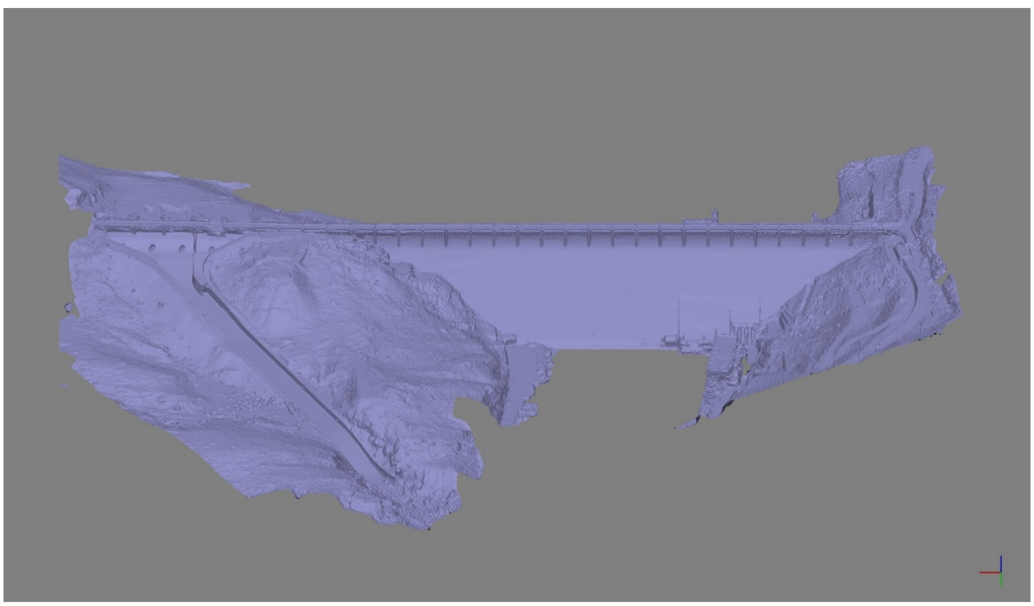
RECLAMATION

Managing Water in the West

Photogrammetric Processing from Unmanned Aerial System (UAS) Data: Elephant Butte Dam

Technical Memorandum No. 8530-2016-28
Research and Development Office
Science and Technology Program
(Final Report) ST-2016-7738-02



U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

August 2016

Mission Statements

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REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*
T1. REPORT DATE SEPTEMBER 2016	**T2. REPORT TYPE** Research	**T3. DATES COVERED**
T4. TITLE AND SUBTITLE Photogrammetric Processing from Unmanned Aerial System (UAS) Data: Elephant Butte Dam		**5a. CONTRACT NUMBER** 16XR0680A1-RY1541IS201627738 **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER** 1541 (S&T)
6. AUTHOR(S) Matthew Klein, PE, PhD mjklein@usbr.gov 303.445.2368		**5d. PROJECT NUMBER** 7738 **5e. TASK NUMBER** **5f. WORK UNIT NUMBER** 86-68530
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Concrete, Geotechnical and Structural Laboratory U.S. Bureau of Reclamation PO Box 25007, Denver CO 80225		**8. PERFORMING ORGANIZATION REPORT NUMBER** 8530-2016-32
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Research and Development Office U.S. Department of the Interior, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007		**10. SPONSOR/MONITOR'S ACRONYM(S)** **R&D: Research and Development Office** **BOR/USBR: Bureau of Reclamation** **DOI: Department of the Interior** **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** ST-2016-9384-02
12. DISTRIBUTION / AVAILABILITY STATEMENT **Final report can be downloaded from Reclamation's website: https://www.usbr.gov/research/**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT: A UAV was flown over Elephant Butte Dam to collect optical and IR photogrammetric data to be used as a condition assessment of the structure.		
15. SUBJECT TERMS: photogrammetry, unmanned aerial system, UAS, aerial condition assessment, aerial inspection		

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON:** Matthew Klein
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	**U**	**20**	**19b. TELEPHONE NUMBER** 303-445-2125

S Standard Form 298 (Rev. 8/98)
P Prescribed by ANSI Std. 239-18

PEER REVIEW DOCUMENTATION

Project and Document Information

Project Name: Photogrammetric Processing from Unmanned Aerial System (UAS) Data: Elephant Butte Dam

WOID: X7738 Document: Final Report ST-2016-7738-02

Document Author(s): Matthew Klein Document date: September 2016

Peer Reviewer: Kurt von Fay

Review Certification

Peer Reviewer: I have reviewed the assigned items/sections(s) noted for the above document and believe them to be in accordance with the project requirements, standards of the profession, and Reclamation policy.

Reviewer KURT VON FAY Digitally signed by KURT VON FAY Date: 2016.09.28 14:07:52 -06'00'

(Signature)

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Acknowledgements

This project was made possible through the hard work and consideration of many, many people: Woody Irving and Mike Landis from the El Paso Field Office, Erin Foraker, John Whitler and Levi Brekke from the Research Office, Ed Frazer from the Construction Management and Specifications Office, Rex Amicone and Christina Mohamed from the Acquisition Operations Branch, Shellie Nall as the Upper Colorado (UC) Regional Aviation Manger, Stacey Smith as the Project Aviation Manager, Ken Rice as the Albuquerque Area Office (AAO) Manager, Bob Morton as the AAO Safety Officer, Brent Rhees as the UC Region Director, Andy Wood as the UC Region Safety Officer, Kristin Swoboda as the DOI UAS certified Pilot in Command (PIC), Jeff Sloan from USGS, Brad Koeckeritz and Mark Bathrick from the DOI Office of Aviation Services (OAS), Alex Stephens and Peter Soeth from the Denver Public Affairs Office, Mary Carlson from the AAO Public Affairs Office, Jack Brynda as the former National Aviation Manager, Pheobe Percell as the current acting National Aviation Manager, Bruce Muller, Jr. as the Director of Reclamation's Security, Safety and Law Enforcement (SSLE) Office, Cassie Gills, Mark Travers, Bruce Schulte, Kurt von Fay, Bill Kepler, Janet White, Dick LaFond, Bob Baumgarten and Tom Luebke from the Reclamation Technical Service Center (TSC) in Denver, Joe Millette, Zak Zaklan and New Mexico State University (NMSU), Zach Mott, Brian Koch, Garrett Porter and Geotech/Leptron, and finally Jay Powell, Ben Kalminson and Billy Elbrock from Elephant Butte Dam.

Acronyms and Abbreviations

3D	three dimensional
AAO	Albuquerque Area Office
APS-C	advance photo system type-C
ASTM	American Society for Testing and Materials
ASSURE	Alliance for System Safety of UAS through Research Excellence
CGSL	Concrete, Geotechnical and Structural Laboratory
COA	certificate of authorization
DDR3	double data rate type three
DO	Denver Office
DOI	Department of the Interior
EPFO	El Paso Field Office
FAA	Federal Aviation Administration
FTC	Flight Test Center
GB	gigabyte
GCP	ground control point
GHz	gigahertz
GPS	Global Positioning System
HD	high definition
IBWC	International Boundary and Water Commission
INC	Incorporated
IR	infrared
JHA	job hazard analysis
kw	kilowatt
LIDAR	light detecting and ranging
LiPo	lithium polymer
MHz	megahertz
mins.	minutes
MOA	memorandum of agreement
mph	miles per hour
NAM	National Aviation Manager
NASA	National Aeronautics and Space Administration
NAVD 88	North American Vertical Datum of 1988
NM	New Mexico
NMSP	New Mexico State Plane
NMSU	New Mexico State University
OAS	Office of Aviation Services
OPM	Operational Procedures Memorandum
PAM	Project Aviation Manager
PASP	project aviation safety plan
PIC	Pilot in Command
PLA	polylactic acid
RAM	random access memory

RAM	Regional Aviation Manager
RLT	Reclamation Leadership Team
ROV	remotely operated vehicle
S&T	Science and Technology
secs	seconds
SIFT	scale invariant feature transform
SOW	statement of work
SSLE	Security, Safety and Law Enforcement
TIN	triangular irregular network
TSC	Technical Service Center
TVA	Tennessee Valley Authority
UAS	unmanned aerial system
UC	Upper Colorado
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USGS	United Stated Geological Survey
USSD	United States Society on Dams
VO	visual observer

Executive Summary

In 2015, the Reclamation Research Office Science and Technology (S&T) program provided support for an investigation to determine if unmanned aerial systems (UAS) could be used to collect quality photogrammetric data. The project was a joint effort between the El Paso Field Office (EPFO), Albuquerque Area Office (AAO), Upper Colorado (UC) Region and the Concrete, Geotechnical, and Structures Laboratory (CGSL) in Denver. In June of 2016, optical and infrared (IR) data was collected at Elephant Butte Dam by New Mexico State University's (NMSU's) UAS Flight Test Center (FTC). The data was used to build a georeferenced photogrammetric 3D model, topographical map of the dam and surrounding area, printing of a 3D model and allowed for subsurface defect detection using the IR data. A photogrammetric model was also built using the IR images.

