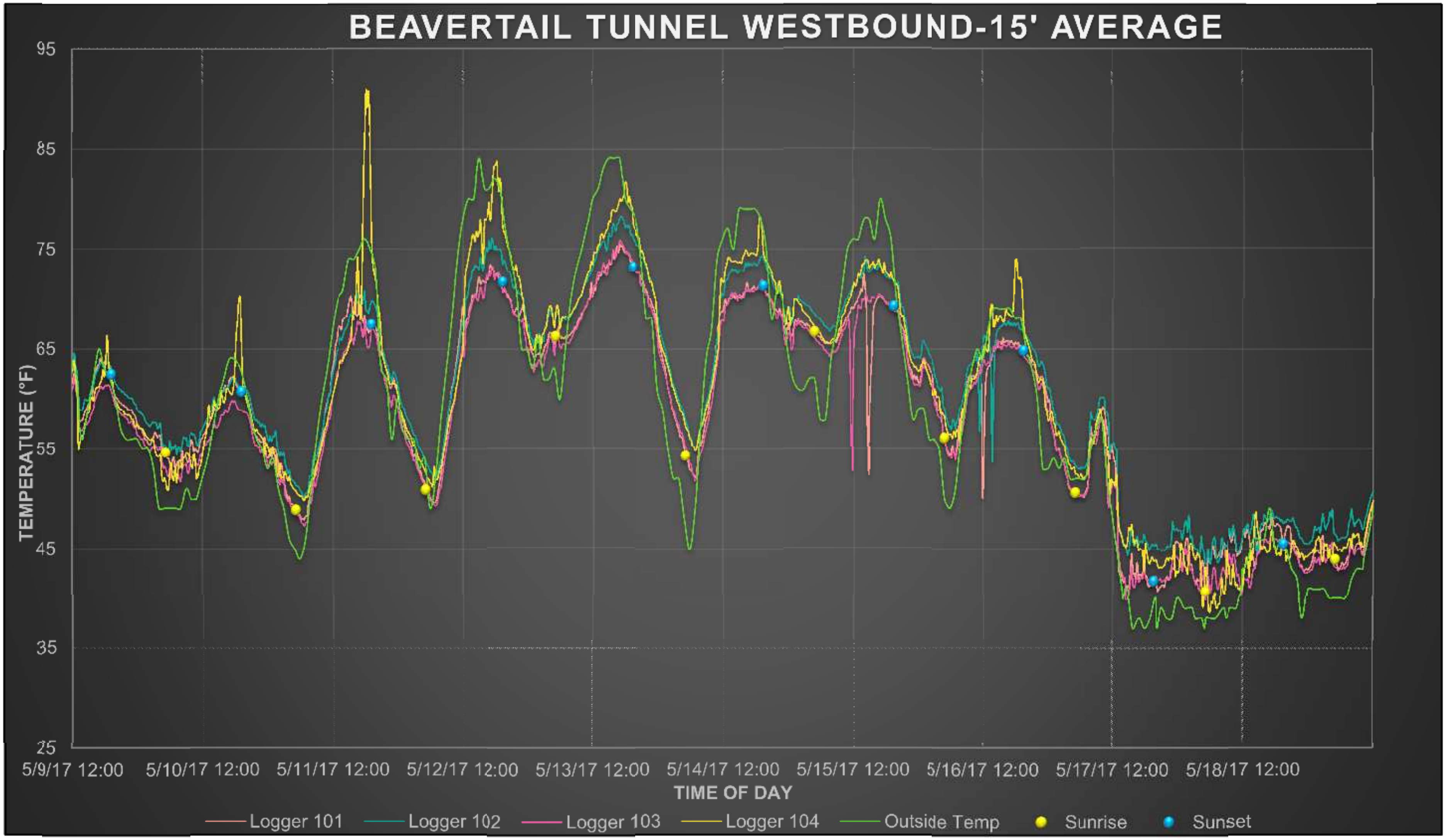

Figure 27: Results from logger averages

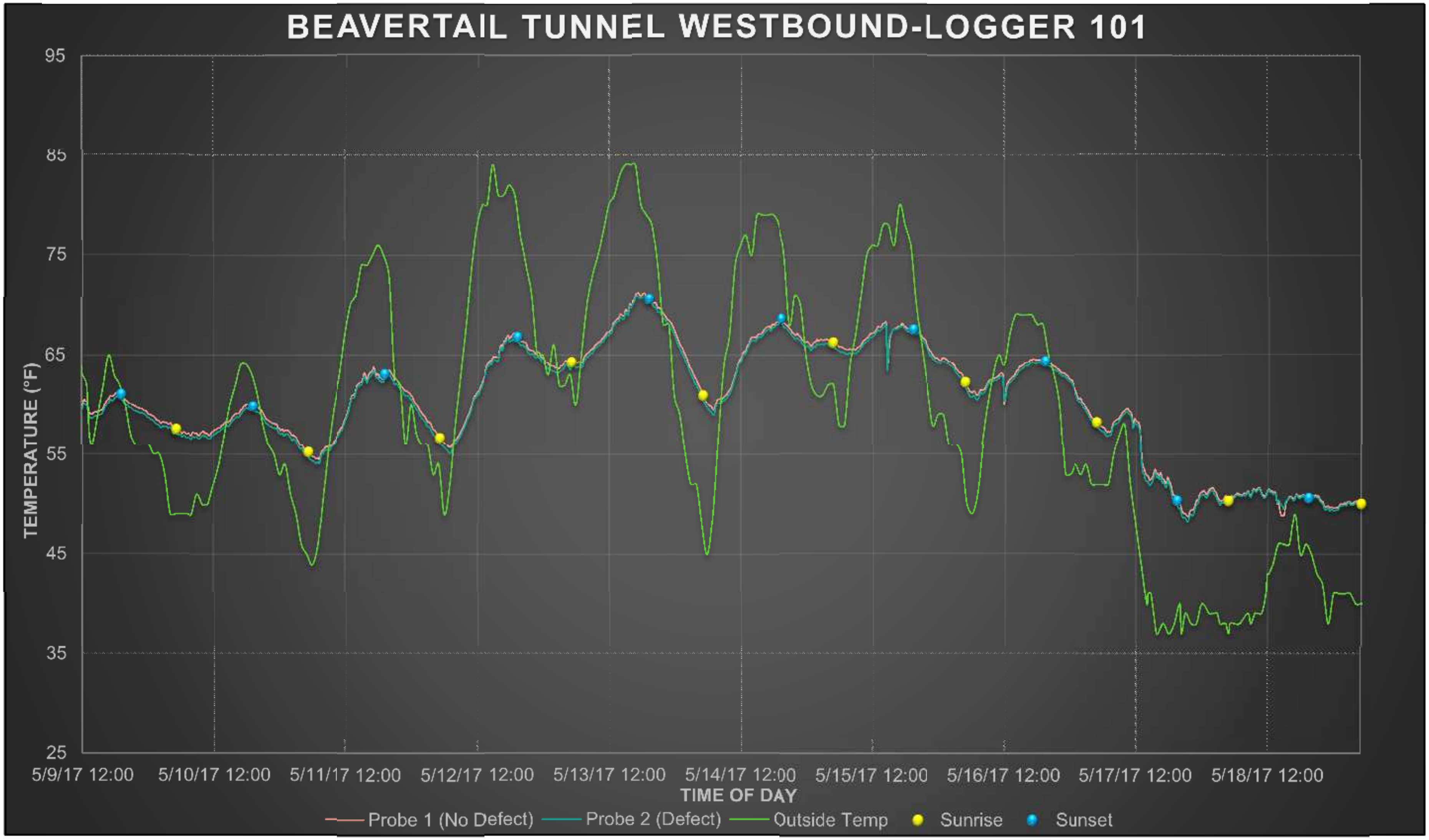

Figure 28: Results from logger installed at the east portal of the eastbound bore ~50' to avoid the sun's influence

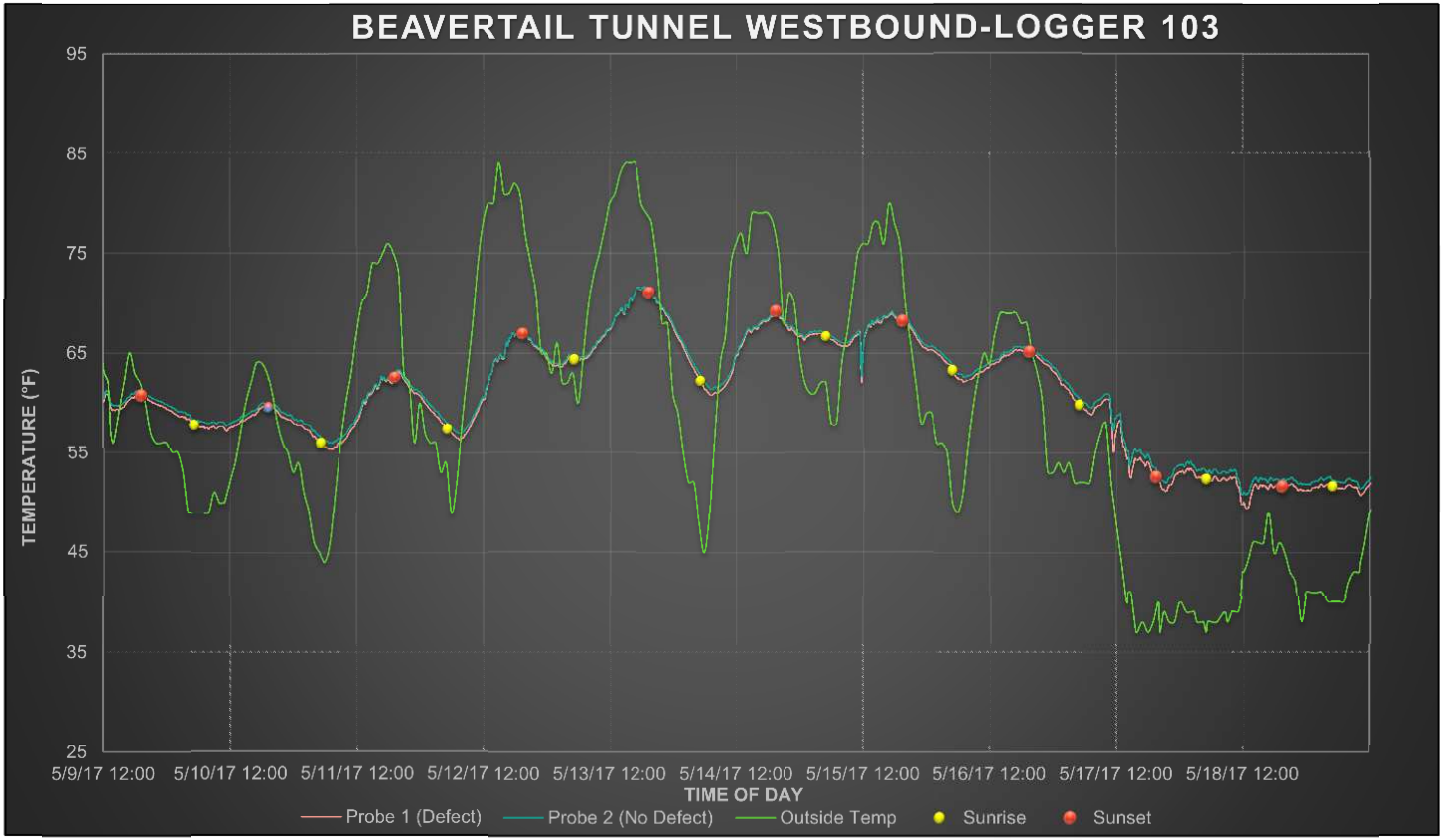

Figure 29: Results from logger installed in the middle of HLT

4.1.2 RGB CAMERA INTEGRATION

After evaluating the results of Phase 1, SAM identified a way to improve the quality of the information gathered and chose to incorporate RGB cameras into the collection process to provide another perspective to the data. The images may show items of interest, such as small cracks that do not necessarily have a thermal signature that differs from the surrounding surface. The RGB image could serve as a check or possible validation of the thermal image. For example, a spider web in the corner may show as a thermal area of interest due to its composition opposed to the surrounding tunnel liner, but after referencing the corresponding RGB one could rule that spot out as artificial influence.

SAM explored RGB camera options, the best way to couple them with the thermal camera and optimal mounting locations on the survey vehicle. Initially, the original equipment manufactured (OEM) cameras integrated into the Lynx Mobile LIDAR system were evaluated for this acquisition, but although they provided quality imagery they proved to be unacceptable for the challenging lighting conditions of a tunnel environment. SAM ultimately selected a GoPro Hero 5, as it had been successfully used extensively for other applications, including a custom 360 GIS mapping platform.

Two RGB cameras were mounted on the vehicle in the same location as the thermal cameras and were set to operate manually. Manual lighting was required for the RGB cameras, because tunnels can be illuminated in a variety of ways and light levels differ over the length. Some have consistent white lighting throughout, some have yellow lighting, light levels may be dim near the middle, and reflective surfaces can affect imagery. A high-powered, rotating, 10” Cree LED light bar producing 5400 lumens was attached to the custom camera mount to provide light where it was needed on the tunnel lining. As with the RGB cameras, the lights were controlled with switches from within the cab of the truck so as to minimize impacts on other drivers.

4.1.3 HIGH-DEFINITION THERMAL CAMERAS

SAM commissioned a third party to custom machine and fabricate a new camera mount similar to those used in film-making. The new mount had the ability to accurately and repeatedly replicate precise camera angles. The camera mount location was moved from the passenger side to the back of the driver’s side, keeping it close to the IMU for spatial precision and allowing a 360° view allowing collection in one-way traffic tunnels. Two HD thermal cameras were then attached, offering a coverage area that changed with distance. This meant that, depending on a tunnel’s size and shape, thermal imagery could be collected in fewer passes.

Figure 30: Custom camera mount with light bar, thermal and RGB cameras

4.2 DATA COLLECTION

One consideration with using additional equipment for Phase 2 was the management of such a large amount of data at one time. The Mobile LIDAR system is self-contained, meaning that all of its sensors (DMI, IMU, two GNSS receivers, and two LIDAR sensors) are all connected to the main rack, which is where the sensors interact and active measurements are stored. A laptop is connected to the rack to monitor and control the system, but most of the data collected by the sensors are stored on special solid state drives (SSDs) inserted on the rack. With the two LIDAR sensors collecting up to a million survey grade data points per second, the file sizes can grow quickly.

Between all of the cameras and sensors, one tunnel could easily result in the collection of half of a terabyte (TB) of data. Two high-end laptops with high-speed storage capabilities were connected to the cameras and placed inside the vehicle. The thermal cameras do not require excessive amounts of processing power, as that occurs on the sensor itself. However, they do require high speed SSDs and a capable connection between the SSD and the camera. In short tunnels, the data could be written to the cameras' RAM or the computers' RAM, a workflow that would avoid streaming issues. With the tunnels collected by SAM that was not an option.

SAM also found it beneficial to use large SSDs for the thermal sensors. Typically, moving data from the laptop to an external hard drive can be time-consuming, but no time was wasted during the collect. It is also crucial, and a standard practice for SAM, to review data and perform quality assurance/quality control (QA/QC) in the field. The large SSDs allowed for real-time management of the thermal data, as well as the ability to review the information and back it up before leaving the site.

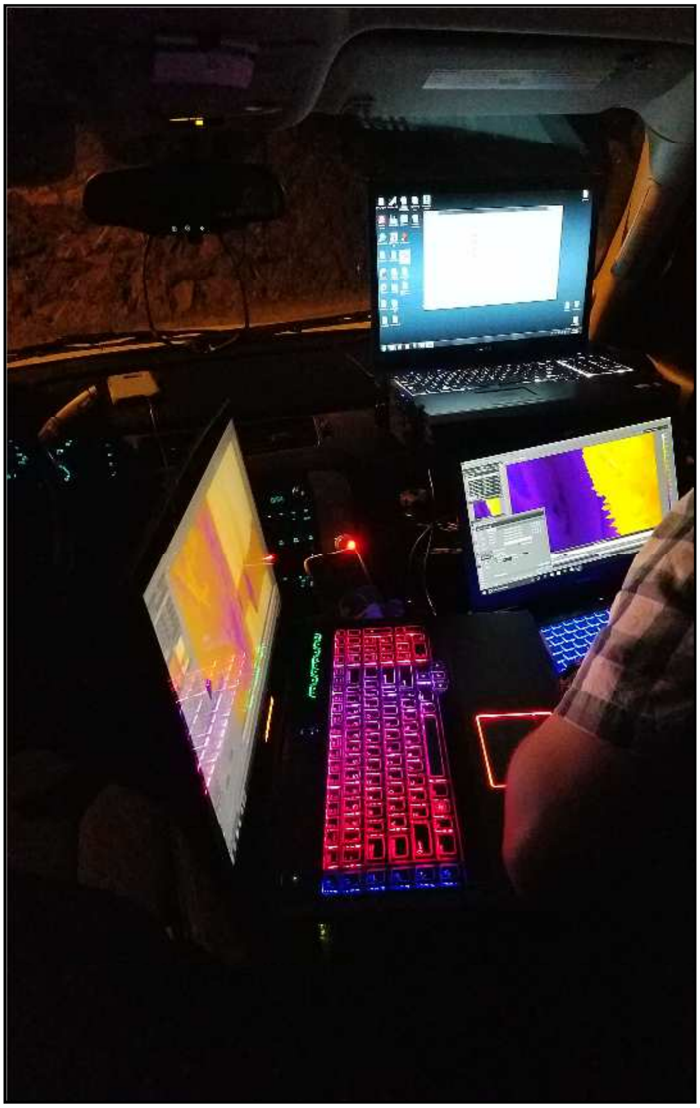

Figure 31: Collection and operation laptops

Since most of the tunnels were actively in use by the traveling public during data collection in Phase 2, coordination with CDOT was necessary prior to each site visit to ensure the safety of SAM field staff and other drivers. As previously noted, BT was closed for on-going rehabilitation work. SAM coordinated with CDOT and its contractors to work outside of working hours. When the crews left for the evening, they would move as much of the equipment and materials outside the tunnel as possible. Coordination for work at BT did not take more than a few days' notice.

Coordination at HLT was more challenging, as collection times needed to be scheduled outside of any maintenance, shift changes (the tunnel is manned 24 hours a day, seven days a week, 365 days a year), and within SAM's identified optimal thermal collection window.

4.2.1 BEAVERTAIL TUNNEL

Figure 32: Beavertail Tunnel aerial

Figure 33: East portals of Beavertail Tunnel approach

The first tunnel in which data was collected for Phase 2 was Beavertail Tunnel (BT), which travels through Beavertail Mountain in De Beque Canyon in Mesa County. It is located between mp 48 and mp 52 on Interstate 70 (I-70); specifically, it is found at 39°11’45.42” N, 108°16’13.31” W. The tunnel is oriented generally east-west. In 1987, the drilled and blasted concrete-lined tunnel was completed. The eastbound bore measures approximately 615 feet long, while the westbound side is approximately 625 feet long.