The data was collected over a total of five flights and two days (a sixth was added to capture a high definition (HD) video overview of the dam). While the resolution was not high enough to detect cracks and other deterioration due to safety concerns from the contractor, the flights showed that the data collection is high quality and repeatable. With different equipment that the contractor did not have, the desired resolution could be obtained. The alternative inspection would be performed by personnel hanging off of ropes and measuring the deterioration by hand. This method would take much longer than the UAS inspection. In addition, the UAS is much safer. This results in cheaper inspections that can be measured in the office and archived for future reference.

While the UAS data collection was successful, the project demonstrated the need for an internal UAS program at Reclamation. Reclamation had little control in the data collection procedures which resulted in lower resolution data than what was expected. In addition, contracting and scheduling required much more time and money.

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Background

The purpose of this research was to determine if an unmanned aerial system or UAS could be used to collect quality inspection data including data to be used for photogrammetry. UAS's have the potential of collecting high quality data cheaper and safer than other alternatives. Many of Reclamation's facilities consist of large scale structures that are time consuming to inspect and require special safety equipment and procedures to access. Current alternatives include manned rope access teams.

Recent technological advancements over the past several years have improved the operation and data collection capabilities of UAS. These advancements assist in reducing data collection costs and increase safety and include:

- Multi-rotor configurations for redundancy,
- Flight controllers with on-board global positioning satellite (GPS) for stability during hovering and for maintaining tightly controlled flight paths even in high winds,
- Autonomous waypoint flight management,
- Accelerometer and gyro stabilized camera gimbals to isolate the optics from vibration and movements,
- Standardized programmed failsafes to control the machine during loss of connection and return it to a predetermined landing position,
- Improved lithium polymer batteries to give longer flight times,
- Dual control allowing the UAS pilot to control the airframe while another person can operate the camera allowing for more precise inspection control and safer operation,
- Enhanced digital optics for detailed records including high resolution digital imagery and high definition (HD) video up to 4K resolution,
- HD video downlinks for real-time monitoring of the inspection, and
- Additional payloads including infrared (IR), multispectral and laser illuminated detection and ranging (LiDAR) equipment.

Photogrammetry as a condition assessment tool is a relatively new idea at Reclamation. The process of photogrammetry involves stitching a series of images to create a digital 3D model. The 3D model is overlaid with a photorealistic texture with the same resolution as the original images. Thus the model can be inspected in lieu of an actual inspection. By inspecting the digital model, the inspector is not encumbered by weather, safety, gravity, or other physical limitations. This reduces the time to make the inspection and makes the inspection safer.

Elephant Butte Dam was identified for the aerial inspection due to its age and challenging configuration requiring specialized procedures for detailed manual inspections. This nearly 100 year old structure was completed in 1916. It is located on the Rio Grande River about five miles northeast of Truth or Consequences, New Mexico. The 301-foot high, 1,174-foot long concrete structure impounds about two million acre feet of water that is used for irrigation and power generation at the 28 kilowatt (kw) powerplant constructed in 1940. The powerplant is located on the left side of the dam and the concrete spillway is located on the right side as shown in Figure

1. The structure is an ideal test for UAS inspections given its simple plan layout and tall inaccessible downstream dam face. In addition, the structure is showing signs of deterioration that would provide a real world test the UAS inspection capabilities.

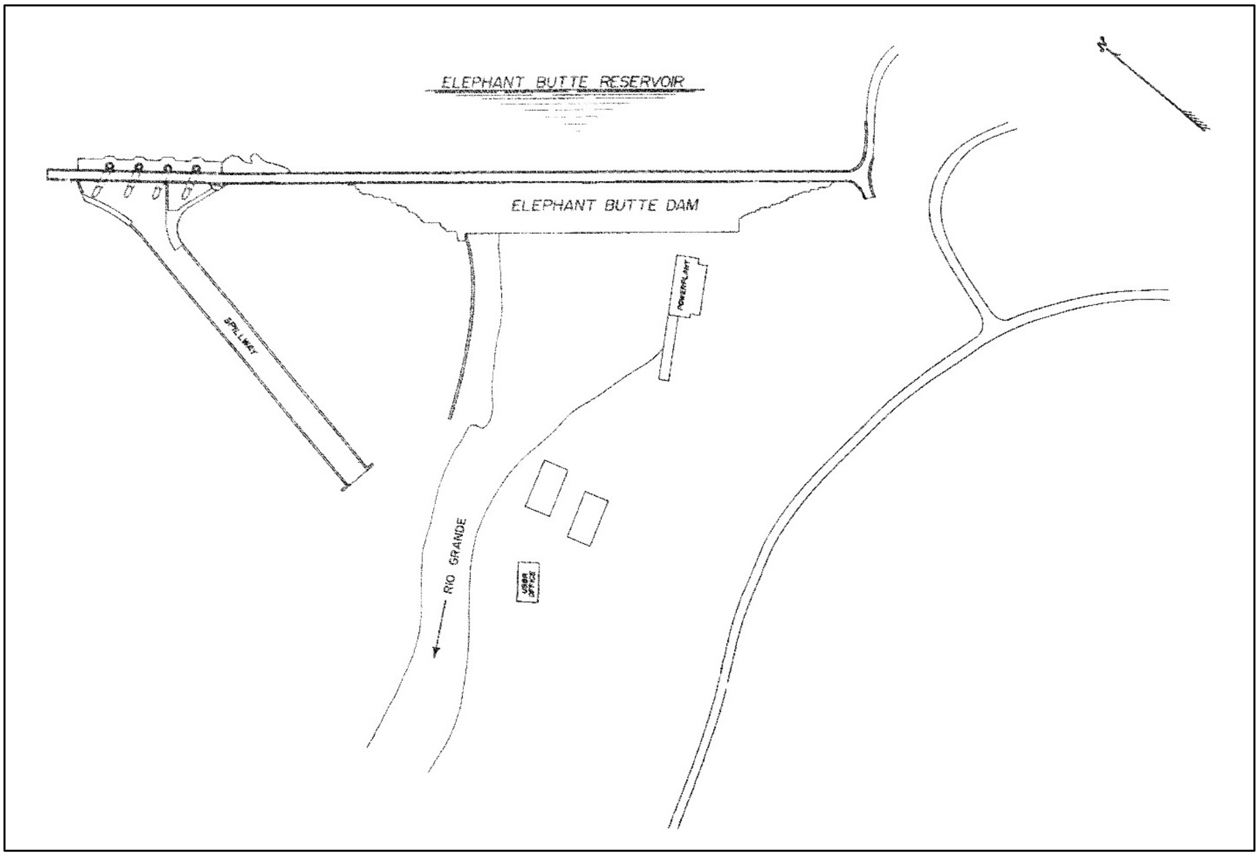

Figure 1: Elephant Butte Dam Site Map

Reclamation does not have an official UAS program. This project relied on a contractor to provide the UAS services. New Mexico State University's (NMSU) UAS Flight Test Center (FTC) was identified as the sole source provider of UAS services because of their special relationship with the Federal Aviation Administration (FAA) as an Alliance for System Safety of UAS through Research Excellence (ASSURE) partner in the airspace surrounding Elephant Butte Dam. ASSURE partners have been identified as a leading industry, government or research institution because of investments in expertise and infrastructure. NMSU was also the original FAA UAS test site [1]. NMSU subcontracted the UAS and UAS flight crew from Geotech Environmental Equipment, INC.

Project Management Notes

Michael Landis and Woody Irving from the El Paso Area Office (EPAO) had the initial idea for using UAS as an inspection tool. In the winter of 2015, they contacted the Denver Office for technical expertise relating to types of data that would be useful to be able to use for completing an inspection of Elephant Butte Dam. The project was closely related to another project processing photogrammetric data from a remotely operated vehicle (ROV) at Trinity Dam and the scope was changed to include photogrammetric processing of Elephant Butte Dam.

Acquiring NMSU's services required approval from the Department of Interior's (DOI's) Office of Aviation Services (OAS). The approval was given in January of 2016. The data collection was performed during the summer of 2016. Photogrammetric processing was conducted by Reclamation also in the summer of 2016.

Procedure

The project was divided into the following parts: scope, planning, data collection, data processing and analysis. The scope referred to the requirements of the contractor. Planning involved working with Reclamation's national aviation manager (NAM) and the DOI OAS to understand and adhere to Reclamation, DOI and FAA aviation requirements for UAS missions. Data collection referred to the actual flights at Elephant Butte for collecting the data. Data processing was performed at Reclamation's Concrete, Geotechnical and Structural Laboratory (CGSL) along with the data analysis.

Scope

The statement of work (SOW) included a total of 8 tasks, however, 2 tasks were optional (Task 5: photogrammetric processing and Task 6: repeat flight to develop difference model. Task 8: airworthiness evaluation was also dependent on whether Task 7: airworthiness process was not sufficient to demonstrate airworthiness to DOI OAS. Task 8 involved travel to the NASA Ames Research Center to perform an airworthiness assessment of the proposed airframe. Table 1 summarizes the task number, title and description.

Table 1: Summary of SOW Task List

Task	Title	Description
1	Airframe and Sensor Selection	Airframe requirements: autonomous flight, waypoint navigation, HD video transmission, sufficient flight time Sensor requirements: optical camera for high resolution images and HD video, radiometric infrared (IR) camera
2	Mobilization and Demobilization	Access to dam, launch and recovery sites, identification of potential hazards
3	Data Collection	Capture HD inspection video, high resolution photogrammetry and IR inspection images suitable for photogrammetry
4	Report	Equipment and methods used to obtain data including an error discussion

Task	Title	Description
5	Post Processing – Optional	Build georeferenced 3D model using high resolution images
6	Repeat Data Collection - Optional	Conduct 2nd flight after 3 months to build a 3D difference model comparing to the initial
7	Airworthiness Process	Complete DOI UAS Airworthiness and Flight Safety Evaluation Questionnaire
8	Airworthiness Evaluation – Dependent on Task 7	Travel to NASA Ames for flight demonstration and evaluation of proposed UAS

Planning

DOI Operational Procedures Memorandum – 11 (OPM-11) is the document set forth to guide DOI agencies on the operations and management of UAS [2]. The document provides definitions, policy, and coordination with the FAA, procedures and responsibilities of an agency program. The document also describes two types of UAS contracts: flight service or end-product [2]. Flight service contracts are those in which the agency retains control over initiating, conducting and terminating the UAS flight. End-product contracts do not direct the UAS operations but only specify the requirements of the data. The type of contract for this mission was defined as a flight service contract. Because of this, the contractor was required to complete the DOI UAS Airworthiness and Flight Safety Evaluation Questionnaire. Due to the responses given in the questionnaire, a one-time waiver to some of the OPM-11 requirements was granted with the following mitigations [3]:

1. Reclamation Project Aviation Manager
2. DOI certified UAS Pilot-in-Command (PIC)
3. Comply with FAA/DOI Memorandum of Agreement (MOA)
4. Project Aviation Safety Plan (PASP)
5. OAS-2U UAS Flight Use Report Form

Since UAS are not routinely used at Reclamation, special attention and guidance was provided by the Reclamation NAM and DOI OAS. Close coordination was provided from the Safety, Security and Law Enforcement (SSLE) Office which manages Reclamation aviation interests. The requirements for this project by Reclamation included obtaining mission approvals from the BAM, the regional aviation manager (RAM) and the regional director in the region where the mission is to take place. The approval process was to follow guidance given in the Reclamation Leadership Team (RLT) Memo dated 3/26/2015 and had the following requirements [4]:

1. Purpose and scope of UAS usage
2. Data collected
3. Privacy and protection of civil rights controls
4. Data preservation plan

5. Regional Aviation Manager Approval
6. Regional Director Approval

The last step was to schedule the data collection flights. The preferred time for performing the flights was in late spring/early summer. This was because of two things: less risk for adverse weather and a lower reservoir level. Springtime in central New Mexico can bring heavy winds that could affect the UAS stability. Usually in late summer, the area is affected by monsoon rains.

Communication onsite was to be maintained by use of radios and the project chain of command followed down from the DOI UAS PIC to the Reclamation Project Aviation Manager to the Contractor Mission Commander to the Subcontractor UAS Pilot.

Safety

Safety was one of the major concerns with the UAS inspection. Over the past several years, there are many examples of loss of control of a UAS and its impacts even though there has been considerable progress in the safety features incorporated into UAS design. Specific areas of concern related to loss of control include colliding with the dam or powerlines, loss of the equipment by impacting the ground or sinking in the water, and collision with personnel. For these reasons, Reclamation implemented a 50 foot standoff between the powerlines and power plant. The offset to the ground and dam was permitted to be set by the UAS pilot.

A 100 foot distance was mandated between the UAS and the non-participating observers who would be onsite to watch the UAS flight but were not a part of this particular mission.

Visual Observers (VOs) were required to be used to monitor the UAS during its flight. The VOs were positioned at either end of the flight path with radios to communicate to the UAS pilot and provide mission feedback. This ensured that the safety offset would be maintained during the flight despite the lack of depth perception by the pilot and video downlink. The Contractor Mission Commander would convey information between the UAS pilot and the VOs as well as between the Reclamation project lead and facility manager.

Data Collection

Data collection at Elephant Butte were to consist of four types: HD video, high resolution digital imagery, aerial LIDAR and thermal IR imagery. The HD video was intended to be used for an inspection of the structure. It was to include all features of the facility including the upstream face, downstream inclined face, downstream vertical face, crest, intake structure, upstream and downstream spillway gate openings, and the spillway. The powerplant was not included as part of the inspection due to safety concerns. Reclamation inspectors were to be onsite to record potential defects observed from the HD video downlink from the UAS. These observations were to be compared to actual inspections.

The high resolution digital imagery was to be collected using standard photogrammetry technique:

- Images would need to be captured to allow for 60 percent overlap by adjacent images to allow a point on the image to be detected on at least two other images.
- The camera should be oriented perpendicular to the surface so that the distance to similar points would remain constant and reduce error.
- The UAS should be operated smoothly to prevent motion blur.
- The camera should be stabilized by an isolated gimbal to reduce vibration effects such as jello effect.
- The camera should feature a fixed focal length to reduce error in the photogrammetric calculations.
- Post-processing features of the camera such as image or color enhancement should be turned off so that the raw image contains the actual data resulting in less error.
- The camera should be positioned to allow for a ground sampling resolution of 1/32 inch.
- A grid pattern would be employed to collect data to ensure complete coverage and consecutive data collection.
- Ground control points (GCPs) should be captured to enable georeferencing of the facility.
- The minimum pixel pitch (or size) should be 4 microns.

The resulting images were to be used to build a 3D model. The model was to be a test to see whether the resolution of the model was high enough to allow a 3D model inspection of the structure to compare with the HD video inspection and an actual inspection of the facility.

Originally LIDAR data was to be collected to verify and compare data quality with the photogrammetric 3D model. The specified resolution for the LIDAR was given as 150,000 points per square foot. However, during early negotiations with the contractor, it was evident that no aerial LIDAR system at that time could reach that resolution and therefore LIDAR was removed from the contract.

Thermal IR data was to be used to supplement the video and 3D inspections. Thermal IR data is used to detect subsurface defects such as delaminations in concrete. The concept is that as the sun warms the concrete mass the heat is dissipated to the underlying concrete. However, if a boundary is created that cannot transfer heat at the same rate such as a crack, the heat will not be dissipated and the area will be warmer than areas that do not have cracks. This procedure was originally developed for detecting bridge deck delaminations and is outlined in the ASTM Standard D4788 – Standard Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography [5]. The inspection technique has been tested successfully by Reclamation at Webster Dam using a handheld IR camera [6]. The IR camera was calibrated and checked against existing delamination mapping of the spillway (see Appendix A).

Data Processing and Analysis

The HD video inspection will not require post-processing as the inspection is to occur onsite with Reclamation inspectors. The video will be available for reference.

Photogrammetric processing will be performed by Reclamation's Concrete, Geotechnical, and Structural Laboratory. The processing will be conducted on a custom built Windows based computer with the following specifications: liquid cooled Intel i7-4960X overclocked to 4.5 GhZ, 64 GB DDR3 2400 MhZ RAM, 2 – NVIDIA Geforce GTX 980 TI cards and a solid state drive. The process includes filtering the images to include only the images taken of the facility that are of good quality. The photo-realistic textured 3D model will be used for the digital inspection and orthophotos will be taken of the face of each feature for mapping any damage.

The IR data will be either processed photogrammetrically or as an overlay to the optical photogrammetry. A delamination map will be created of the spillway using an orthophoto and will be compared to the existing delamination map in Appendix A.

Results

The UAS data collection occurred during June 28 and 29 of 2016. The weather during the operations was mostly sunny with a light afternoon shower on June 28 though it was late enough to not impact the operations. Temperatures ranged between the upper sixties and low nineties for both days. Winds gusted at about 15 mph on June 28 but were calmer on June 29.

The subcontractor on the project did not feel comfortable operating their equipment any closer than about 100 feet from the structure. They were concerned that the structure might interfere with the GPS signal used to position the airframe and cause loss of control. Because of this, the HD video inspection data would be unusable due to the low resolution. Thus no HD video inspection data was collected. Instead, video was collected to highlight the facility. In addition, the ground sampling distance from this offset turned out to be about 20 times greater at 5/8 inch and the photogrammetry data would not be able to be used for an inspection either. The IR image resolution was reduced as well which reduced the ability to verify all delaminations in the spillway.

It should be noted that the resolution on the images could have been improved while maintaining the desired offset by simply using a zoom lens. This was pointed out to the contractor but the equipment was not available onsite and the gimbal was not balanced to accept a different lens combination than what was used. In addition, other UAS navigation systems feature obstacle and collision avoidance sensors that allow for closer offsets.