On August 23, 2017, the weather was sunny with a high of 96°F outside of Beavertail Tunnel. SAM arrived at the site around 8:00 p.m. to set up equipment. A Global Navigation Satellite System (GNSS) reference base station was set up outside of the tunnel in CDOT right of way (ROW). In SAM’s experience, using some form of positioning is crucial in order to give the data an absolute location that is relative to the DOT’s working coordinate system. Without applying a spatial reference to the data, the DOT has limited use of it outside of its face value visual inspection application. With survey grade LIDAR and positioning, the data has value from a design and as-built standpoint, adding value to the data and the DOT deliverable.

Figure 34: Prepping equipment and setting up the GNSS reference station before collection at Beavertail

By the time SAM mobilized for data collection, the temperature had dropped to 77°F. The first pass through the tunnel and strip of data collection occurred at 9:55 p.m. A total of four passes were made through the tunnel with the vehicle, with the last recorded at 10:10 p.m. Each pass was accomplished at a speed of 35 mph. The tunnel closure proved to be beneficial for a number of reasons, as it allowed SAM to collect data in a shorter time frame without having to factor in a traffic management strategy, was safer for field staff and the public, and did not require any permits on CDOT's behalf.

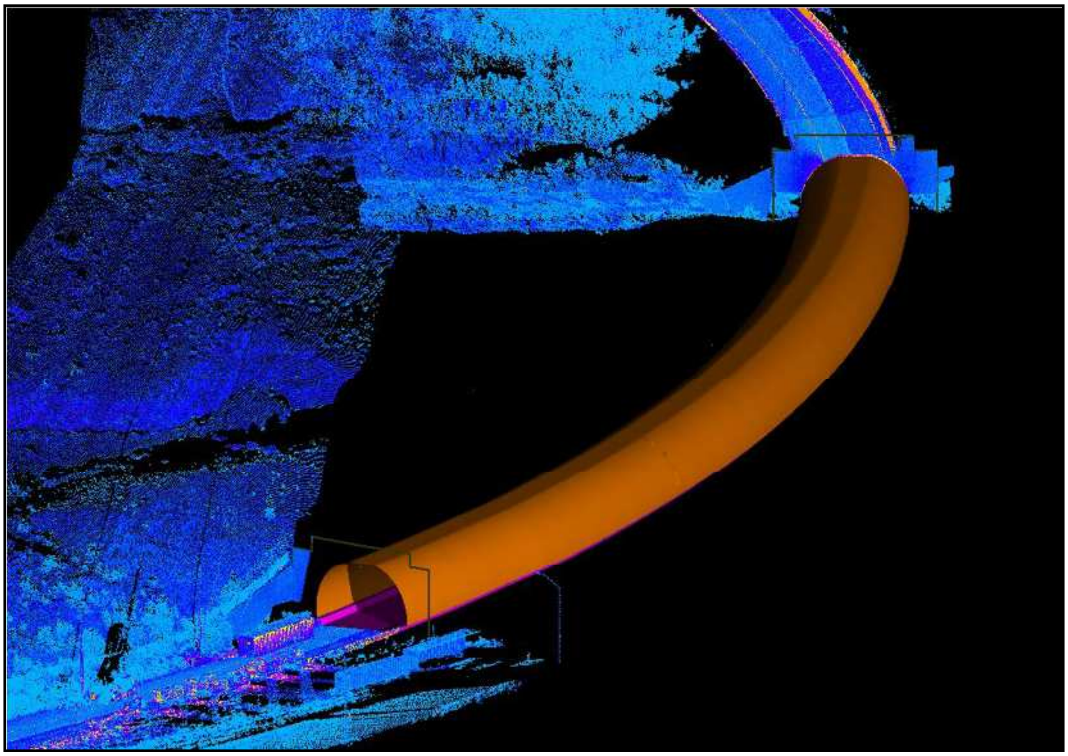

Figure 35: Looking eastbound at LIDAR and 3D model of Beavertail

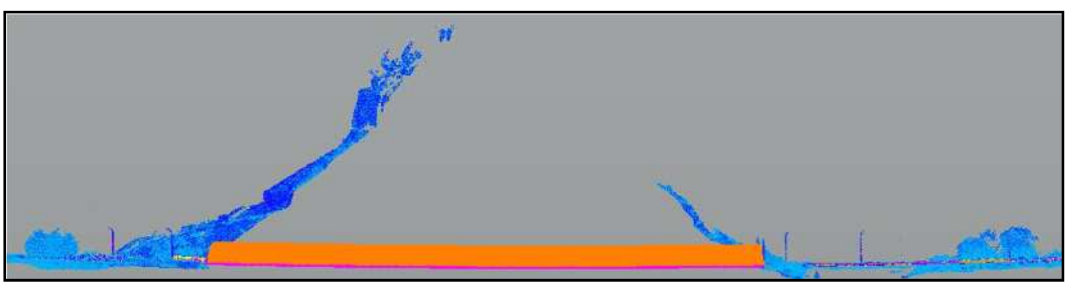

Figure 36: Cross section of Beavertail and LIDAR outside (showing partial over burden of the mountain). This data could be supplemented with terrestrial or drone LIDAR to give a full surface over the tunnel.