A total of 8 flights were conducted: 6 flights gathered data while the remaining flights were used to verify system operations. All flights with the exception of Flight 3 were conducted from a take-off/landing site located on the south bank of the reservoir about 100 feet east of the crest of the dam. Flight 3 was conducted from a point about 300 feet downstream of the dam. The data collection summary is shown below in Table 1 and the plan and elevation of the approximate flight paths are shown in Figures 2 and 3.

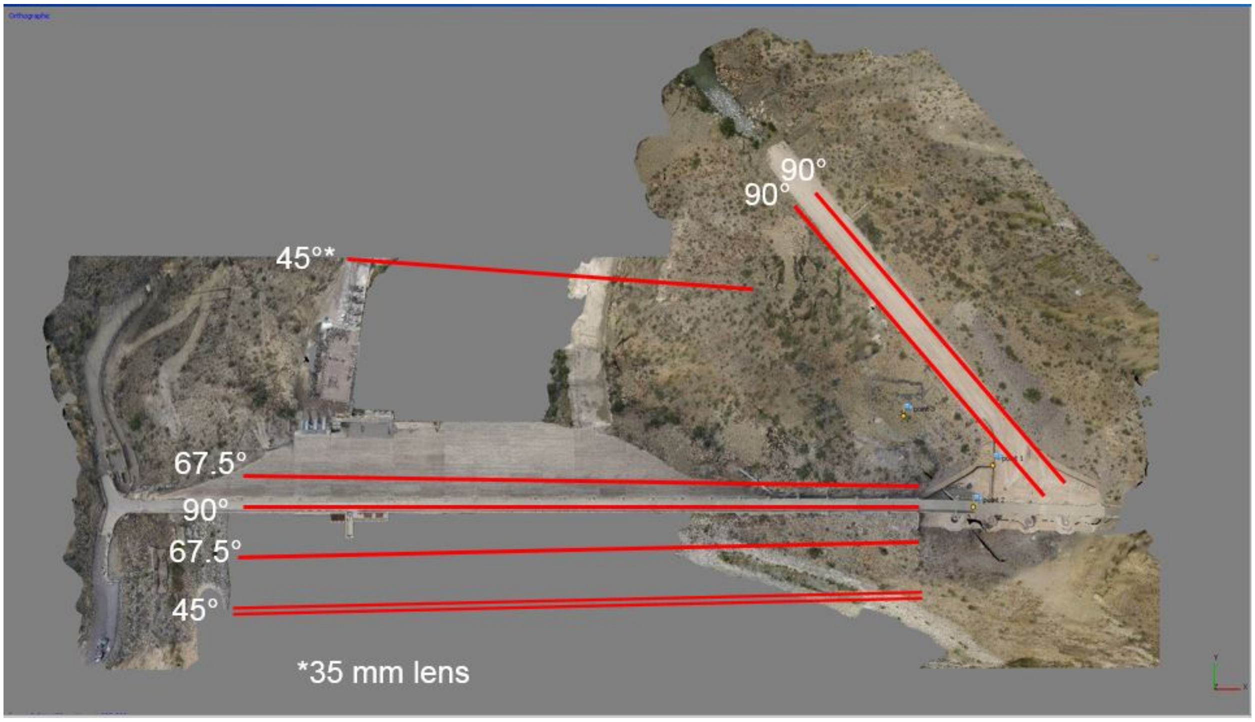

Figure 2: Flight Plan Locations

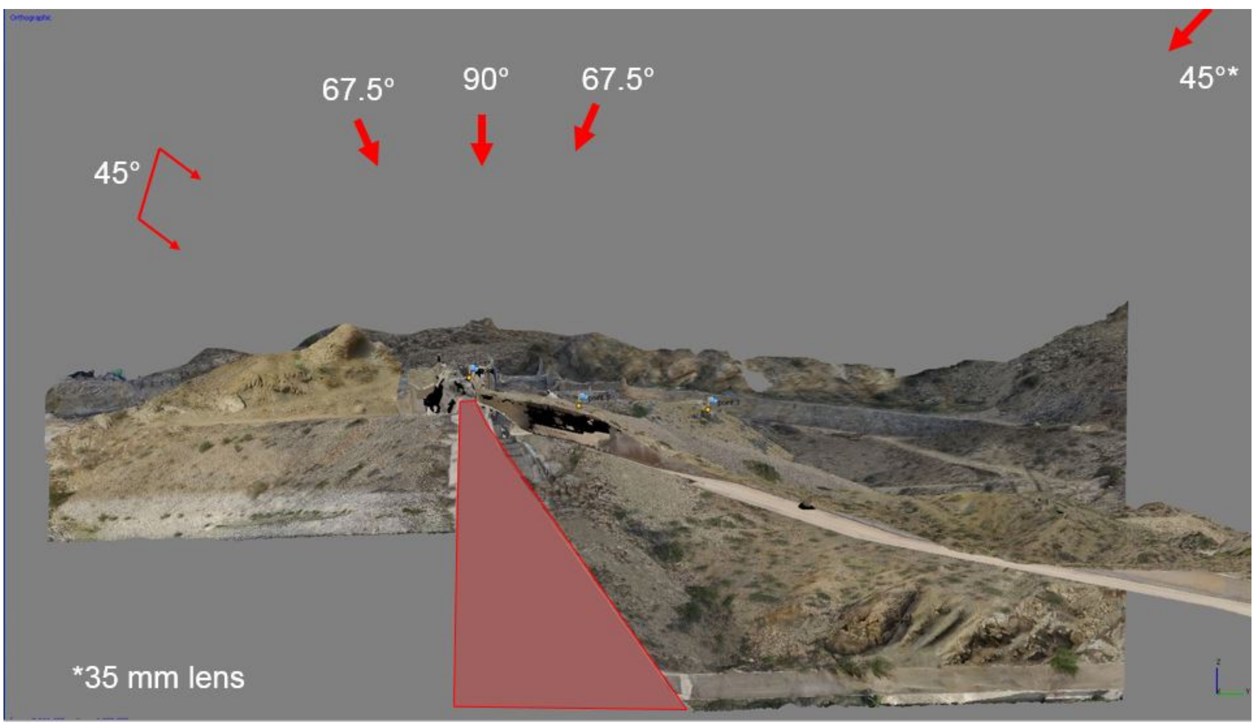

Figure 3: Flight Plan Angles

Since the project drew interest from many Reclamation and non-Reclamation agencies, accommodation was made for their observation of the project. A site was set-up at a public access overlook to the south of the structure. Representatives from the International Boundary and Water Commission (IBWC), various Reclamation field and area offices, the New Mexico Office of the State Engineer, and US Army Corps of Engineers (USACE) were present. In addition, a reporter from the local television station reported on the use of a UAS to inspect the dam [7].

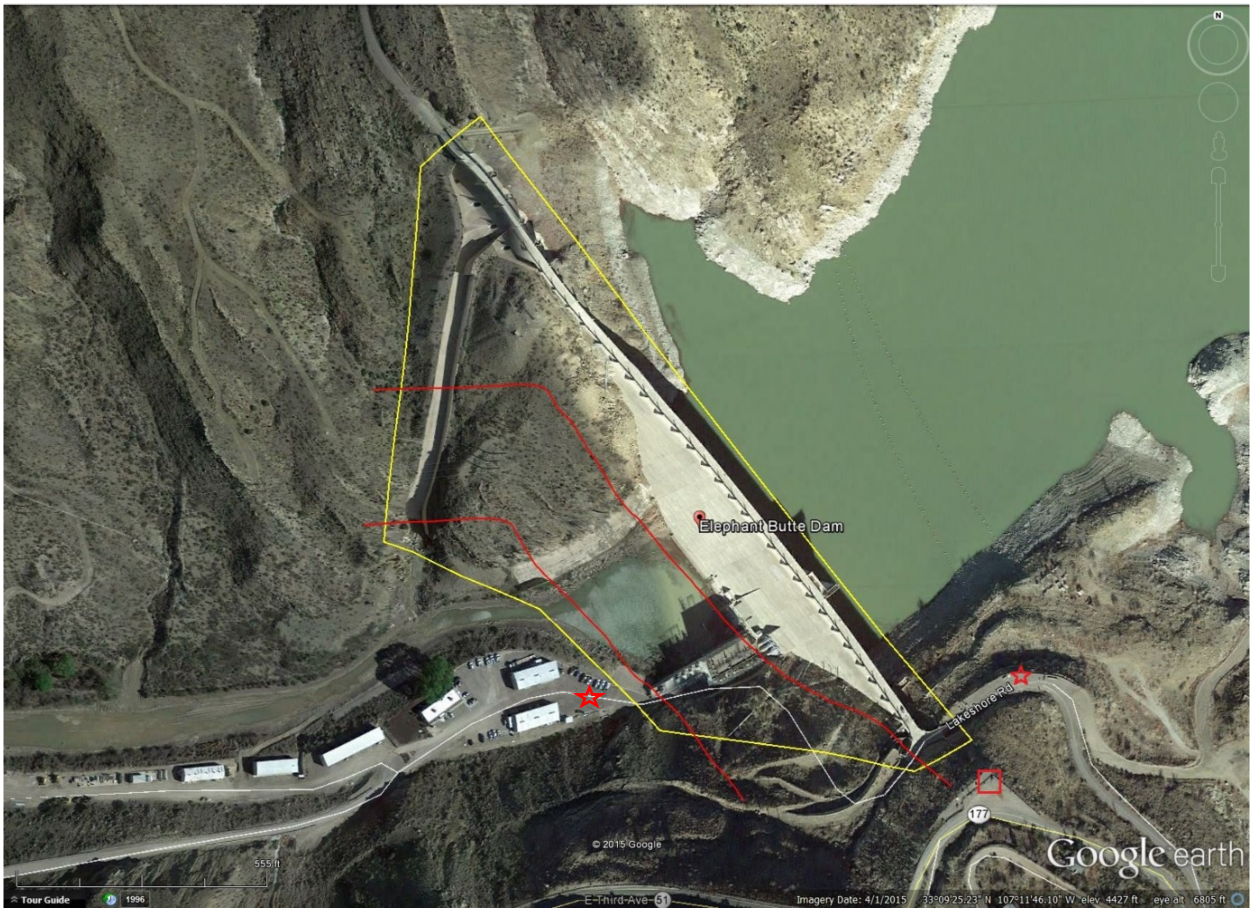

Figure 4: Extents of Data Collection (boundary line) with Take-Off and Landing Locations (stars)[1]

Flight 1 collected data of the upstream face and crest of the dam. The data consisted of both optical and IR data. The upstream face data was collected at a 45 degree angle from vertical at an offset of about 150 feet. On the return flight, the UAS flew over the crest at about 100 feet above the dam and with the camera directed straight down (nadir). During the upstream face data collection, the gimbal malfunctioned and rotated the gimbal from left side to front side resulting in numerous motion blurred images.

Flight 2 repeated the upstream face data collection without incident.

Flight 3 collected data from over the spillway. Since the spillway was inclined, the offset from the UAS ranged from about 100 to 250 feet. The camera was oriented nadir over the spillway. For the first flight up over the spillway, the UAS was positioned just over the south wall and on

[1] The lines are the locations of the power lines and the square is the location of the public access overlook.

the return flight, the UAS was positioned over the north wall. This gave an overlap of about 90 percent but with a low angle between the two flight paths and thus a low angle between similar points on either corresponding image.

Flight 6 was more data collected over the dam. Photogrammetry data verification was performed after each flight to ensure that the data would be able to be used. A model was able to be generated from the crest data and the upstream face data but the two models could not be combined. This was because data needed to be collected at an angle between the two orientations. This set of data was collected at 22.5 degrees from vertical on either side of the crest – about 110 feet offset from the dam.

Flight 7 collected HD video data. The flight was made following the river downstream over the dam and then returned upstream. This was performed a total of two and a half times. During the flights, the camera was tilted down to take on overview of the dam and then tilted up to view the horizon. On the upstream shots, Elephant Butte, the dam's namesake, is visible rising out of the reservoir (see Figure 3).

Figure 5: Elephant Butte

Flight 8 collected the inclined feature of the downstream face. Several powerlines were location downstream of the structure and the offset for this data set was about 350 feet from the structure.

In order to maintain the ground sampling resolution, a longer focal length lens was used (see the Equipment section below). The camera was oriented about 45 degrees from vertical.

Table 2: Data Collection Summary

Date and Time	Flight #	Data Collected	Features Examined	Duration
June 28, 2016 9:20 am	1	Optical and IR Images	45 degree view Upstream Face Crest	9 mins. 47 secs.
June 28, 2016 10:30 am	2	Optical and IR Images	45 degree view Upstream Face (repeat)	6 mins. 31 secs.
June 28, 2016 1:21 pm	3	Optical and IR Images	Spillway	8 mins. 32 secs.
June 29, 2016 11:01 am	6	Optical and IR Images	22.5 degree view Upstream and Downstream face	8 mins. 59 secs.
June 29, 2016 12:00 pm	7	HD Video	Overview of Dam	11 mins 49 secs.
June 29, 2016 2:41 pm	8	Optical and IR Images	45 degree view Downstream Face	7 mins. 57 secs.

Equipment

The equipment used on the project consisted of the UAS and sensors. The UAS was the Leptron Avenger E which is a single rotor model helicopter. It is about 20 inches tall, and 50 inches long. The main rotor is 58 inches long with a smaller rotor on the tail to provide stability and control direction (see Figure 6). It is powered by lithium polymer (LiPo) batteries and can operate for between 20 and 30 minutes.

Figure 6: Leptron Avenger E UAS at Elephant Butte Dam (note sensor gimbal at the front of the airframe)

The optical sensor was a Sony a6000. The Sony a6000 features an APS-C sensor that is 23.5 by 16.5 mm and 24.3 megapixels. The resulting pixel pitch is 3.9 microns. The camera can also capture 1080 video. The camera was paired with a 20 mm lens for every flight except for the downstream inclined face data collection. There a 35 mm lens was used.

The IR sensor was an ICI 8640 P-series infrared camera. The camera is a radiometric IR camera meaning that it collects absolute thermographic data from each pixel. This is important so that the data can be calibrated for the minute temperature differences that allow delamination detection. In addition, the data can be processed photogrammetrically because the pixel values do not change.

Both the optical and IR sensors were triggered simultaneously by the UAS at about 1 second intervals to provide the minimum 60 percent overlap required by the photogrammetry. In addition to triggering the sensors, the UAS also recorded the GPS position when the cameras were triggered.

HD Video

As mentioned above, the safety offset that the subcontractor operated the UAS at prevented a HD video inspection from providing any usable data. Cracks would not be visible from the distances flown. However, an HD video was collected of a flyover of the facility for other uses (see Figure

7). The gimbal however does not completely isolate the camera from UAS vibrations and causes shaking in the video. The video was stabilized during post-processing which removed most of the vibration.

Figure 7: Image taken from HD Video showing Elephant Butte Dam and Elephant Butte

High Resolution Images and Photogrammetry

Some of the photogrammetric processing was performed onsite to verify the data quality. The full processing was performed at the CGSL in Denver, Colorado. The first step was to organize the images. A total of 1,677 images were taken but only 693 were able to be used in the processing. Some of the images did not show the facility but had were taken while the UAS was still on the ground or when the gimbal malfunctioned. Some of the images were too blurry to use.

After sorting the quality images, they were processed using Agisoft PhotoScan Professional. This is performed in two steps: key point selection using the scale-invariant feature transform (SIFT) algorithm and a least squares nonlinear function fit of the location of the camera positions. After the camera positions are solved, error is removed iteratively from the model to improve the accuracy of the model. After that, the point cloud model can be generated.

Due to lack of overlap between the two data sets, the model had to be built in two parts: the dam and the spillway. When the two models were complete, they were joined using manually selected tie points. The tie points or markers are shown as flags in Figure 8.

Figure 8: Dam and Spillway Manual Tie Points

The completed model was built to a maximum error of 1.09 inches on less than 1 percent of the images with over 51 percent of the images having only 0.27 inches of error. The camera was field calibrated meaning that the individual camera parameters needed to solve the model were given by refining the model itself without the need for a separate camera calibration. There were a total of over 46 million points in the point cloud yielding a point density of about 50 points per square foot.

After the point cloud was generated, the points were meshed resulting in an irregular surface draped over the points. The mesh is then textured with a photorealistic overlay from a stitched mosaic of all the images. The result is a 3D model that appears like the actual subject captured.

Once the model was complete, the ground control markers were identified. Existing survey markers were used. A total of 10 markers were identified with most of them found on the crest. One marker was located at the toe of the structure. The markers were referenced to 1 inch accuracy. Georeferencing the model provided both scale and a coordinate system. The coordinate system used was the New Mexico State Plane (NMSP) West system with the North American Vertical Datum of 1988 (NAVD 88) used for elevations. A photogrammetry processing report was generated and gives the error analysis for both the ground control points and the camera calibration and in shown in Appendix B.