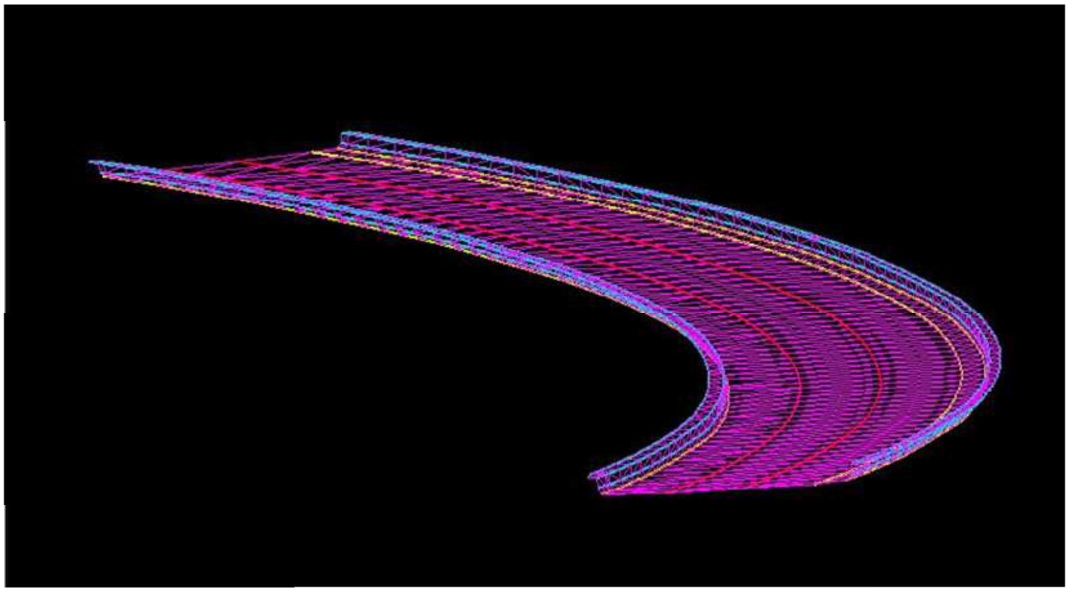

Figure 37: Beavertail roadway mesh with tunnel lining removed

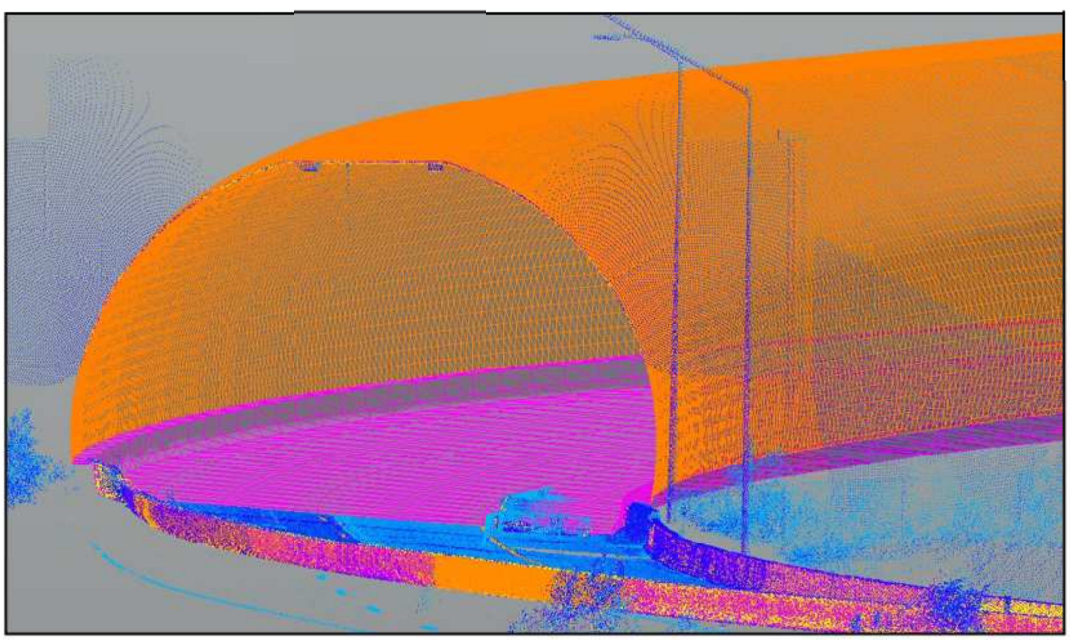

Figure 38: Beavertail full 3D mesh

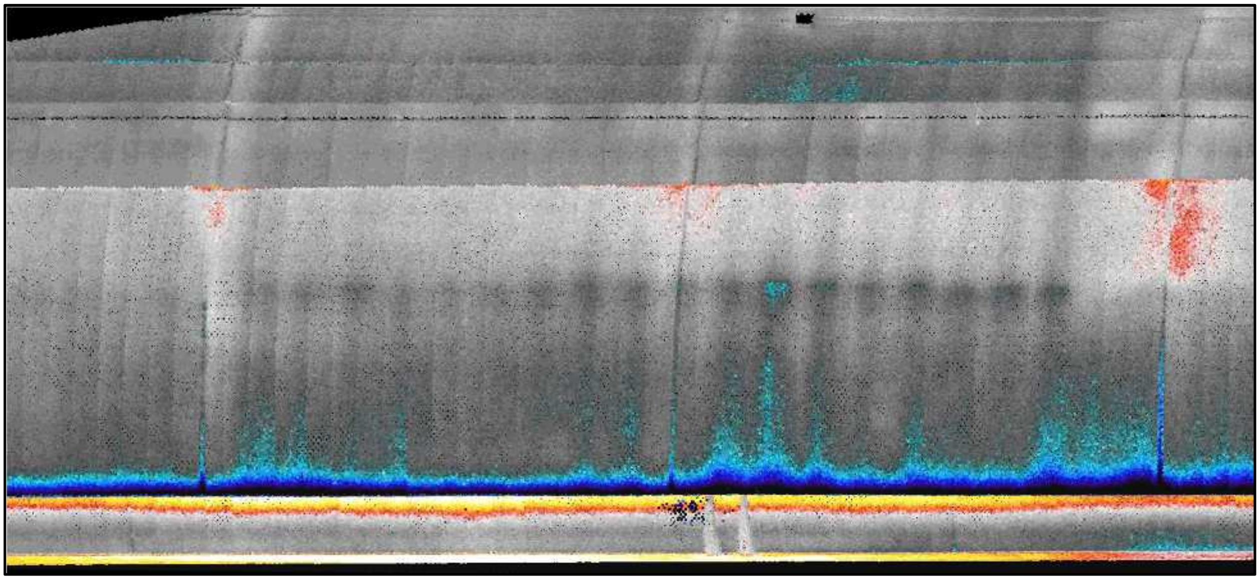

Figure 39: Beavertail LIDAR Colorized by Thermal

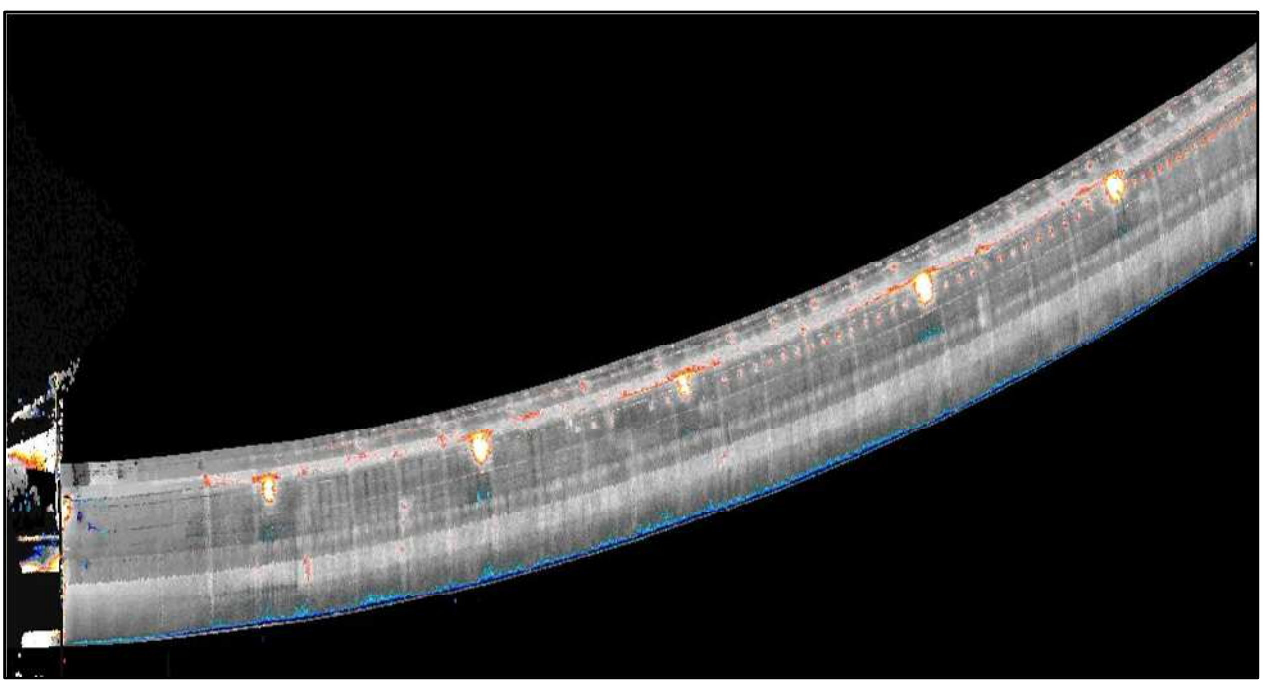

Figure 40: Beavertail LIDAR Colorized by Thermal

Figure 41: Beavertail RGB

Figure 42: Beavertail RGB

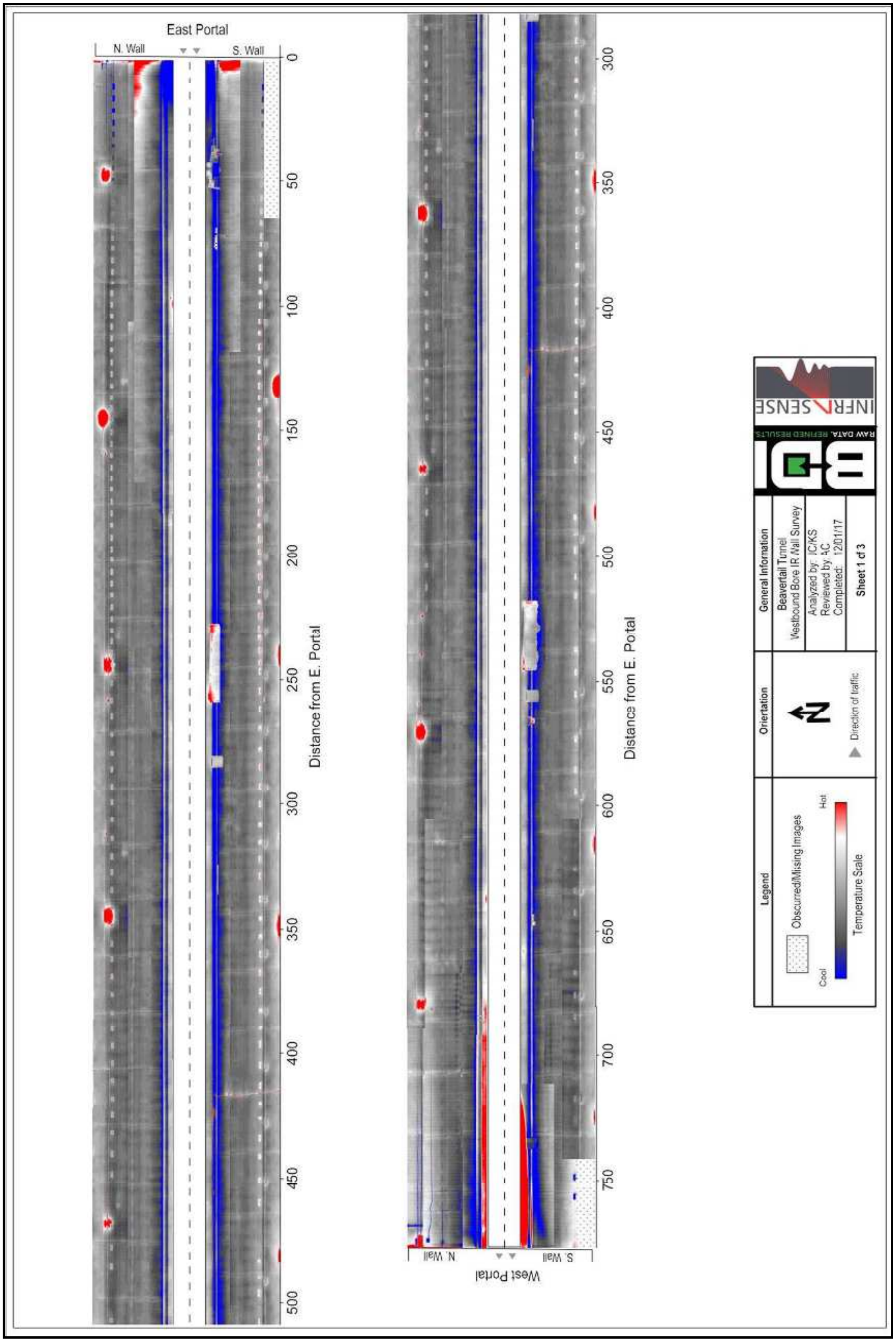

Figure 43: Infrared wall survey of Beavertail westbound bore

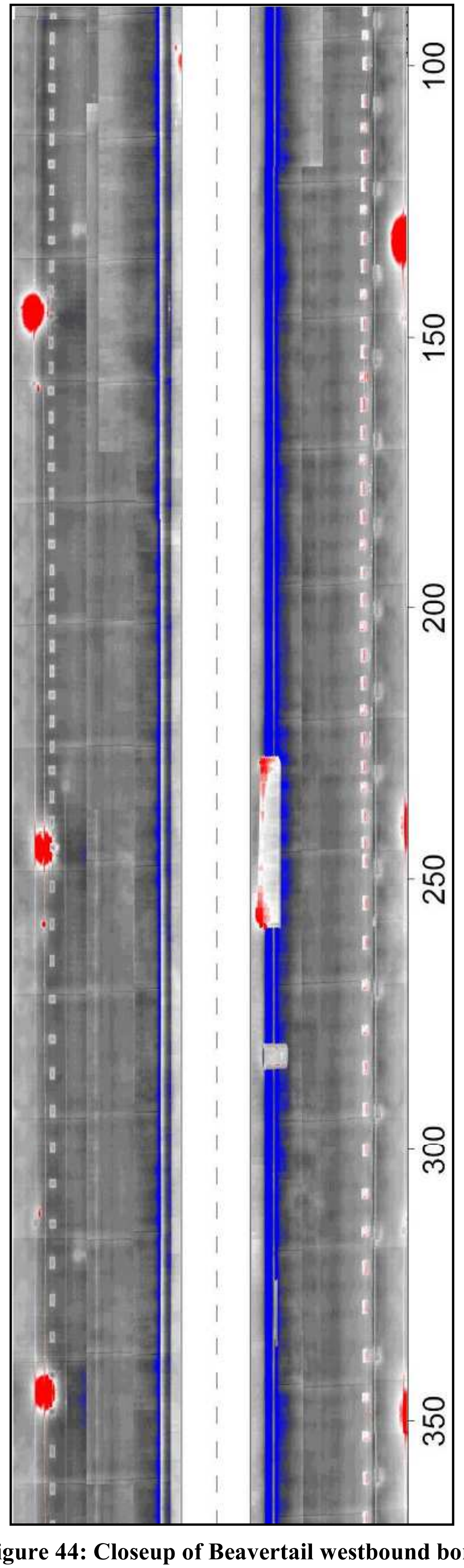

Figure 44: Closeup of Beavertail westbound bore

4.2.2 HANGING LAKE TUNNEL

The second tunnel in which data was collected for Phase 2 was Hanging Lake Tunnel, which travels through Glenwood Canyon in Garfield County. Specifically, it is found at 39°35’16.75” N, 107°11’16.45” W. The tunnel travels in a slight, southward-trending crescent shape from west to east. In 1992, the tunnel was completed as a segment of a larger design for maximizing efficiency in the use of narrow space and was part of the final segment of I-70 through Glenwood Canyon. Hanging Lake Tunnel was built from the center of a daylight section, and consists of two bores and a ventilation and control building.

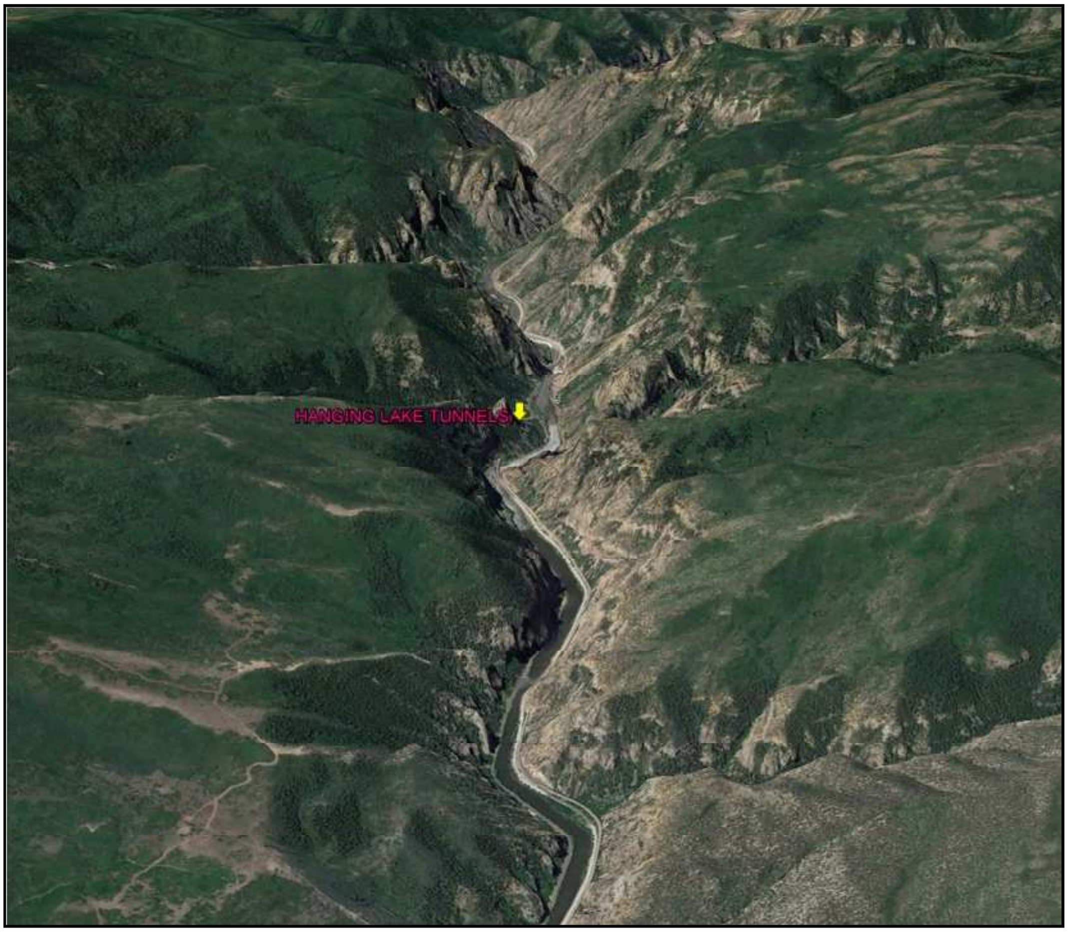

Figure 45: Hanging Lake Tunnel aerial

Each bore measures 4,000 feet long, with false ceilings and ceramic tile lining the walls. The structure located between the bores houses a five-story, state-of-the-art command center that monitors tunnels and miles of roadway around them. A known issue associated with the tunnel is the fact that it passes through several fault zones.

Figure 46: West portals of Hanging Lake Tunnel

On August 24, 2017, the weather was sunny with a high of 84°F in nearby Glenwood Springs. SAM field staff arrived at the Bair Ranch Rest Area, approximately 11 miles east of the tunnel, and coordinated their arrival at the tunnel with CDOT operations. The site of the rest area allowed for cell phone coverage and served as a good location to set up the GNSS reference base station.

At 9:00 p.m., SAM field staff entered the tunnel maintenance facility and were taken up to the operations level offices. They discussed their process with the CDOT staff working that shift, and everyone agreed to the safest and most efficient plan for all involved. Data collection would occur on the eastbound bore, followed by the westbound bore. Each pass would be initiated from the west end and completed by exiting at the east end. A chase truck would follow SAM's survey vehicle, and a second truck would be stationed outside the tunnel in a lane of traffic that would be shut down.

By the time SAM mobilized the equipment, the temperature had dropped to 66°F, where it held for the duration of the data collection. The left lane of the eastbound bore was already closed to through traffic from contractor work earlier in the day, and CDOT's trucks were already in position. The size of the chase truck limited its ability to easily make the turn at the east end of the tunnel, so only one-way passes were made. Data collection of the eastbound bore started at 10:26 p.m. and concluded at 11:26 p.m. at an average speed of 35 mph.

The westbound bore required a single lane closure initiated by the control room using the existing lane boards and lights leading up to, and within, the tunnel. After each pass of the survey vehicle, the operations room shut down the entire bore, allowing SAM and the chase truck to back up the entire length of the tunnel. Once the vehicles were out of the tunnel, the unused lane was released back to through traffic. Data collection of the westbound bore started at 12:05 a.m. and concluded at 12:57 a.m. Four passes were made at an average speed of 35 mph. Due to the late hour and length of time required to collect data, no significant traffic delays were created as a result of SAM's work.