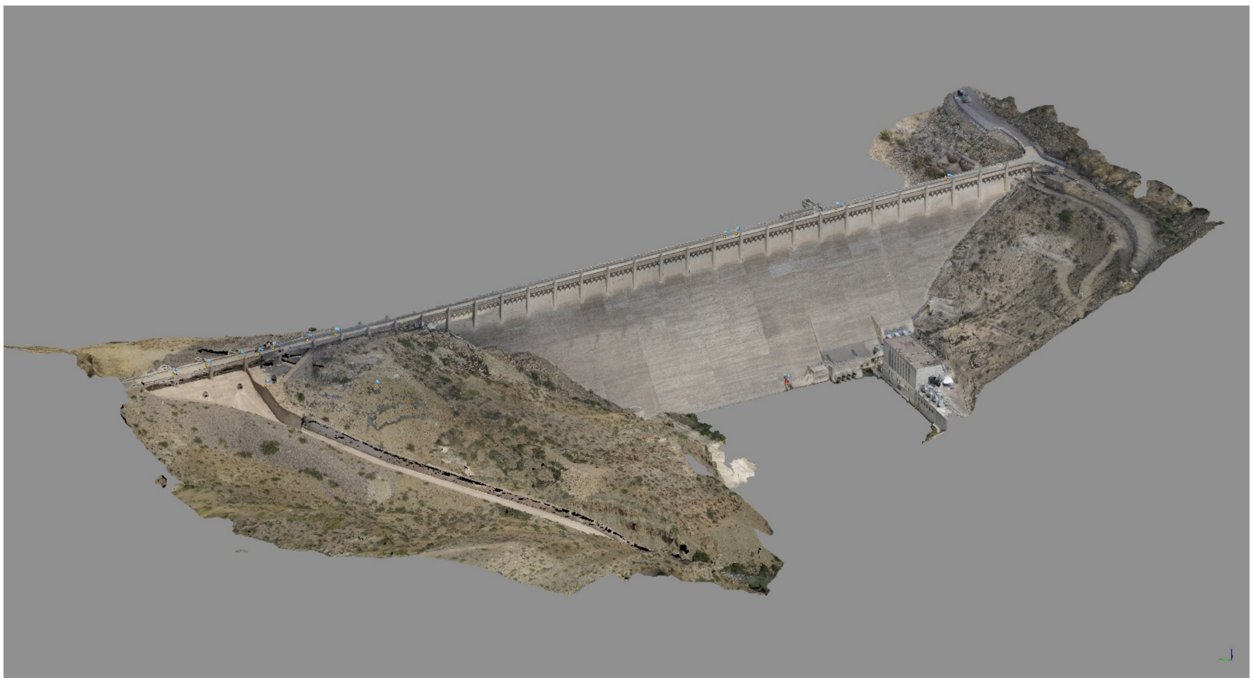

Figure 9: Georeferenced 3D Model of Elephant Butte Dam

After the model was georeferenced, a projection of the surface without distortions based on perspective was created, which is called an orthophoto. A topographical map was created by exporting the height map (elevations of each point) to GRASS GIS and generating a contour layer that could be read by ArcGIS mapping software. In ArcGIS, the contour file and georefenced orthophoto were aligned to produce the topographical map (in Appendix C).

After the topographical map was generated, a 3D print of the facility was made. First, the x, y, and z positions of each point were exported into AutoCAD 3D Civil and a triangular irregular network (TIN) surface generated – similar to meshing the model in Agisoft PhotoScan Professional. The TIN is then simplified because the 3D printer does not have the same resolution as the digital model. Then the TIN is converted to a solid object using the D3D Surface AutoDesk add-in by DotSoft. The solid object is imported into the 3D printing software, in this case Cura, and the model is printed using the Lulzbot Taz 6 3D printer using reels of polylactic acid (PLA) or co-polyester plastic.

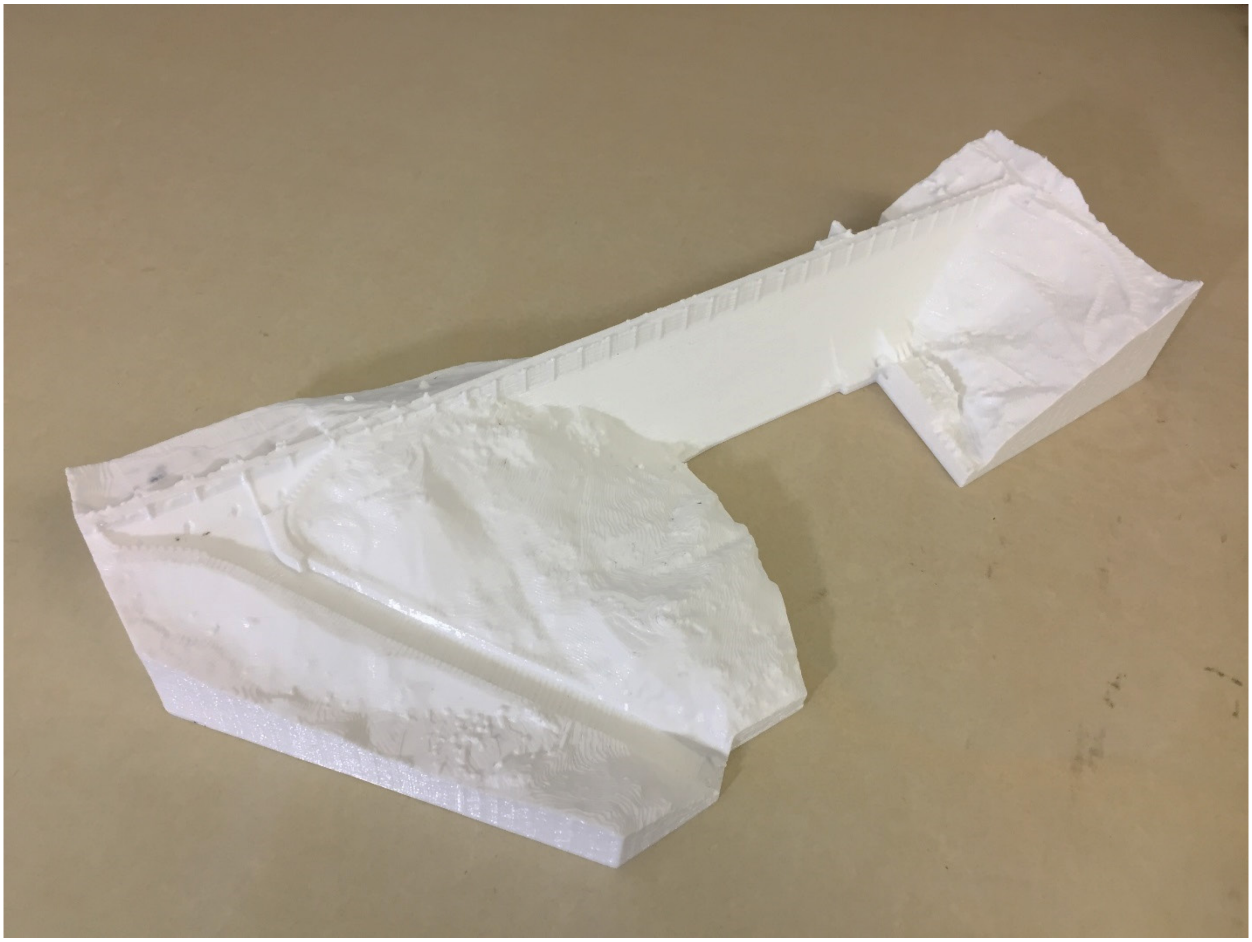

Figure 10: 3D Print of the Photogrammetric Model of Elephant Butte Dam

Radiometric IR Thermography

The radiometric IR data was processed the same way the optical data was in Agisoft PhotoScan Professional. The result was two separate models as before: the dam and spillway. Because of the low resolution, simultaneous points between the two models were difficult to find and the models were left separate. The downstream face of the structure was captured when the face was in the shadow and thus the surface had not heated enough to show any noticeable defects (see Figure 11). In addition, a lack of resolution created problems at the north side of the structure (left side of Figure 11) where the crest appears to sag.

A comparison was made between the IR and optical models in Figure 12. Note the white vertical areas in the IR model correspond with the dark stains from the crest drains in the optical model. This occurs because the dark stains absorb more heat than the surrounding areas. In addition, several other hot spots can be seen which correspond to adjacent areas where spalling has occurred. The presence of spalling is usually an indicator that deterioration is occurring adjacent to the spall.