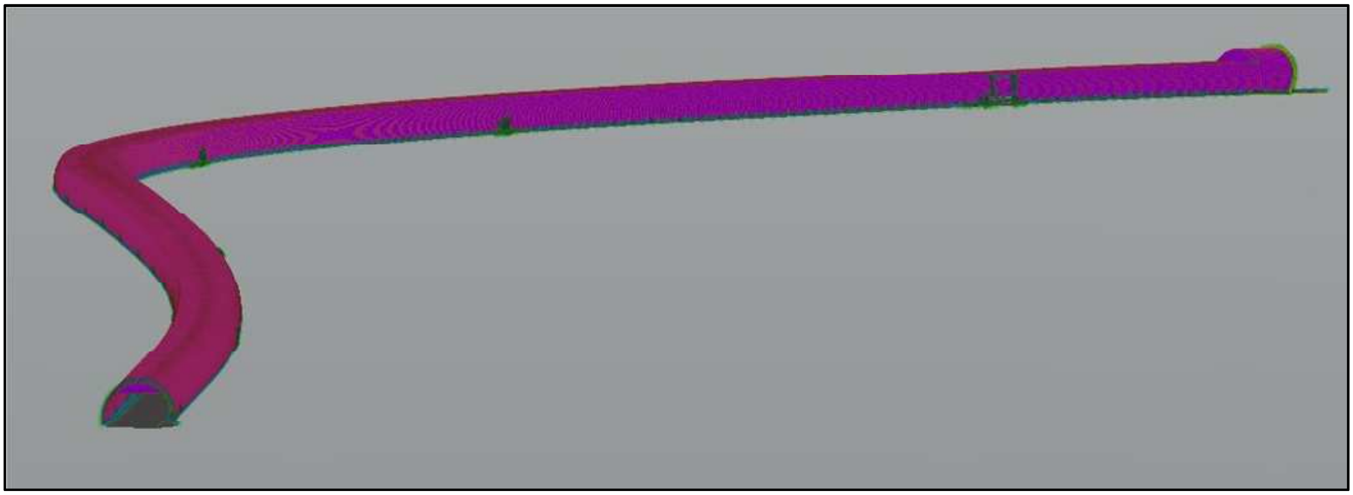

Figure 47: Hanging Lake Tunnels East Bound Bore Full Model

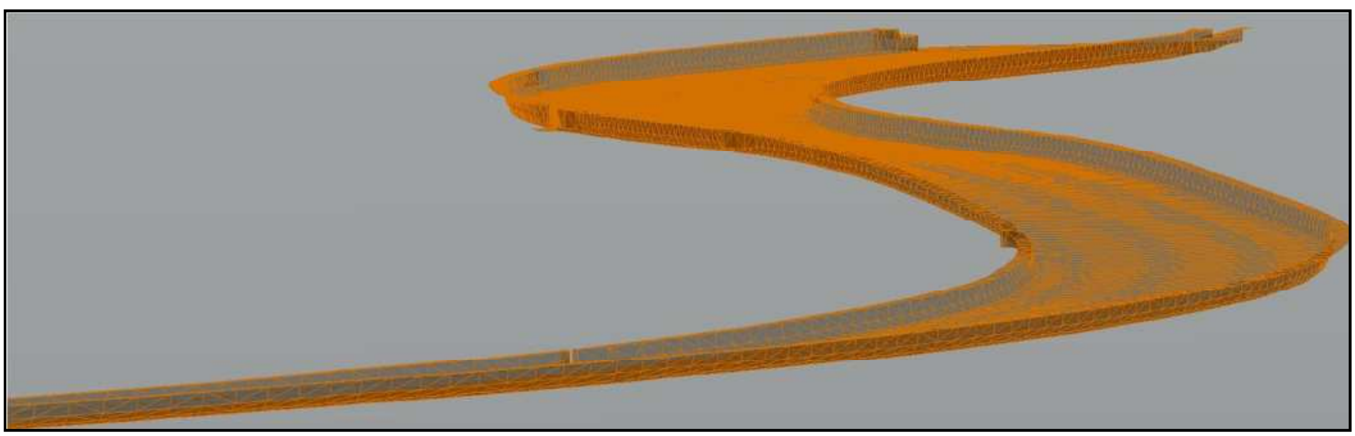

Figure 48: Hanging Lake Tunnels East Bound Bore Road Surface

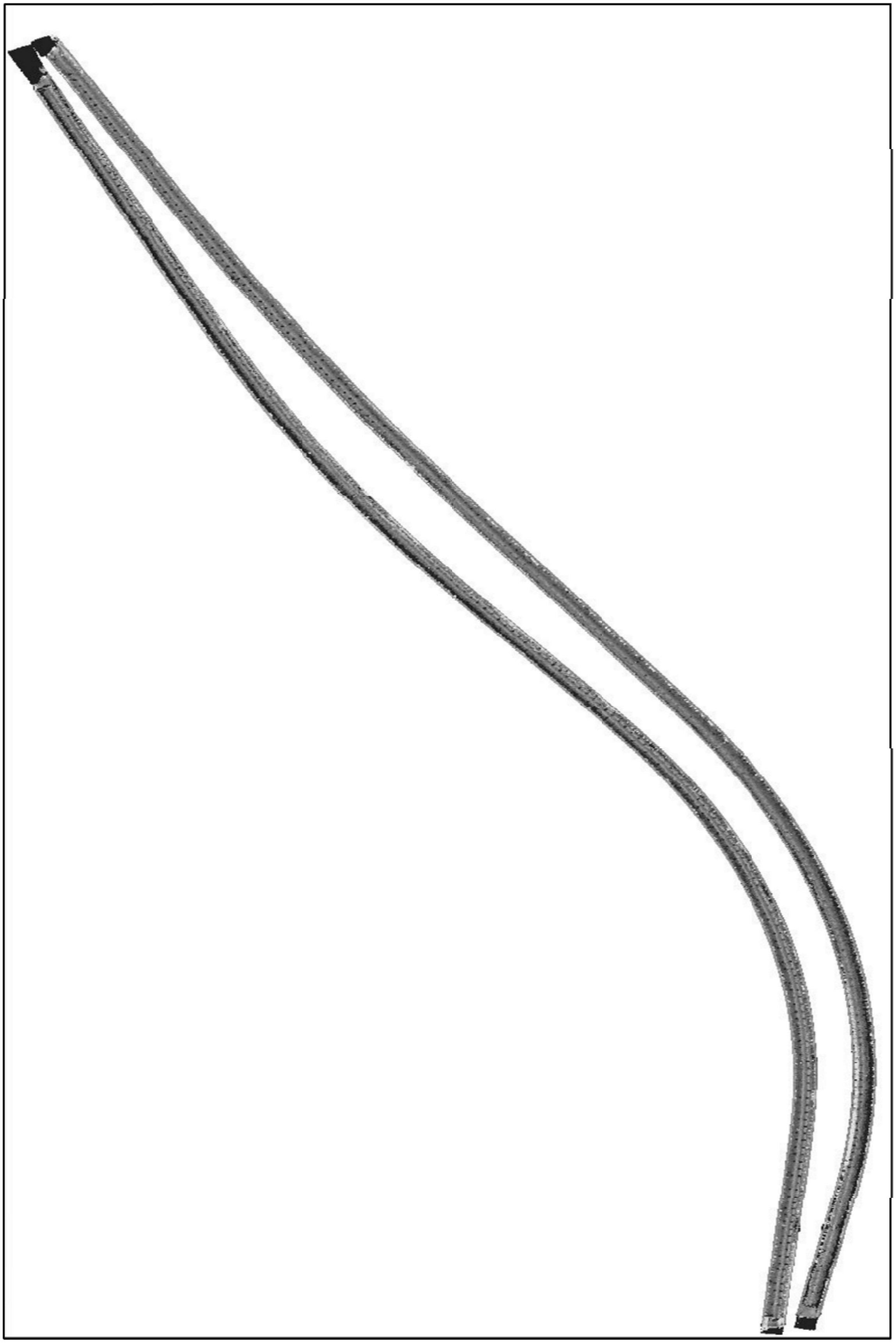

Figure 49: Hanging Lake Tunnels LIDAR Top View

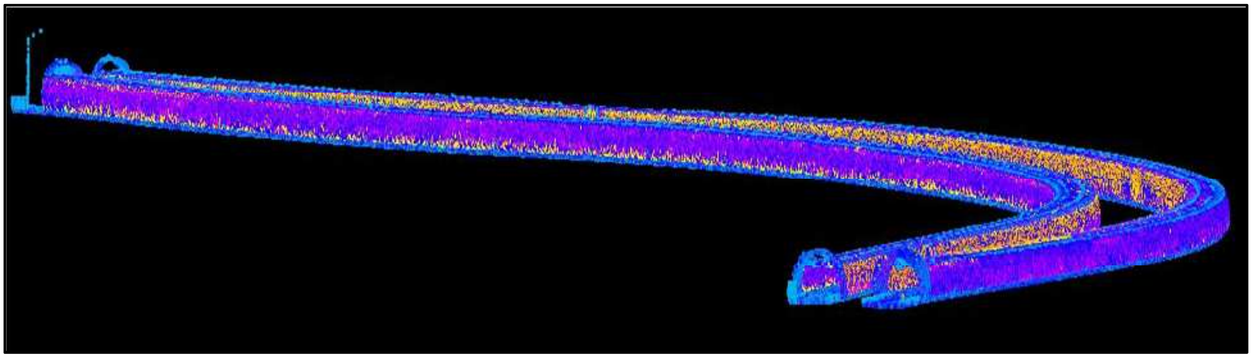

Figure 50: Hanging Lake Tunnels LIDAR Iso View

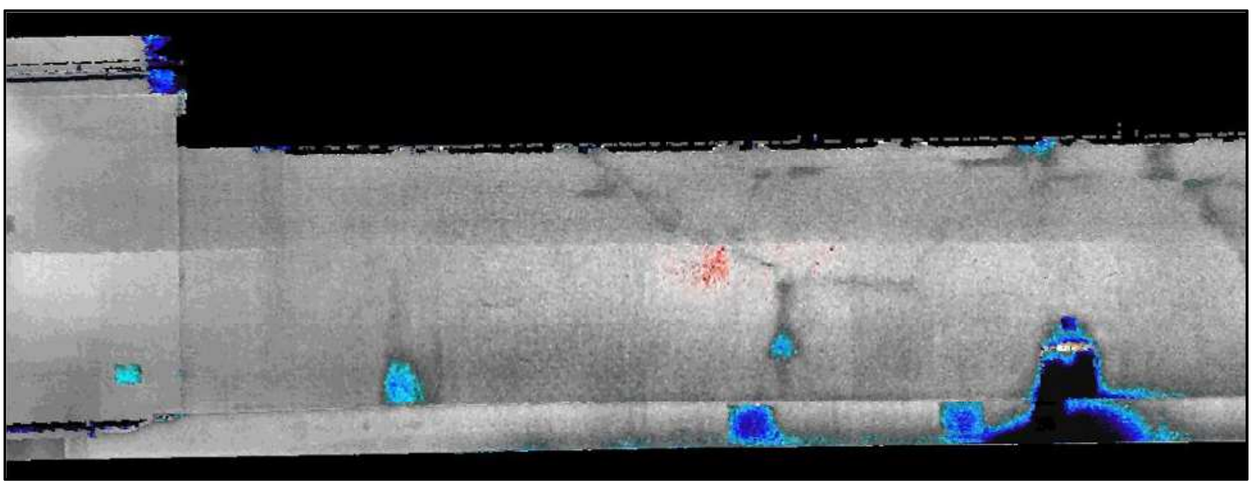

Figure 51: Hanging Lake Tunnels LIDAR Colorized by Thermal

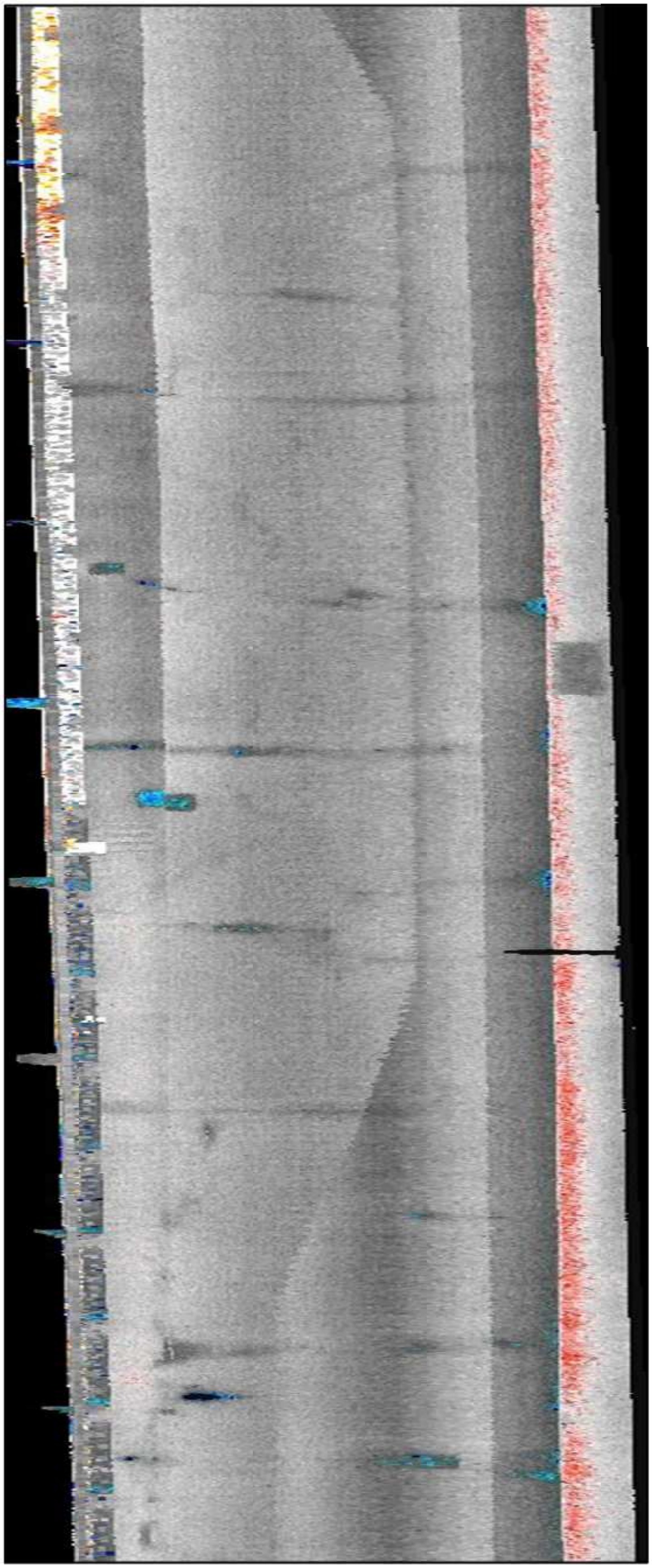

Figure 52: Hanging Lake Tunnels LIDAR Colorized by Thermal

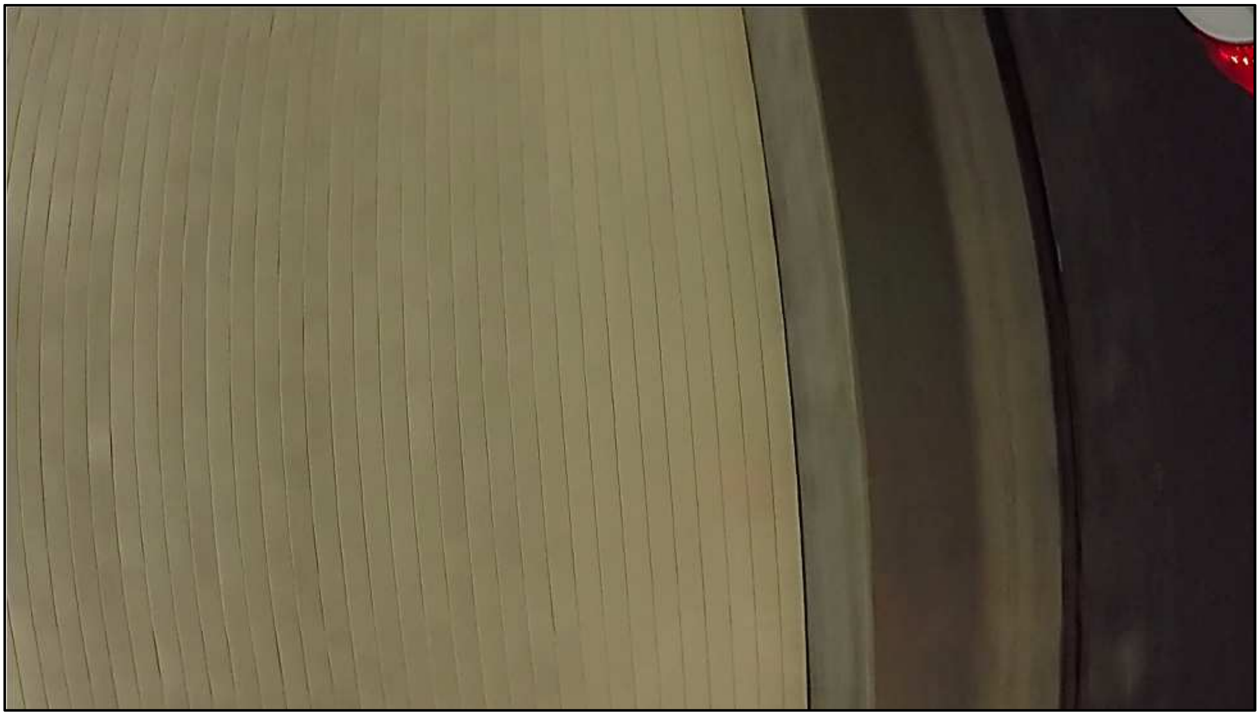

Figure 53: Hanging Lake Tunnels RGB

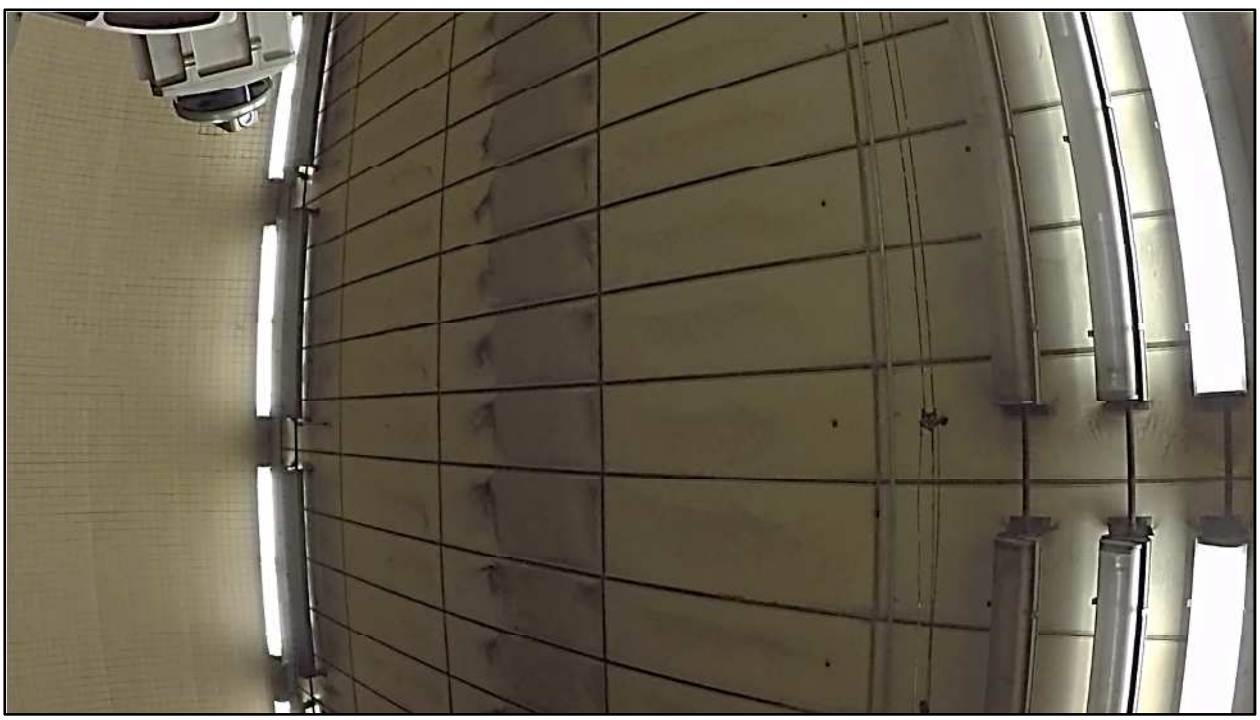

Figure 54: Hanging Lake Tunnels RGB

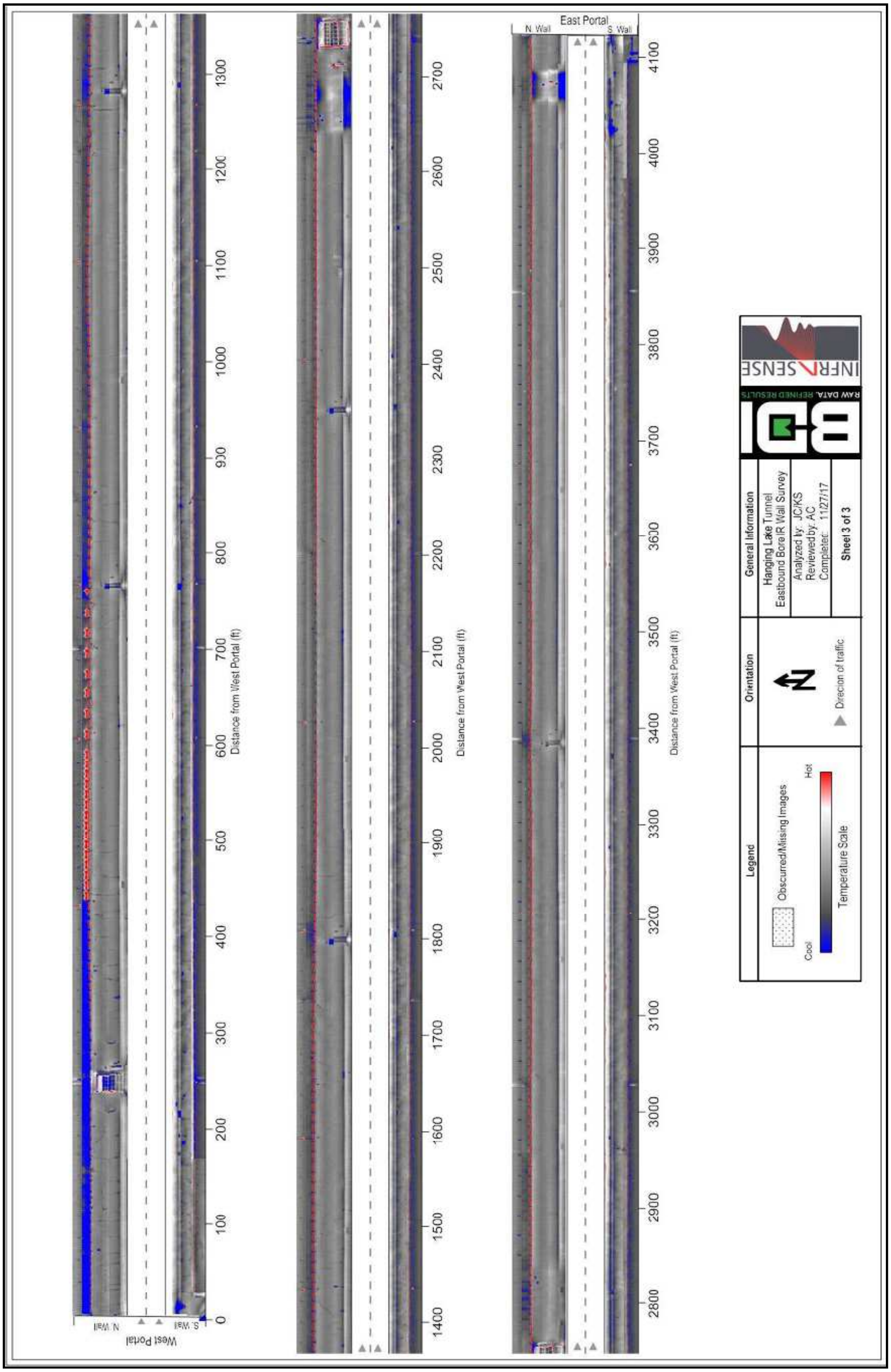

Figure 55: Infrared wall survey of Hanging Lake eastbound bore

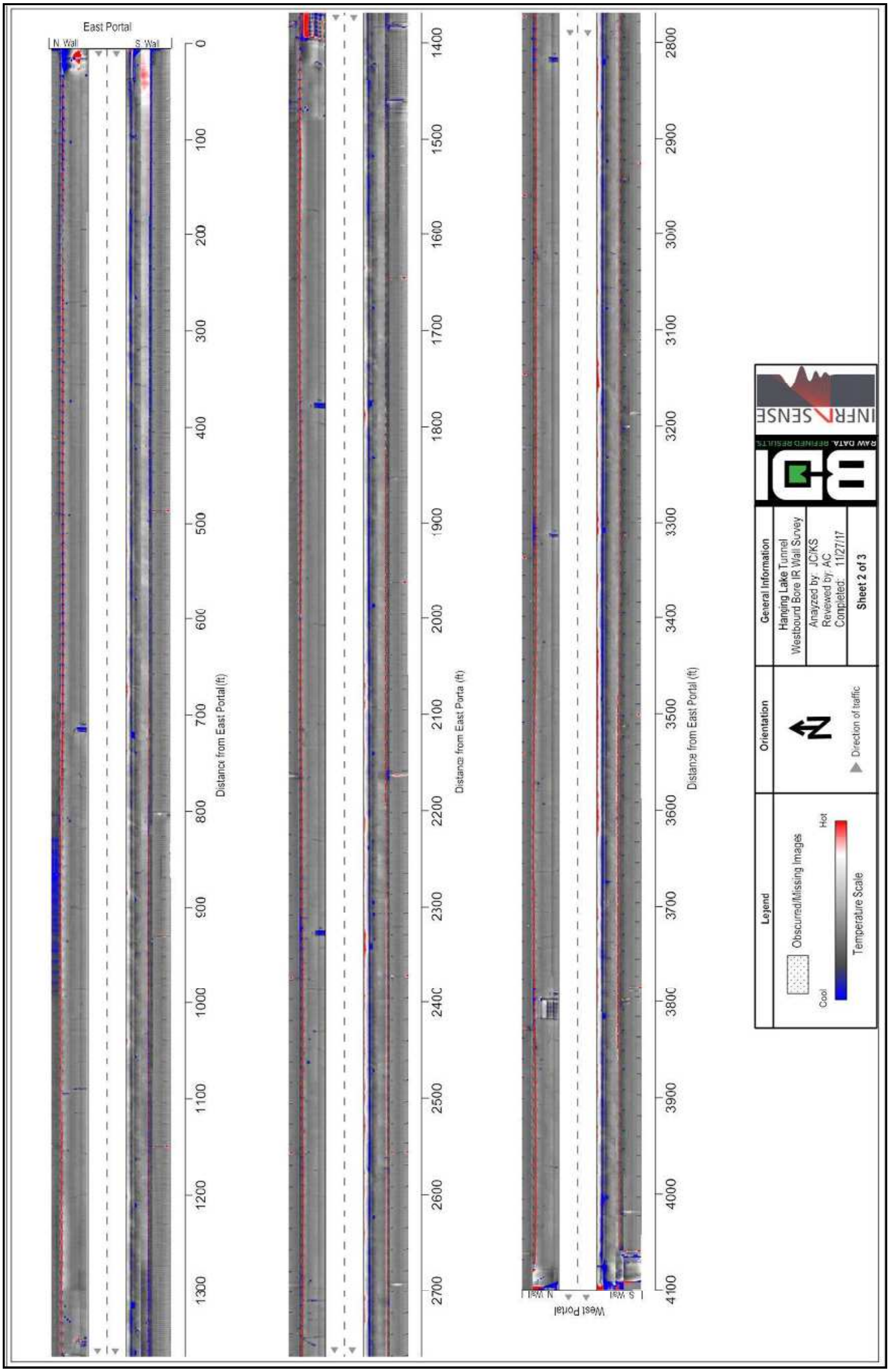

Figure 56: Infrared wall survey of Hanging Lake westbound bore

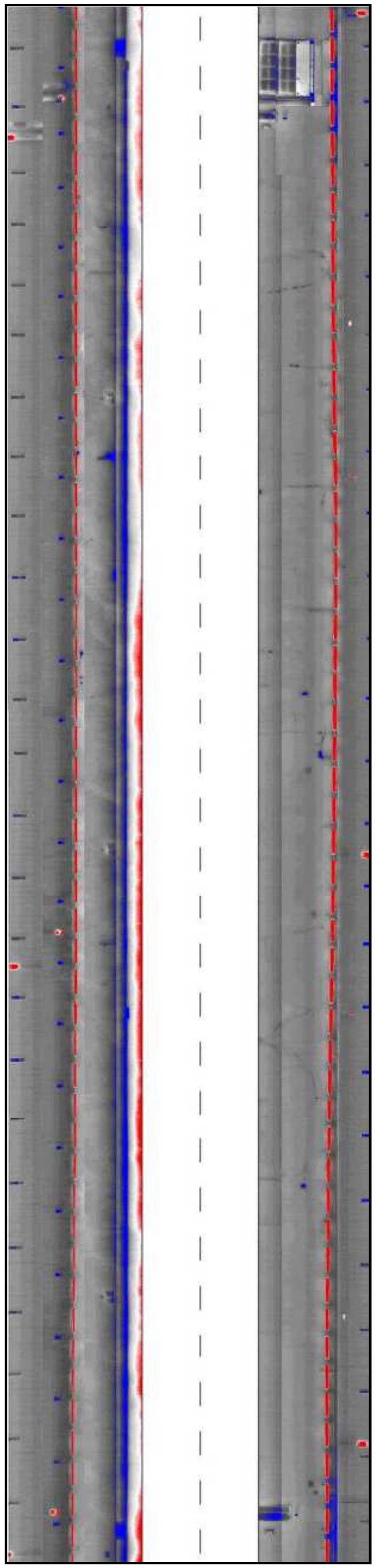

Figure 57: Closeup of Hanging Lake westbound bore

4.2.3 CLEAR CREEK TUNNELS 1, 2, 3, 5, 6

On August 29, 2017, imagery and data from the final five tunnels in Phase 2 were collected. All are located within Clear Creek Canyon on US 6, which is generally considered the scenic route to Black Hawk, Colorado and essentially parallels I-70 to the south. Additionally, it sees significant heavy truck traffic from the Albert Frei & Sons/Walstrum Quarry.

Figure 58: Clear Creek Tunnels 1, 2, 3, 5, 6 aerial

As with Clear Creek Tunnel 4 (Section 3.3), each of these tunnels were constructed by hard rock drilling and blasting then partially lined with concrete and shotcrete. Known issues associated with the tunnels include the fact that they are the oldest tunnels in CDOT's system. Repairs that have been made over the years reflect multiple generations of failures and damage. The tunnels pass through Precambrian shear zones and Laramide era faulting, and some isolated alteration may be present from the fringes of the nearby Idaho Springs-Central City mining district.

- **Tunnel 1**

  Tunnel 1 is located between mp 270 and mp 271 on US 6 in Jefferson County. Specifically, it is found at 39°44’46.88” N, 105°15’4.15” W, is 5,800 feet above sea level and is oriented generally north-south. The tunnel was completed in 1951 and measures 882.6 feet long.

- **Tunnel 2**

  Tunnel 2 is located between mp 265 and mp 266 on US 6 in Jefferson County. Specifically, it is found at 39°44’19.40” N, 105°19’13.35” W, is 6,485 feet above sea level and is oriented generally northwest-southeast. The tunnel was completed in 1941 and measures approximately 1,067.6 feet long.

- **Tunnel 3**

  Tunnel 3 is located between mp 264 and mp 265 on US 6 in Jefferson County. Specifically, it is found at 39°44’29.59” N, 105°19’38.46” W, is 6,540 feet above sea level and is oriented generally east-west. The tunnel was completed in 1957 and measures 768.8 feet long.

- **Tunnel 5**

  Tunnel 5 is located between mp 259 and mp 260 on US 6 in Clear Creek County. Specifically, it is found at 39°44’38.86” N, 105°24’21.81” W, is 7,000 feet above sea level and is oriented generally northeast-southwest. The tunnel was completed in 1939 and measures 411.1 feet long.

- **Tunnel 6**

  Tunnel 6 is located between mp 259 and mp 260 on US 6 in Clear Creek County. Specifically, it is found at 39°44’24.72” N, 105°24’46.46” W, is approximately 7,100 feet above sea level and is oriented generally east-west. The tunnel was completed in 1939 and measures 587.9 feet long.

On August 29, 2017, the weather was sunny with a high of 91°F in Golden, located nearby at the east end of Clear Creek Canyon. SAM arrived at the Mayhem Gulch Trailhead parking lot around 8:00 p.m. and set up the GNSS reference base station. The location was selected because it was roughly in the middle of all of the tunnels to be collected and in an area of the tight, narrow canyon with decent skyview, which would mean better GNSS positioning. Staging and equipment setup occurred at Tunnel 4, as it was permanently closed. No thermocouple data loggers were utilized for the tunnels.

US 6 increases in elevation as it travels west, so SAM began its collection at the westernmost tunnels, 5 and 6, and worked their way down to Tunnel 1. This would allow the tunnels at lower elevations with the warmest temperatures to cool down and aid in the gathering of accurate thermal imagery. The posted speed limit on US 6 through Clear Creek Canyon is 40 mph. SAM’s survey vehicle drove at the speed limit between tunnels, slowed down to 35 mph within the tunnels to collect data, then sped back up to 40 mph once out of the tunnels. Due to the speed and time period during which data was collected, SAM did not cause any delays to the traveling public.

Beginning at 9:12 p.m., the temperature was 69°F, and data was collected for Tunnels 5 and 6 as a pair in order to maximize efficiencies. Four passes were made, two in each direction. After Tunnels 5 and 6, SAM moved down to Tunnels 2 and 3, where the temperature was 65°F. Data was collected on the tunnels as a pair in order to maximize efficiencies. Four passes were made, two in each direction. Data collection was completed at 9:50 p.m. Finally, SAM drove down to Tunnel 1, where the temperature was 70°F, and collected data in four passes between 10:05 p.m. and 10:13 p.m.

Under this Task Order, SAM collected all of the Clear Creek tunnels but did not process any final deliverables, as those will be created under subsequent Task Orders.

4.3 DELIVERABLES

Data collected during Phase 2 was converted by SAM into the following deliverables to CDOT:

- Point cloud with intensity
- Point cloud with thermal mapped colors
- Contours of tunnel created every 2 feet
- TIN mesh of tunnel
- FLIR self-viewing files
- Flattened image of thermal tunnel surface
- RAW FLIR video on .mp4
- Corresponding RGB images for each thermal image

4.4 LESSONS LEARNED

Once improvements suggested after Phase 1 were implemented and data was collected during Phase 2, SAM noted the following:

- A tunnel's size and shape impacts the number of passes required to capture its entire area and it would be helpful to predefine those camera collection positions
- The area that can be captured in an image is restricted by camera angles and lenses, resulting in the need for more passes in smaller tunnels and having those camera positions predefined would help the flow of collection.

B. RGB cameras should capture images in RAW format so they are better quality and can be better manipulated later

C. A better exterior light solution with variable settings to adapt to each tunnel's lighting/surfaces should be used

- The use of LED lights on the survey vehicle initially resulted in uneven lighting on the tunnel surface in images.
- Beavertail Tunnel had no lights, and the bottom half of the walls were painted in a high-gloss white paint.
- Hanging Lake Tunnel had consistent white light, but low levels were subpar for image collection.
- Clear Creek Tunnels had consistent lighting with a yellow cast, so images were somewhat affected.

D. Use of HD thermal cameras is important

- The results were much better compared to non-HD thermal cameras (like those used in Phase 1); and
- The results support an increased cost in the camera from a coverage aspect and from a detail/quality of image aspect

E. Owning thermal cameras is crucial for reliability and scheduling

- SAM experienced issues with the FLIR thermal cameras not having specific calibrations for matching lenses. While at Beavertail, one camera dropped frames, so two additional, failed attempts were made to collect the missing information.
- Implementing the use of such high-end cameras with rare lenses made it difficult for SAM to schedule a time where they could rent both cameras. If either of them experienced problems, no other cameras were available to rent, and the project was delayed until repairs could be made.
- Without complete ownership of the equipment, there is a risk of not being able to acquire the same model for future jobs. The time and money invested in the design and fabrication of a custom mount on the survey vehicle would be wasted, as well as the investment in the man hours required to learn how to operate the equipment and utilize compatible software.

F. Thermocouple data loggers are necessary for large tunnels or tunnels located in areas where the environment is unfamiliar to the data collector

- The first few days that temperatures were logged in Beavertail Tunnel, there was a minimal swing due to a snowstorm holding temperatures more or less consistent the entire time. SAM evaluated whether it was better to leave the thermocouple data loggers in a tunnel for a shorter amount of time and collect data at shorter intervals (i.e., every five minutes for one week) or leave them in a tunnel for an extended period of time and collect data with longer intervals in between readings (i.e., every 15 minutes for two weeks). They determined that the loggers should record temperatures through a variety of weather patterns, which could be a few days or a few weeks.
- If a tunnel has smaller swings in temperatures, or a less sensitive camera is being used, if might be beneficial to reinstall loggers for the collect. This would give a better picture of the thermal conditions of the tunnel linings with which to compare and scale the thermal data.
- Reinstalling the loggers would require lane closures and more time in the tunnels to ensure staff safety, so it should be avoided if possible.

G. Air flow/use of fans/piston effect

- The piston effect of moving traffic was stronger than the draft created by fans
- From the entrances to the halfway point of tunnels the wind speed was

increased by the fans but varied greatly with traffic flow, suggesting the added pull was insignificant.

5.0 PHASE 3 (THIRD TASK ORDER)

Phase 3 included processing, and delivery, of data acquired for Clear Creek Tunnels 1, 2, 3, 5 and 6 in Clear Creek and Jefferson Counties. The only notable variation in post processing procedures in Task Order 3 vs Task Order 2 was the subcontractor used to normalize and stitch exported thermography frames.

5.1 DELIVERABLES

Data collected during Phase 2 was converted by SAM into the following deliverables to CDOT:

- LiDAR with intensity values
- LiDAR colorized by corresponding normalized thermal metadata
- Contours of tunnel created every 2 feet
- Mesh of tunnel liner surface and roadway
- FLIR self-viewing files
- Flattened high resolution normalized thermal tunnel liner PDFs
- RAW FLIR video in .mp4
- Normalized thermal image frames

5.2 LESSONS LEARNED

- Post analysis and normalization of thermography data is key to realize the value of the scientific grade thermal sensor.
- The data collected in Phase 2, and processed in Phase 3, showed deficiencies that correlated to areas of interest in Tunnel 5 between time of acquisition and review of rectified data. The flagged area of shotcrete tunnel liner later released, falling to the roadway below.