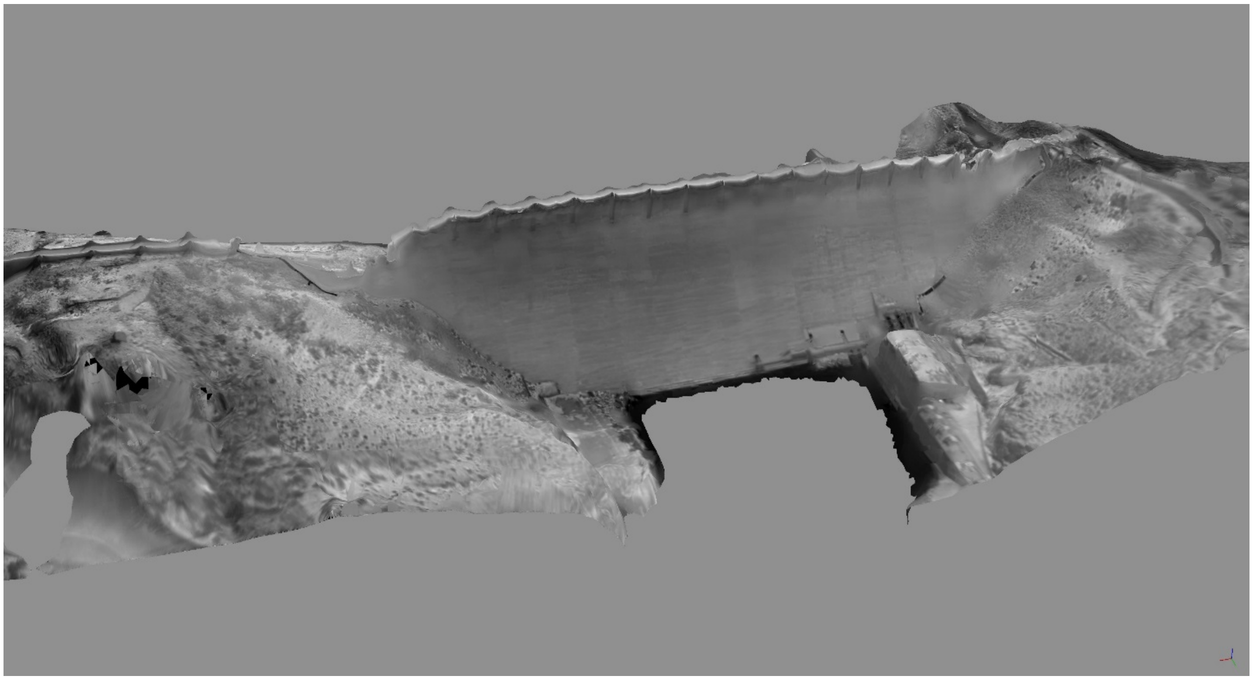

Figure 11: Downstream Face IR Model

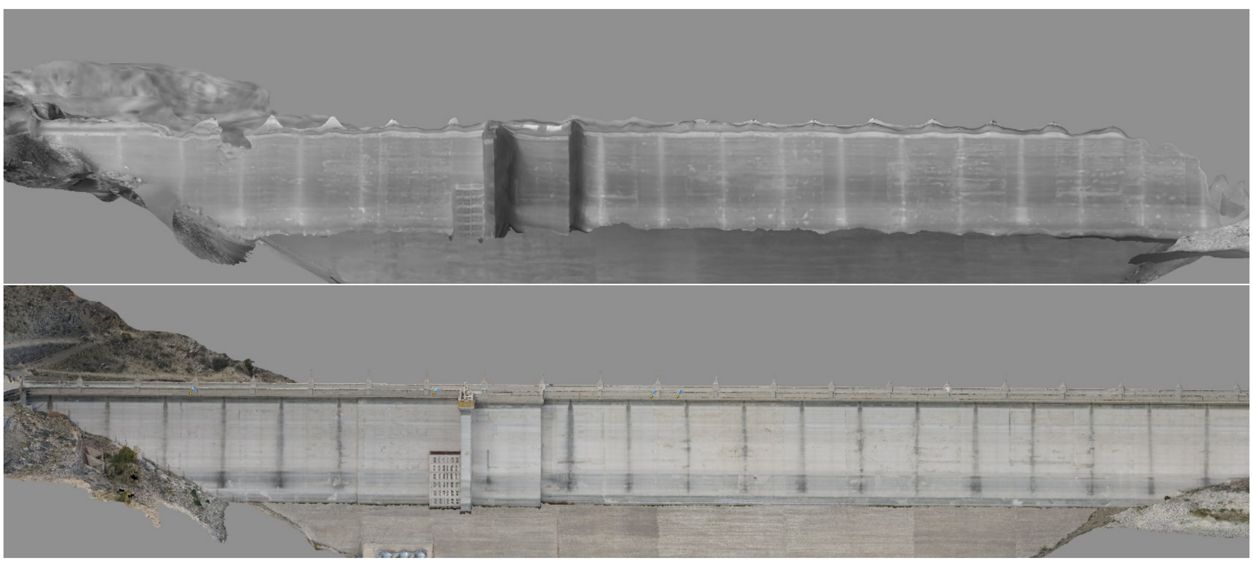

Figure 12: Upstream Face IR Model (top) and Optical Model (below)

Figure 13 shows the IR orthophoto of the spillway. While not easily visible in the document image, there are a series of hot spots indicating delaminations in locations just below the spillway gate outlets and about halfway down the spillway. These correspond to many of the mapped delaminations shown in Appendix A. The delaminations that cannot be seen in the IR image are probably due to the lack of resolution.

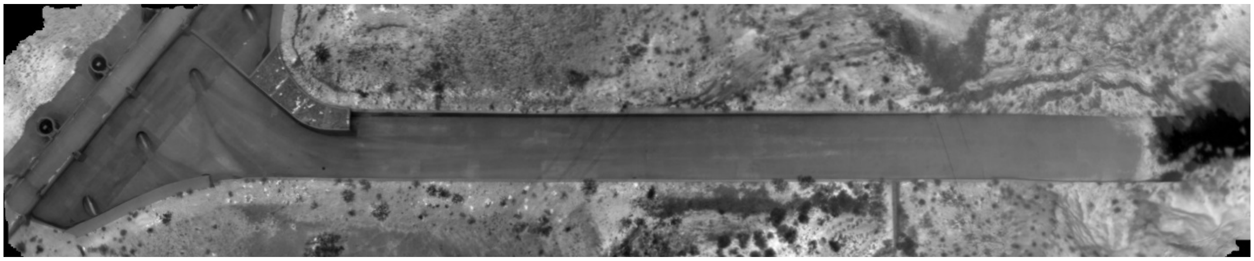

Figure 13: IR Orthophoto of the Spillway

Conclusions

While many challenges were faced in completing this project including acquiring UAS contracts and reduced resolution due to flight operations concerns, the project showed that UAS data collection can be reliably conducted to provide quality data. These challenges underscores Reclamation's need for an internal UAS program.

Considerable interest was generated for this project. Presentations of the project overview, UAS data collection and photogrammetric processing were given at the joint USACE, TVA and USBR 2016 Power O&M Workshop in Muscle Shoals, Alabama, the LC Region August 2016 Technical Tuesday via webinar, the Reclamation Photogrammetry Users Group Webinar #3 and has been accepted for presentation at the 2017 USSD Annual Meeting and Conference in Anaheim, California [8]. A Technical Tuesday presentation is also being arranged for the TSC in Denver.

In summary, following considerations are given:

- UAS can be used for reliable data collection
- Reclamation can benefit by investing in its own UAS inspection and data collection program
- UAS data collection gimbals should be completely isolated from the UAS to prevent blur caused by vibration
- Autonomous UAS flights make data collection higher quality, safer, and repeatable
- Higher resolution can be achieved by increasing the lens focal length while maintaining the same offset
- Other UAS navigation systems feature collision avoidance sensors that allow closer offsets without the risk of an impact
- Photogrammetry data verification can be performed onsite with mobile workstation computers
- Photogrammetry can be performed on optical and IR images
- Photogrammetric processing can be used to create highly detailed topographical maps
- 3D prints can be made from photogrammetric data
- Radiometric IR thermography can be used to identify subsurface defects though some features may be masked in an irregularly colored surface (dark spots absorb heat and vice versa)

References

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[8] M. Klein, "Photogrammetry Users Group," US Bureau of Reclamation , Denver, 2016.