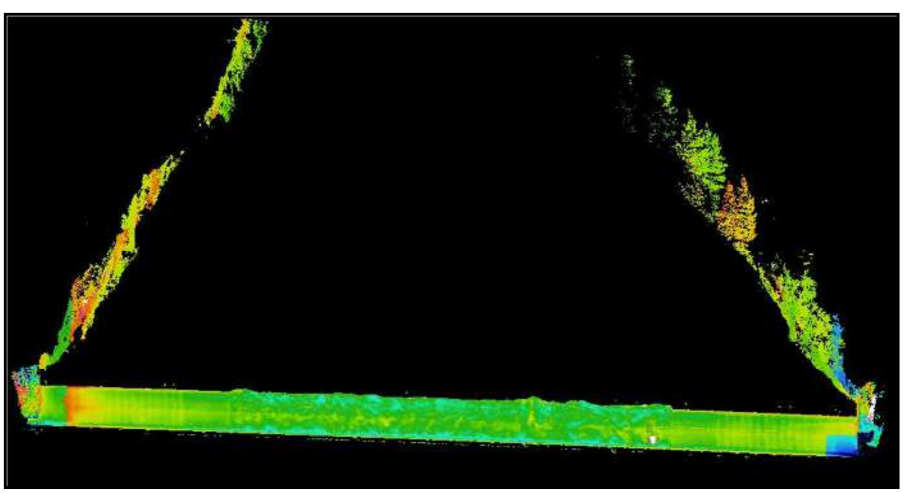

Figure 59: Clear Creek Tunnel 5 LIDAR Cross Section with Overburden

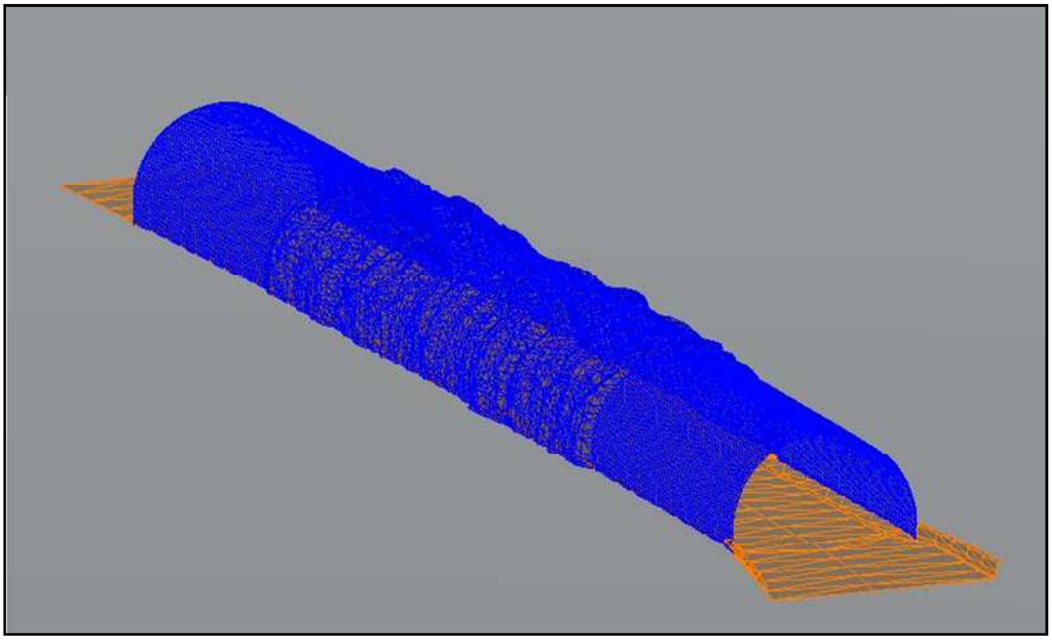

Figure 60: Clear Creek Tunnel 5 Full Model

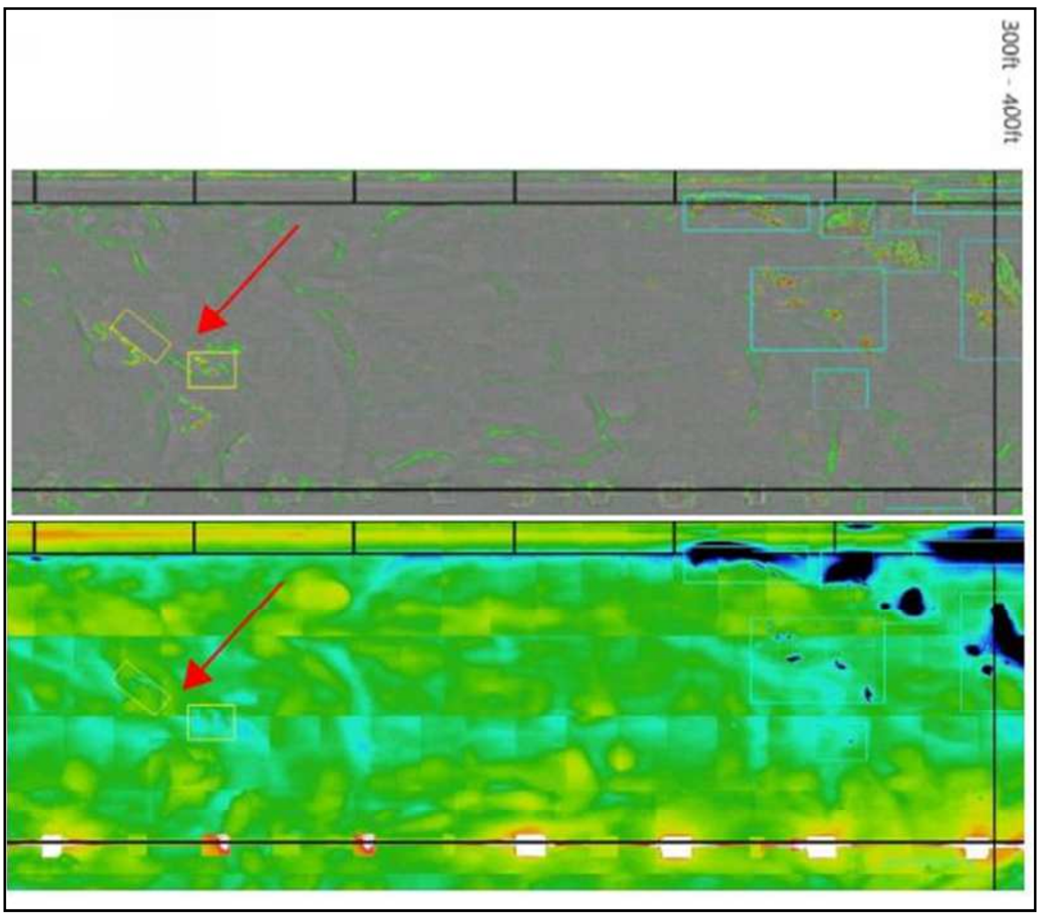

Figure 61: Clear Creek Tunnel 5 Thermal Area of Interest

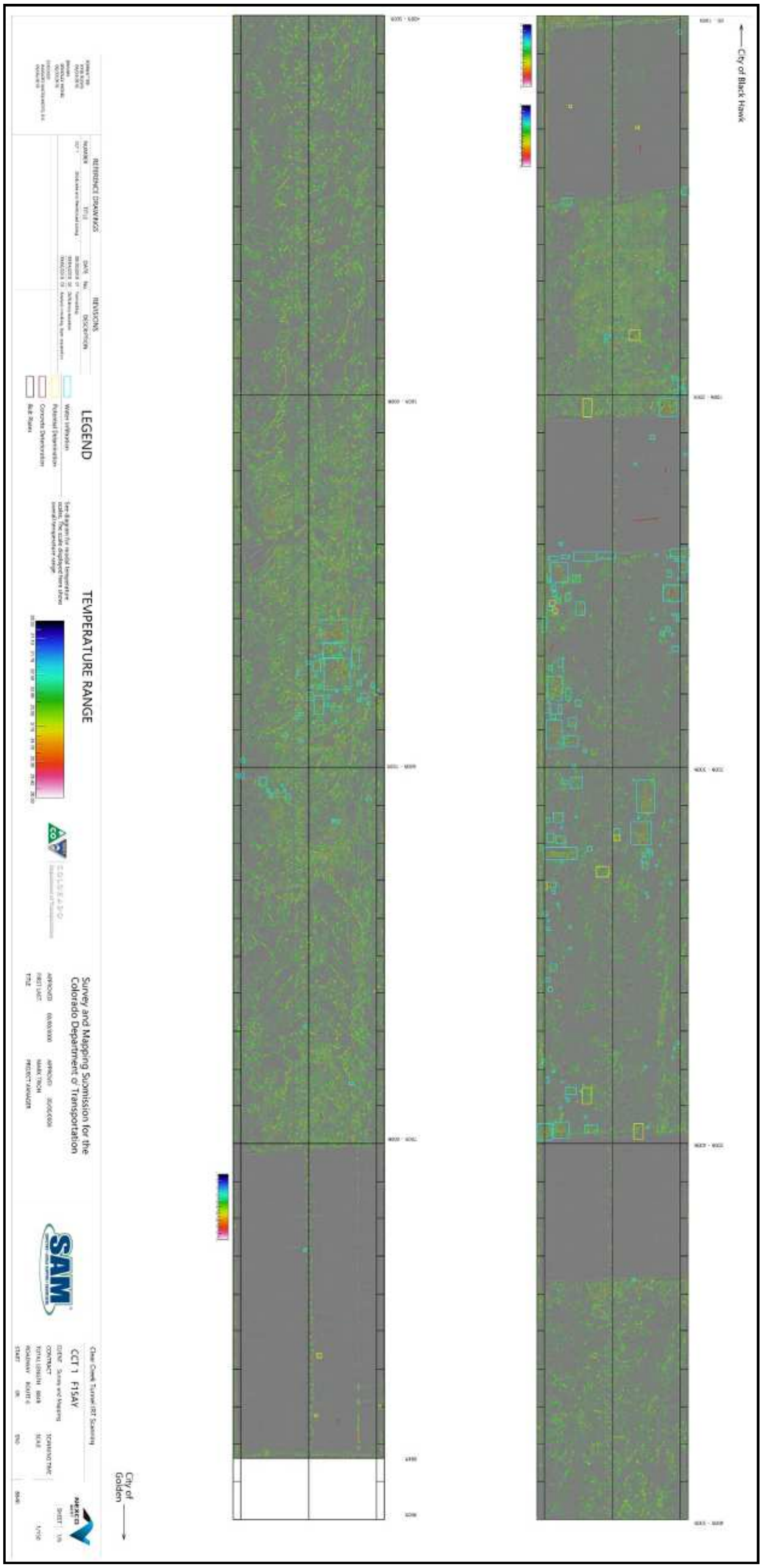

Figure 62: Tunnel 1 Auto Detection

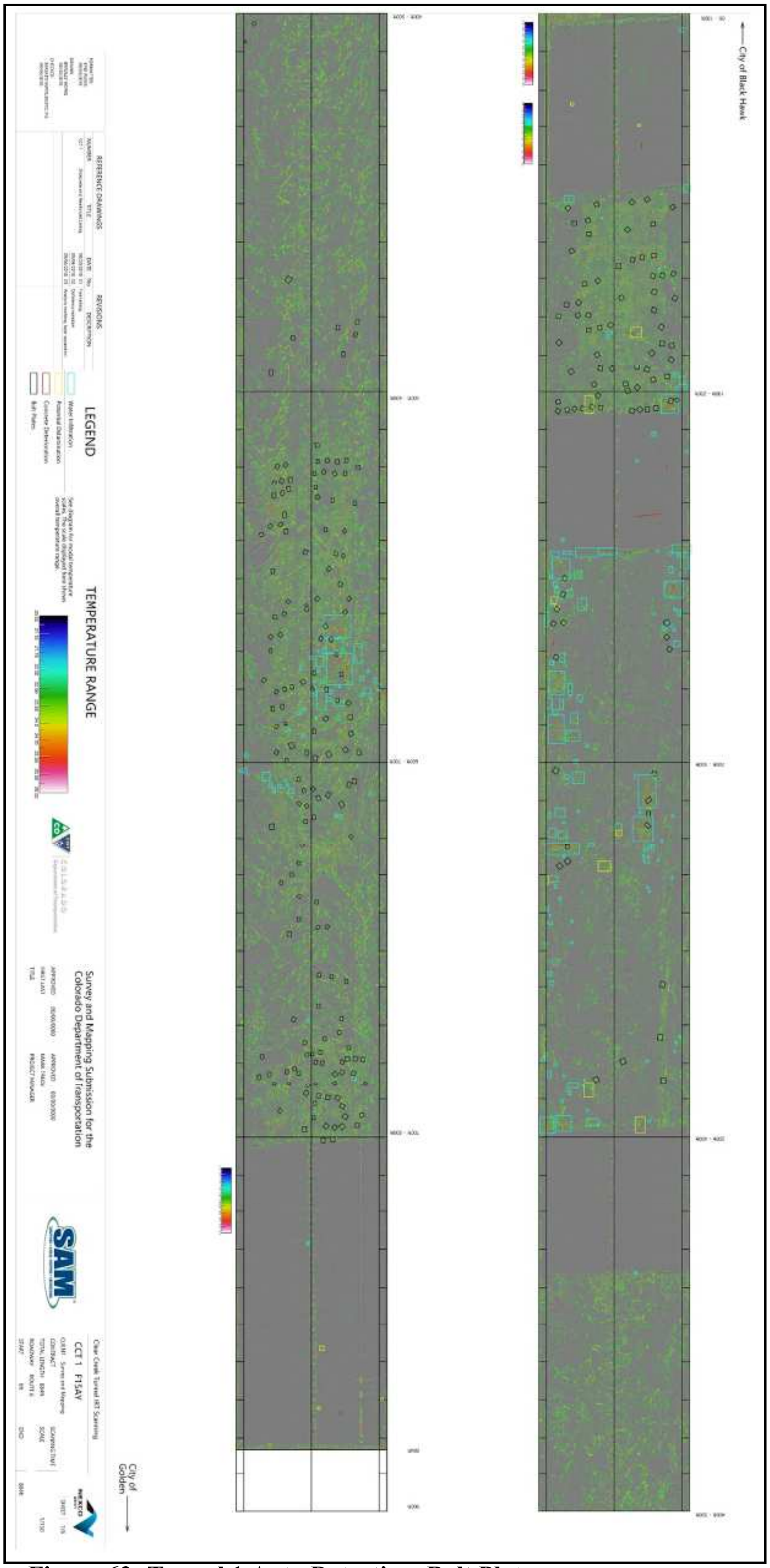

Figure 63: Tunnel 1 Auto Detection, Bolt Plates

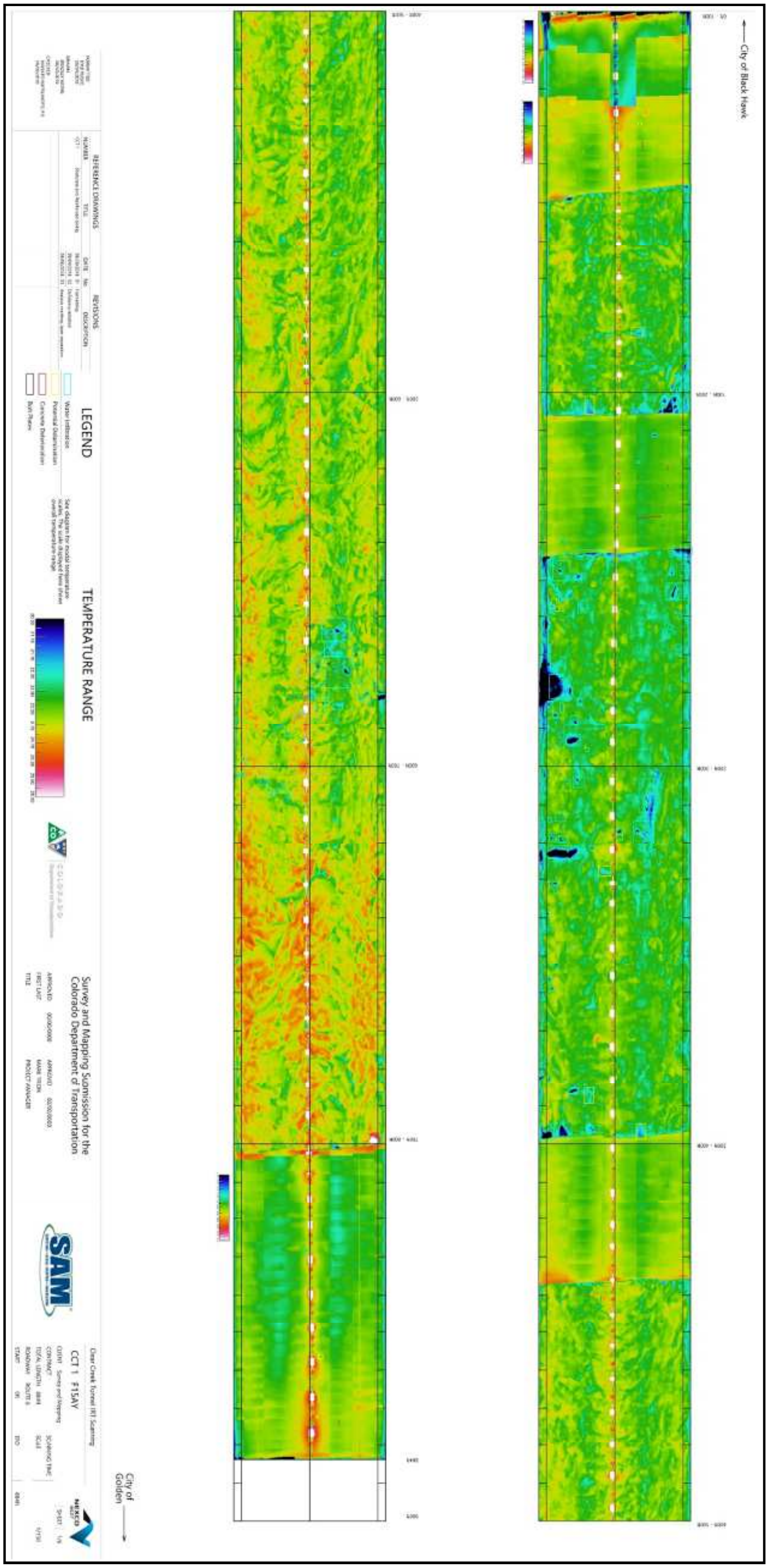

Figure 64: Tunnel 1 Infrared

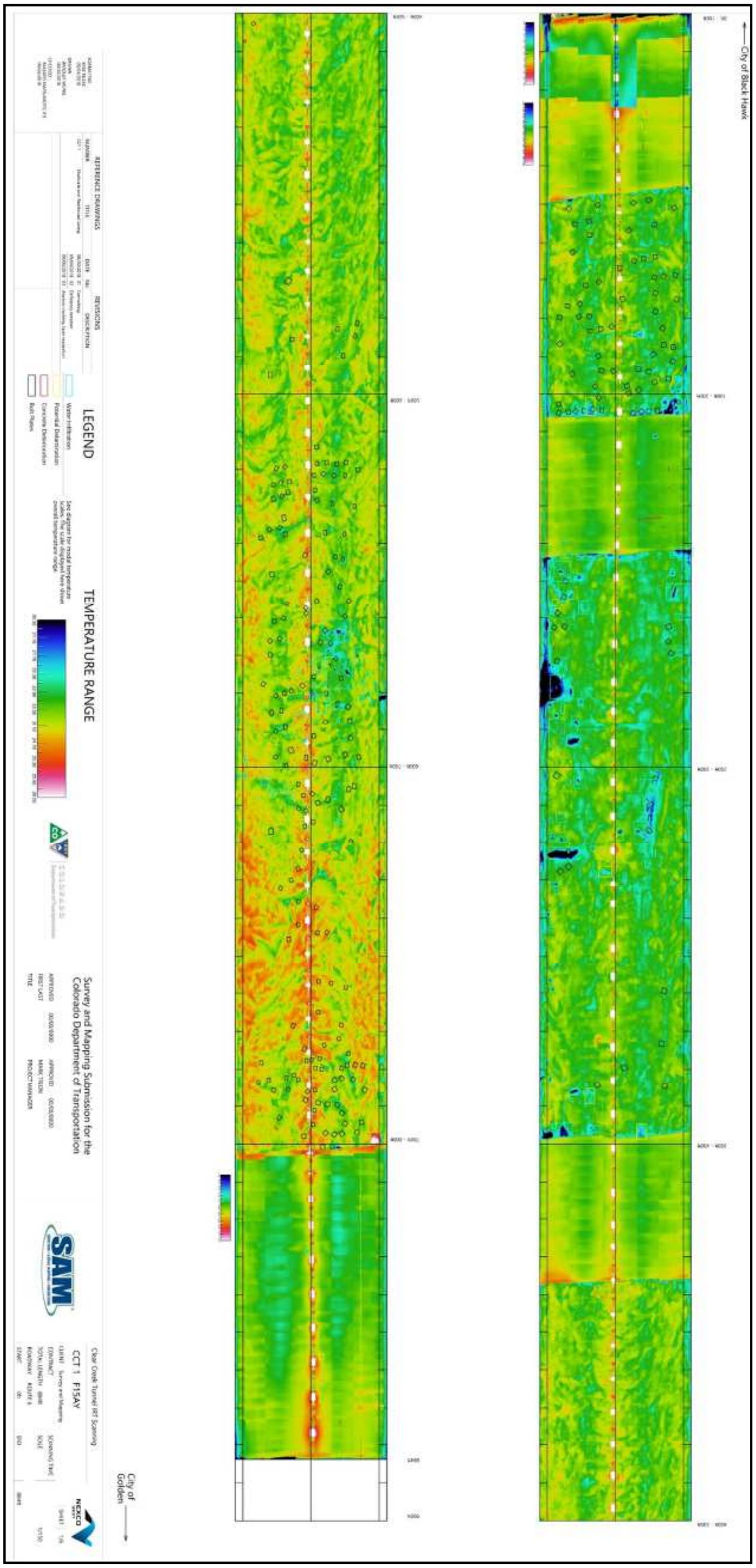

Figure 65: Tunnel 1 Infrared, Bolt Plates

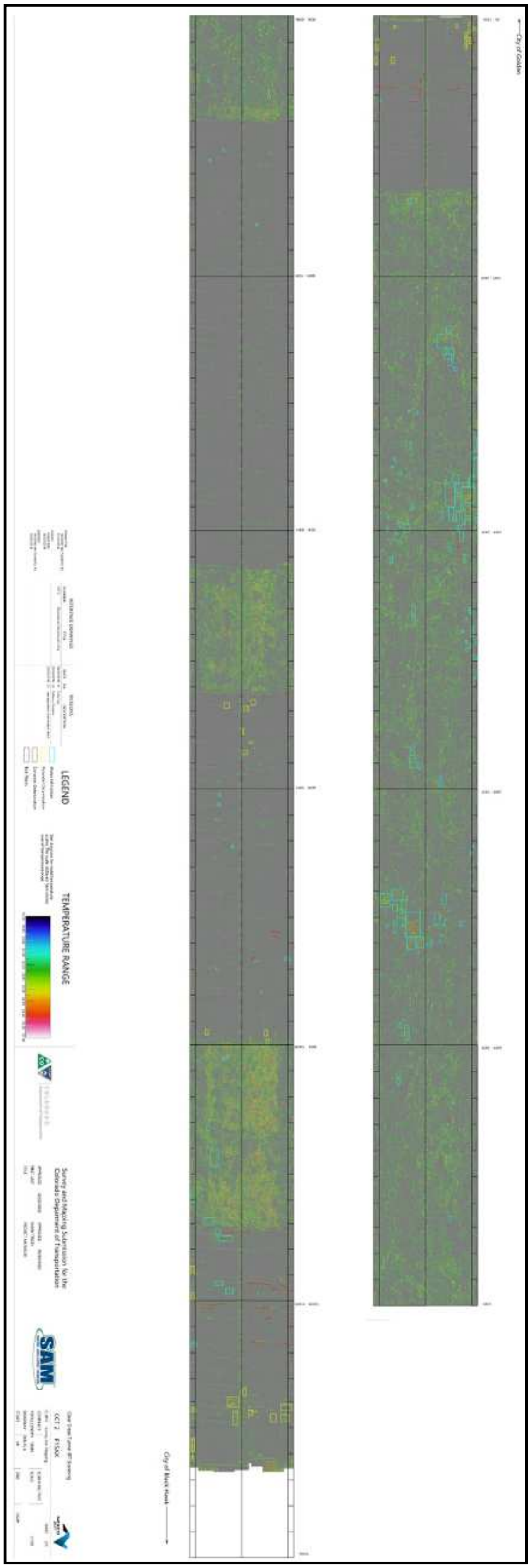

Figure 66: Tunnel 2 Auto Detection

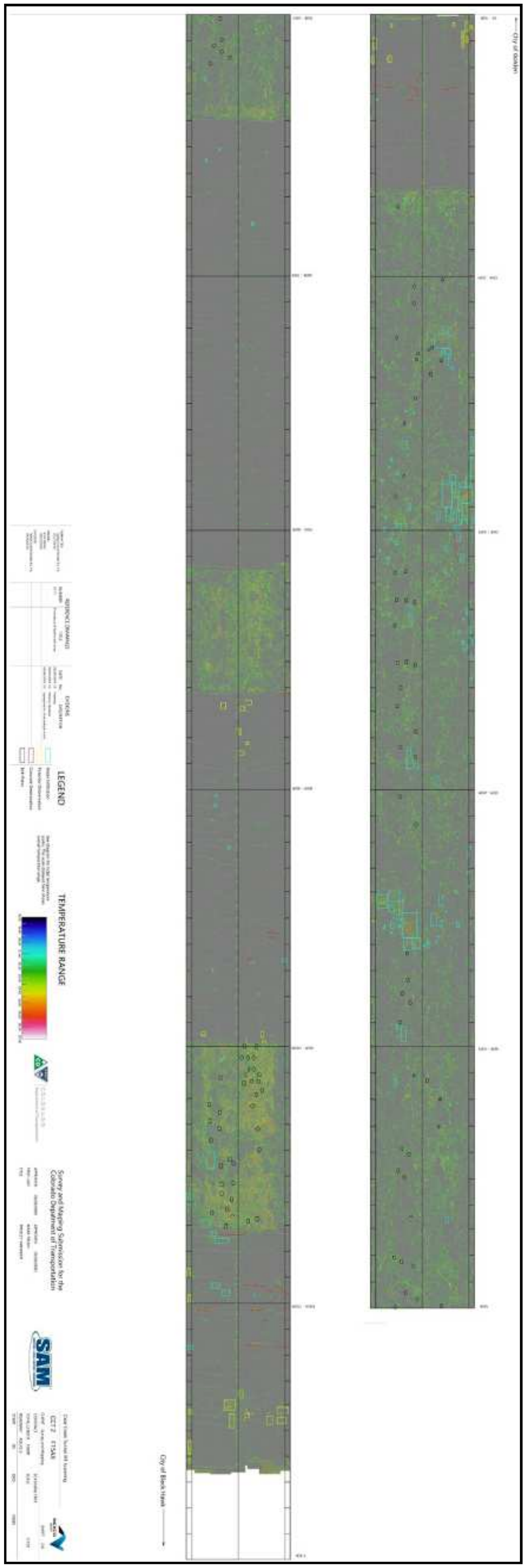

Figure 67: Tunnel 2 Auto Detection, Bolt Plates

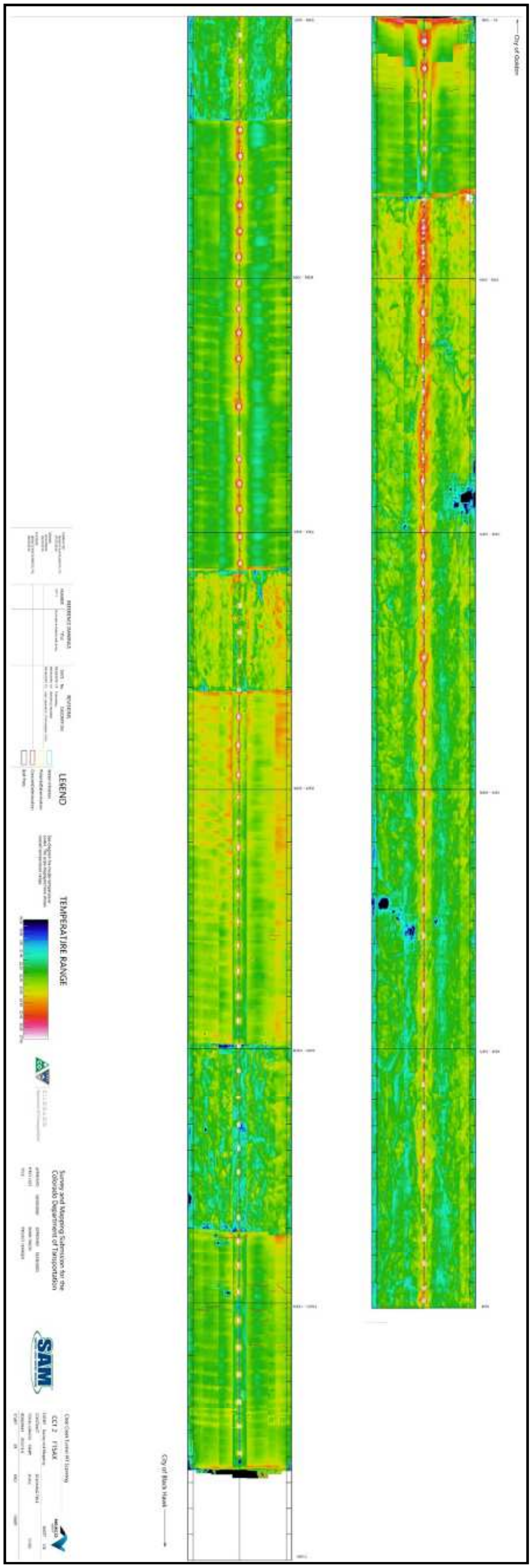

Figure 68: Tunnel 2 Infrared

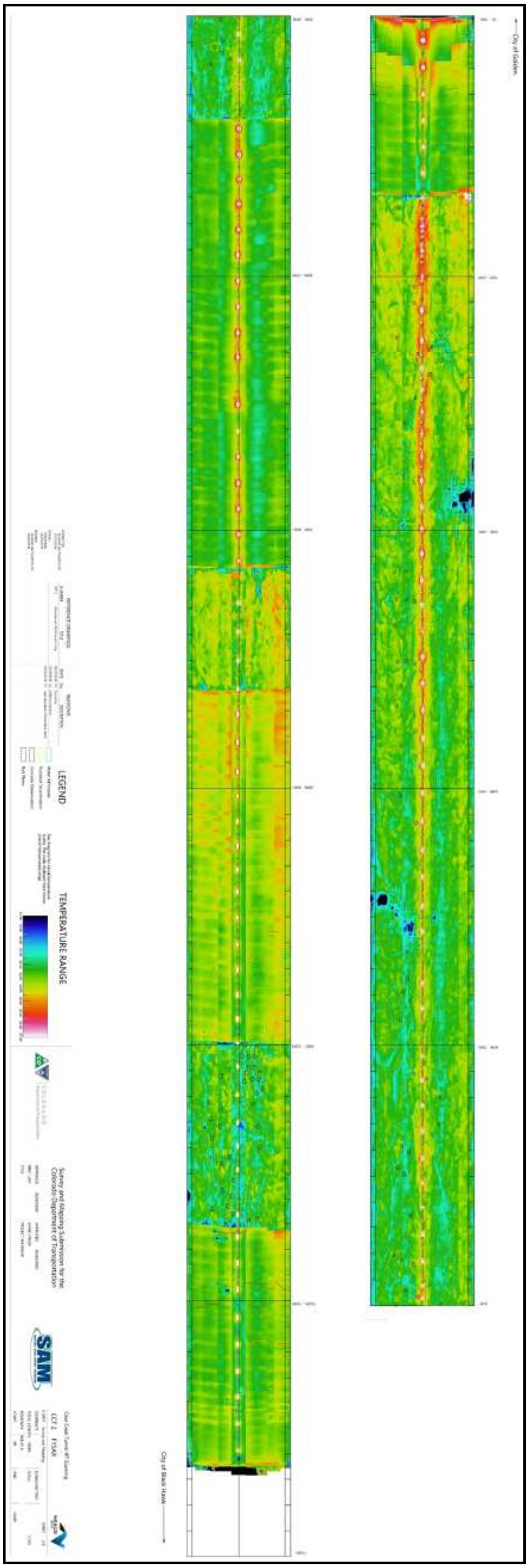

Figure 69: Tunnel 2 Infrared, Bolt Plates

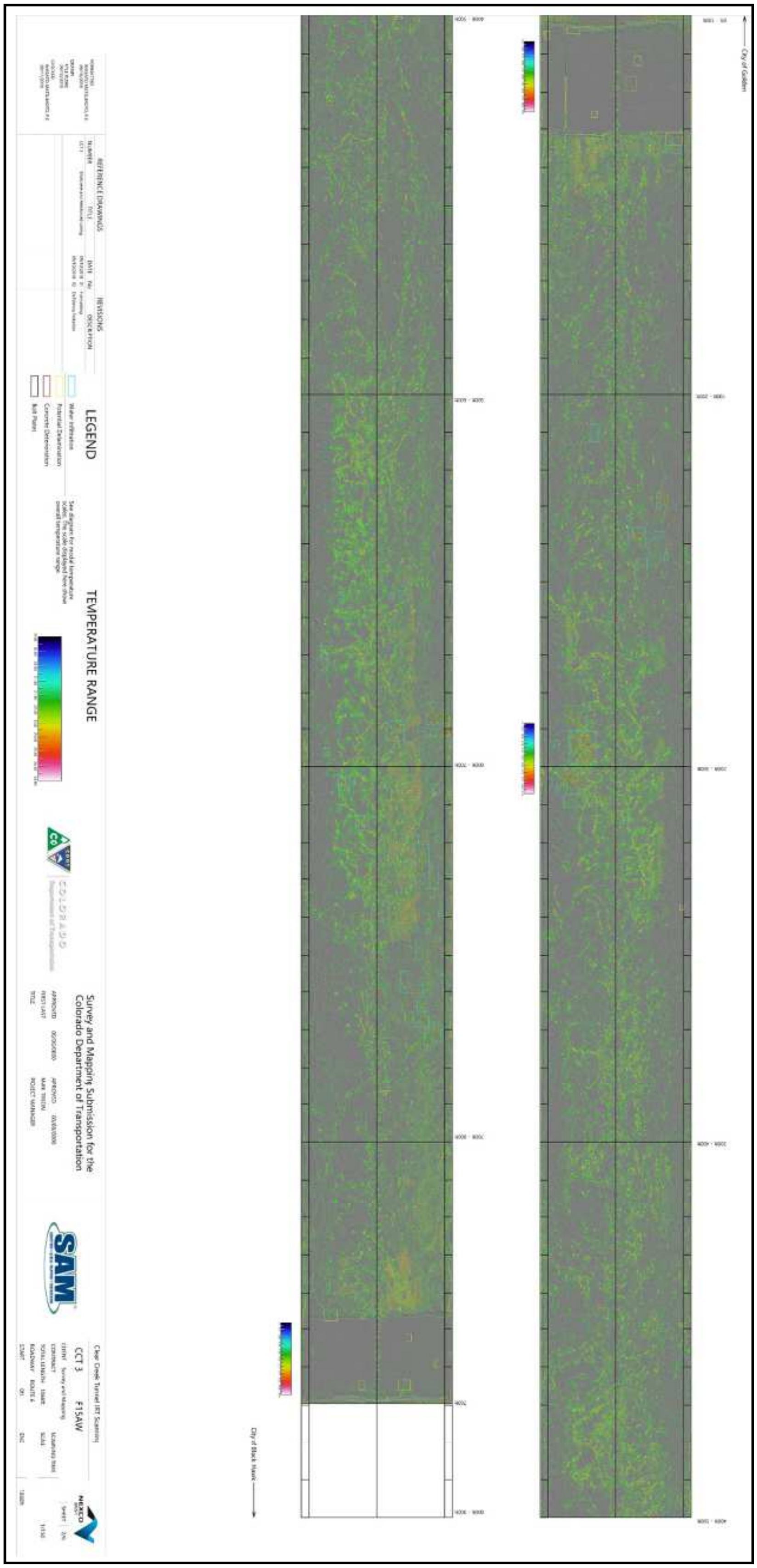

Figure 70: Tunnel 3 Auto Detection

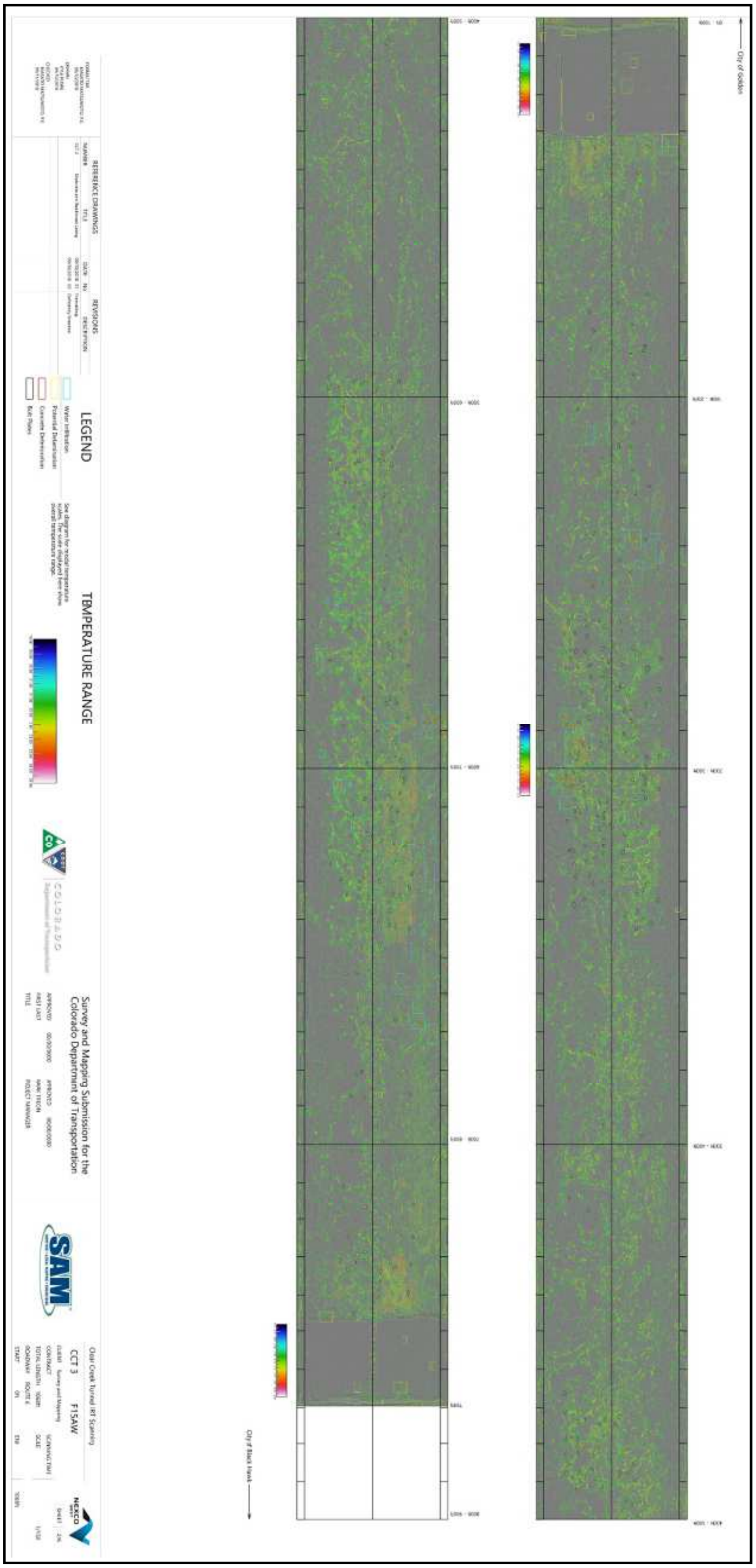

Figure 71: Tunnel 3 Auto Detection, Bolt Plates

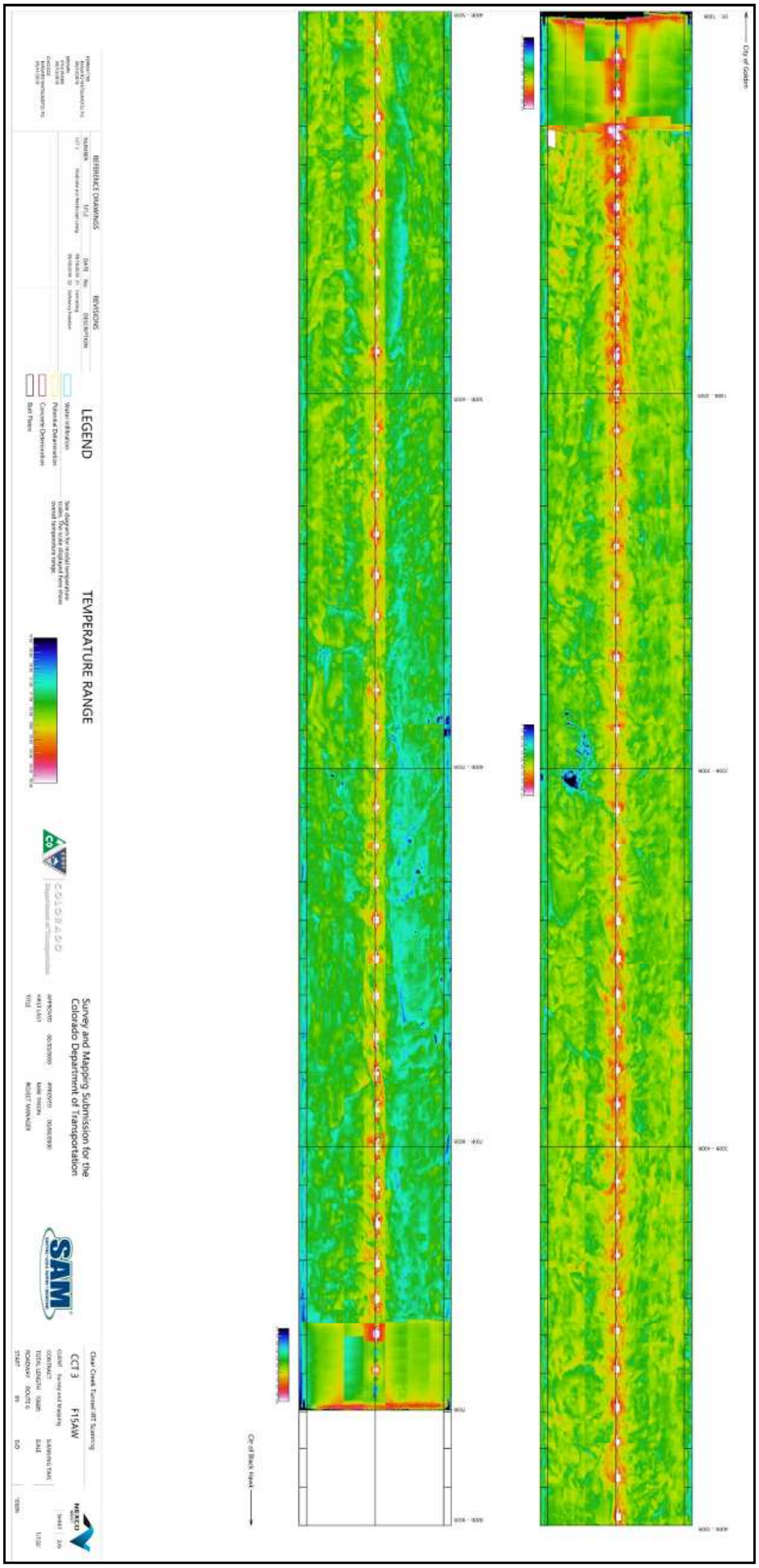

Figure 72: Tunnel 3 Infrared

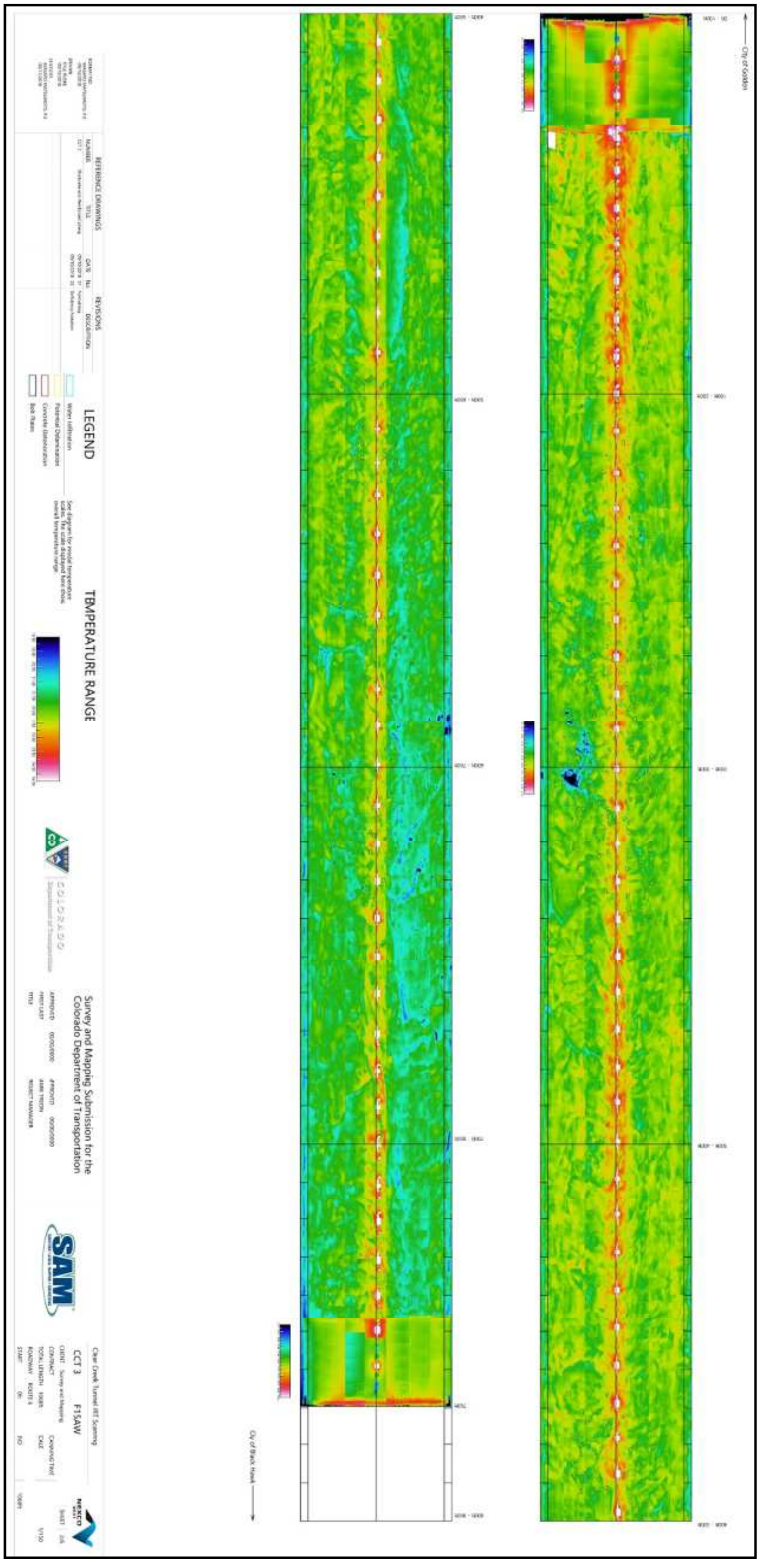

Figure 73: Tunnel 3 Infrared, Bolt Plates

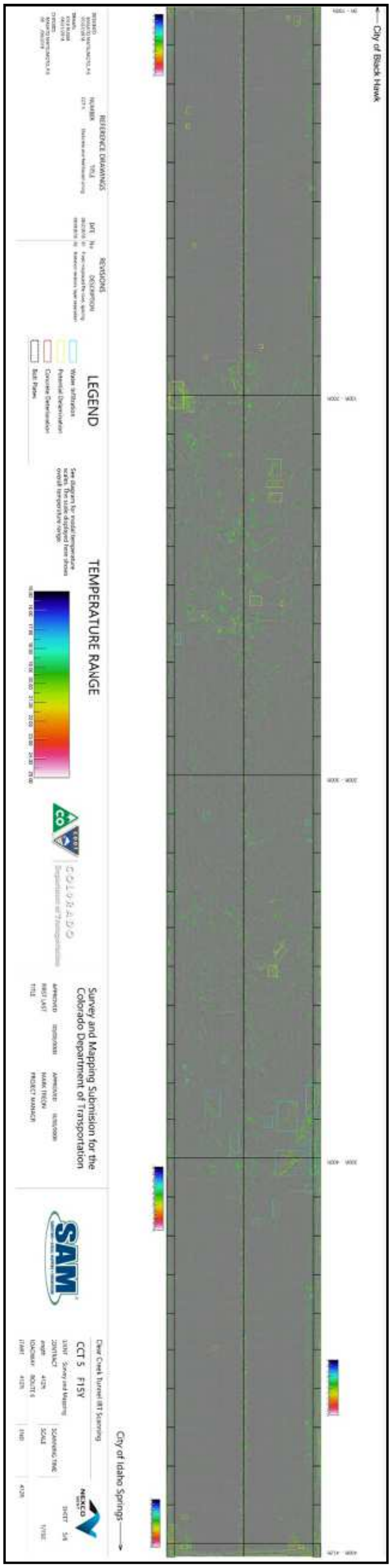

Figure 74: Tunnel 5 Auto Detection

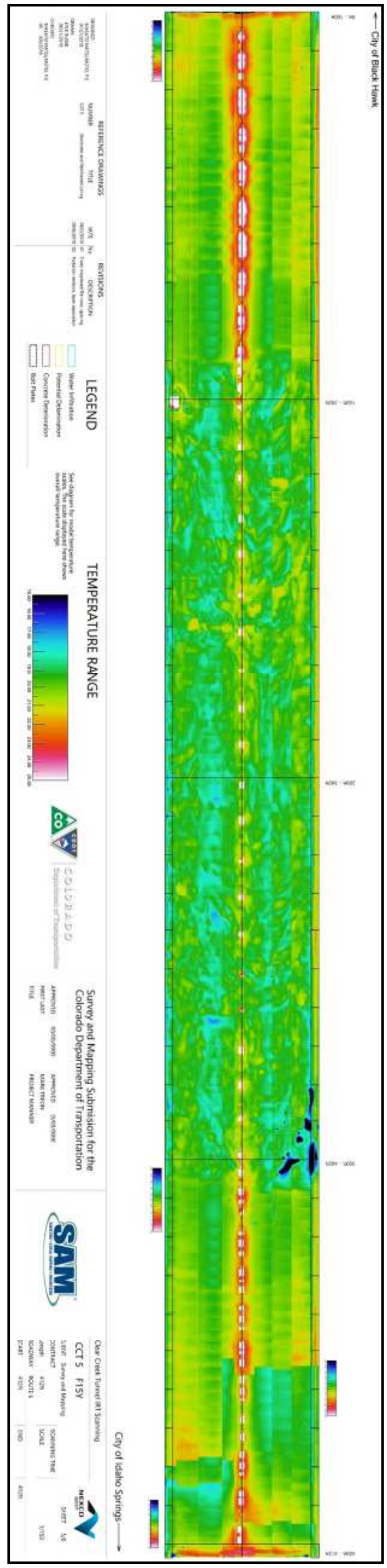

Figure 75: Tunnel 5 Infrared

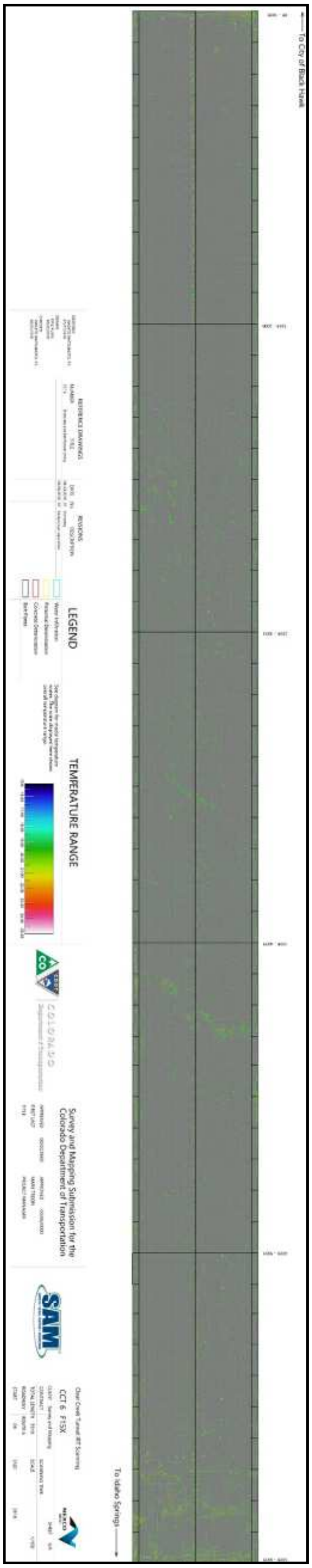

Figure 76: Tunnel 6 Auto Detection

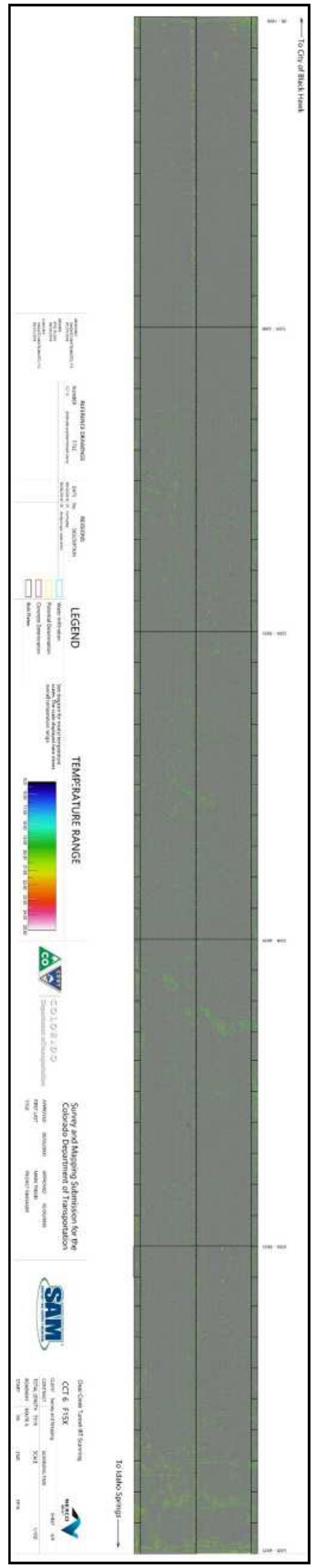

Figure 77: Tunnel 6 Auto Detection, Bolt Plates

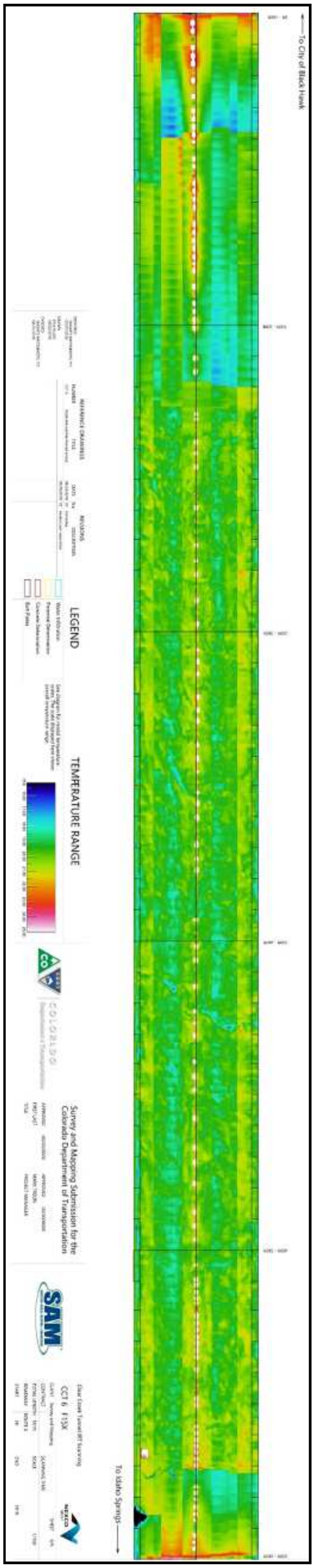

Figure 78: Tunnel 6 Infrared

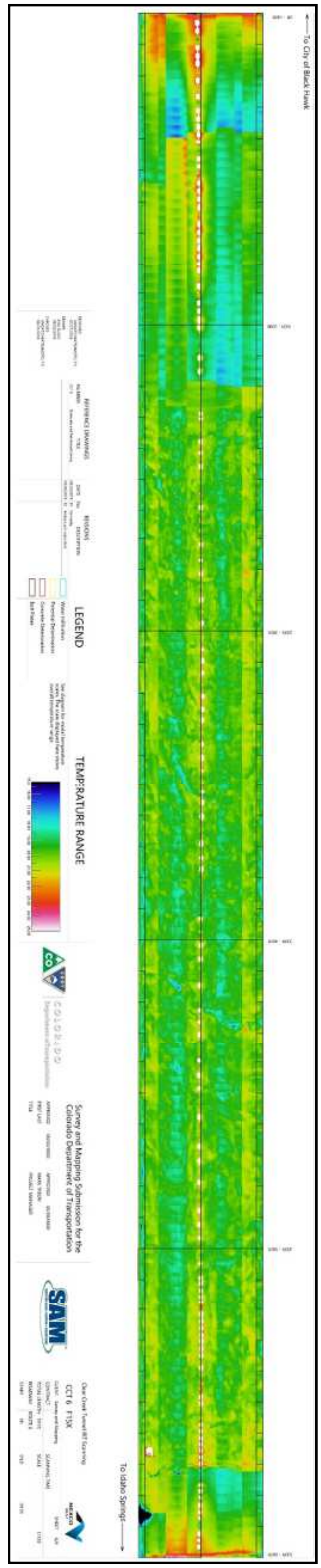

Figure 79: Tunnel 6 Infrared, Bolt Plates

6.0 CONCLUSION
6.1 INSIGHTS

After completion of both phases, making corrections between them, and working through a variety of tunnels with differing factors, SAM gained a better understanding of the process as a whole and the potential for the uses and applications of NDT for tunnel monitoring and noted the following:

- Thermal cameras were beneficial, but they should be scientific grade and cooled. Optimal results came from those that were HD. The use of multiple cameras provided the best information and limited the number of passes needed to collect a complete set of data within each tunnel. Using a lens with a wider field of view also limited the number of passes, but it is important to avoid distortion ("fish eye").
- Limiting the number of passes reduces time spent in a tunnel and impacts to the traveling public, creates cleaner results, and saves processing time.
- LIDAR is a necessary component, but it should be survey-grade. It is most beneficial when accurately and reliably paired with thermal and RGB data.
- It is helpful to gather RGB images, but a camera of higher quality than a GoPro should be used for improved post-processing of the images.
- With such specific information from the data collection, location markers along the tunnel walls would be helpful in identifying problem areas, rather than having to rely on a measuring wheel or visual inspection to revisit an issue on foot.
- Once the data is collected and processed, it can assist with tunnel maintenance from a planning and budgeting perspective. Additionally, the information can be used for conditions monitoring and improvements forecasting from an engineering standpoint.
- After a few data sets have been collected from a tunnel, other data can be associated into the overall equation, creating a more complete narrative of the tunnel. This could include environmental or geological information (effects of freeze-thaw cycles, permeation of snow and rain), traffic loads, and the effects from specific incidents or events. This would possibly allow for even more in-depth analysis to aid in future planning and design considerations of existing and new assets.

6.2 BENEFITS

A. Although it would not be necessary to hire a firm that specializes in this type of data collection, because of SAM's extensive experience and knowledge of both survey work and DOT procedures, the company was ready to engage in the exploration of NDT methods. The controls they already had in place to ensure accurate measurements, positioning, and calculations transferred easily to the technologies and equipment added to develop the approaches outlined in Phases 1 and 2. The data and images gathered, including the spatial components, were readily imported into programs with which SAM is familiar. Additionally, SAM was readily capable of providing data in file formats already in use by CDOT.

B. SAM identified a number of benefits related to these technologies based on field experience during Phases 1 and 2, as well as from collected data that continues to be interpreted. A workflow was developed from beginning to end for acquiring tunnel data without completely shutting down traffic for an extended period of time. This is beneficial to numerous parties, including a DOT, the contractor and the traveling public. Furthermore, the methods advanced by SAM improve safety for those participating in tunnel inspections.

C. By vetting out the concept of NDT for tunnels maintained by CDOT, numerous technologies were identified, explored, ruled out, and improved. Additionally, SAM utilized equipment in ways that it may have never been intended, and by coupling certain technologies was able to identify best pairings of cameras, lenses, sensors, processing software, and other components.

D. The data collected during Phases 1 and 2 is a positive front-end planning tool, as well as a strong quality control component for information determined by inspections conducted manually by professionals. The information serves as a stable reference for DOTs who wish to utilize it for their own tunnel inspection process.

E. Overall, the methods and information gathered by SAM contribute an asset management element to the inspection process. By performing regular NDT of tunnels, more resources and manpower (boots on the ground) can be focused on critical areas. Thus, value is added to a DOT’s procedures.

6.3 RECOMMENDATIONS

A. If at all possible, it would be prudent for a DOT to schedule data collection to coincide with any planned shutdowns.

B. Impacts to traffic on I-70 were minimal because of the time of day and approach to traffic management. Due to necessary thermal conditions for a successful collection, it should not be done during daylight hours and would likely not be allowed by DOTs during peak travel times. Work on minor arterials, where posted speed limits are lower, would not impact the traveling public if performed in a manner similar to SAM’s. In general, performing work late at night and early in the morning would result in fewer delays to the traveling public.

C. The quality of the results was directly impacted by the level of technology in use; therefore, the costs of renting/purchasing/custom fabricating equipment, outfitting survey vehicles, and educating users on all aspects of operations and programs, should be given serious consideration before undertaking NDT methods explored in this report.

D. Further development to improve RGB acquisition to combat variable lighting and high vehicular collection speeds. Light sources, sensor, and shutter type affect the quality of images collected.

E. Virtual Reality is one example of emerging immersive technologies to analyze post processed data in a controlled environment. Immersive technologies can allow various teams and individual members to collaborate on one project while working from dispersed locations. There are numerous benefits related to the utilization of such methods, including improved communication among team members and a more efficient use of everyone’s time, resulting in overall significant project savings.

REFERENCES CITED

American Association of State Highway and Transportation Officials. "SHRP2Solutions." Available from http://shrp2.transportation.org/Pages/R06_NondestructiveTesting.aspx; accessed 15 January 2018.

U.S. Department of Transportation, Federal Highway Administration. *Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual*. Publication No. FHWA-HIF-15-005, July 2015.

_______________. "SHRP2Solutions." Available from https://www.fhwa.dot.gov/goshrp2/; accessed 10 January 2018.

Office of the Federal Register, *National Tunnel Inspection Standards* (available from https://www.federalregister.gov/documents/2015/07/14/2015-16896/national-tunnel-inspection-standards), accessed 7 February 2018.