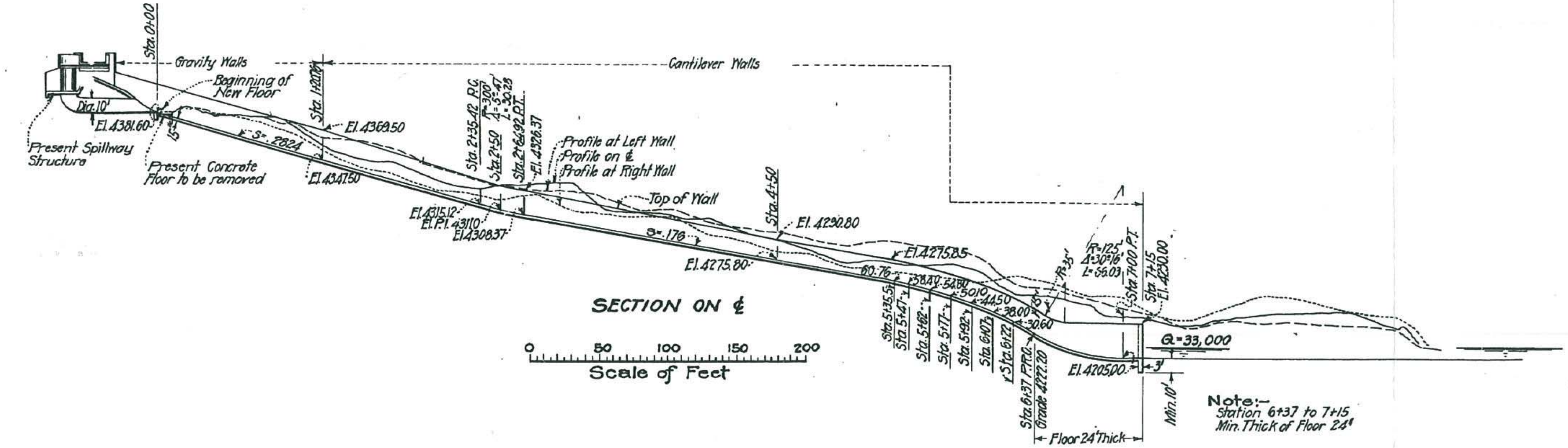
Appendices

Appendix A: Delamination Map

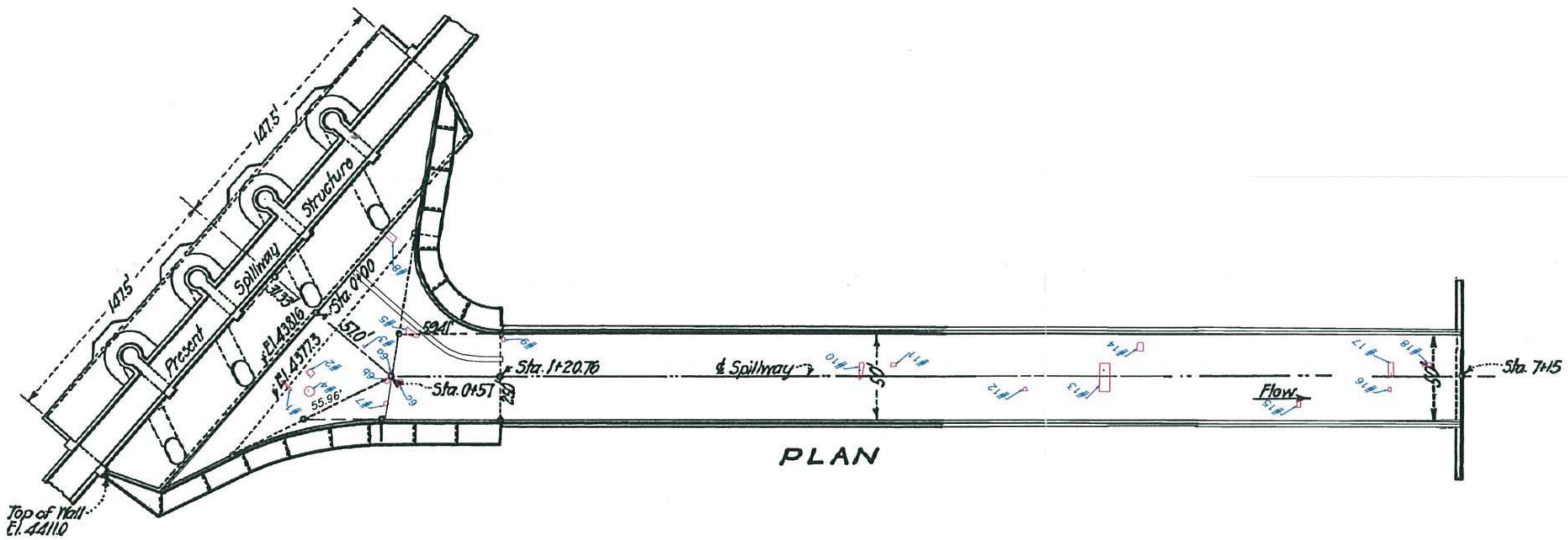
Appendix B: Photogrammetry Processing Report

Appendix C: Topographical Map

Appendix A: Delamination Map



0 50 100 150 200
Scale of Feet



PLAN

REFERENCE DRAWINGS:
SPILLWAY LINED CHANNEL---------24-C-13

Hollow Sounding Areas

Hole #	Depth if drilled	APPROX. STATION
1	1'-8.4"	0+12
2	1'-6.6"	0+19
3	1'-6"	0+33
4	1'-5.4"	0+25
5	N/A	0+67
6	1'-4.2"	0+57
7	N/A	0+57
8	1'-7.4"	0+03
9	N/A	1+20.76
10	1'-8.4"	3+30
11	N/A	3+50
12	N/A	4+26
13	1'-1.8"	4+72
14	N/A	4+92
15	N/A	5+84
16	N/A	6+36
17	1'-3"	6+36
18	N/A	6+57

RECLAMATION
Managing Water in the West

ALWAYS THINK SAFETY

U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
RIO GRANDE PROJECT
ELEPHANT BUTTE DIVISION – NEW MEXICO

ELEPHANT BUTTE DAM
SPILLWAY
PERIMETER SURVEY OF HOLLOW AREAS ON SPILLWAY FLOOR
LOCATION SURVEY

DESIGNED
DRAWN B. KALMINSON
CHECKED D. WRIGHT
TECH. APPR. B. KALMINSON, ENGINEERING TECHNICIAN CIVIL
APPROVED G. HANSON, GENERAL ENGINEER

ELEPHANT BUTTE, NM 2012-05-24

LOCATION SURVEY

24-508-2780
SHEET 1 OF 1

DATE AND TIME PLOTTED Thursday, May 24, 2012 2:02:19 PM
PLOTTED BY KALMINSON, BENJAMIN N

CAD SYSTEM AUTOCAD
CAD FILENAME 24-508-2780_01_00.DWG

Appendix B: Photogrammetry Processing Report

Elephant Butte Dam

Processing Report

06 September 2016

Survey Data

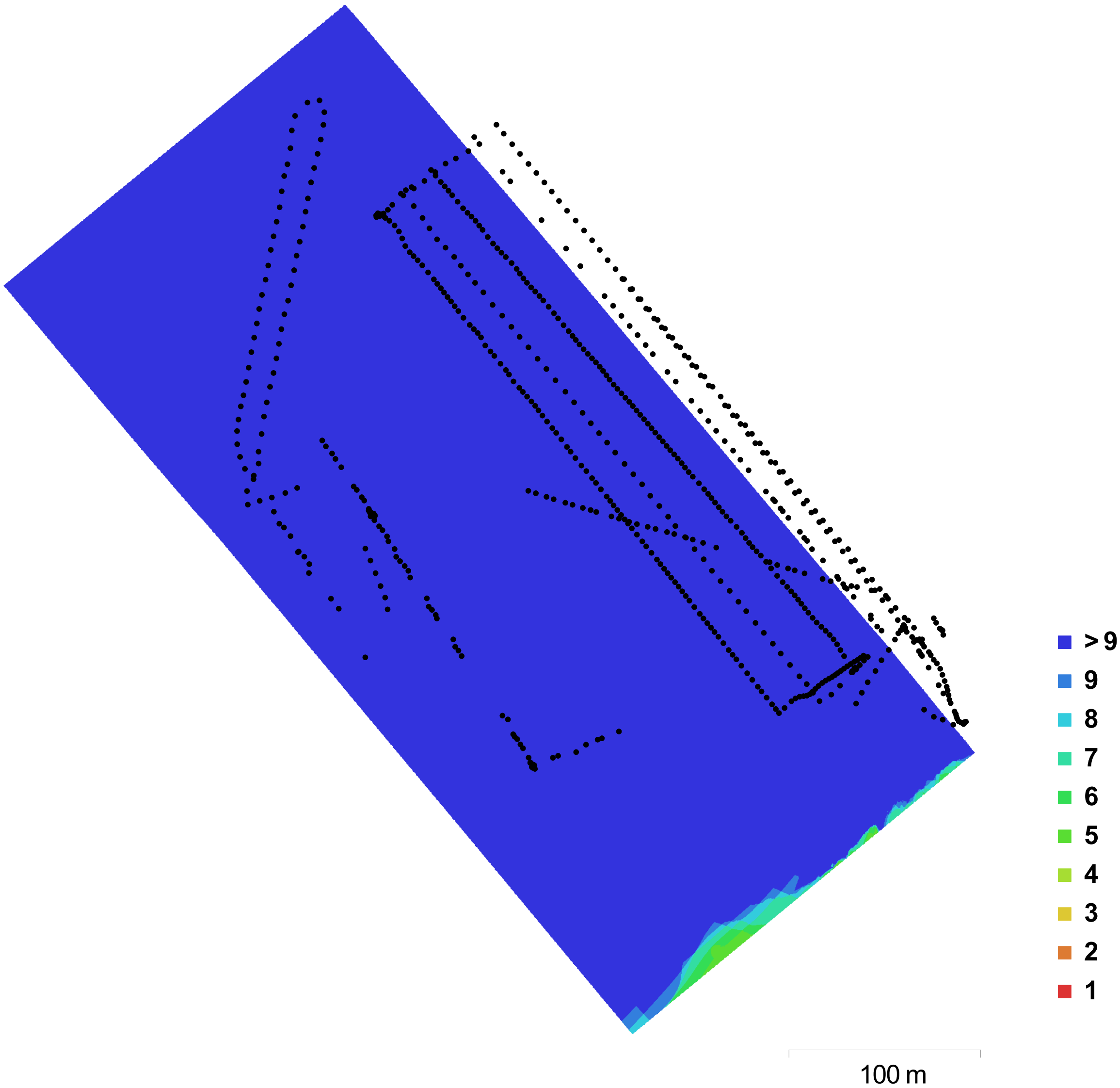


Fig. 1. Camera locations and image overlap.

Number of images:	1,386	Camera stations:	692
Flying altitude:	89.3 m	Tie points:	423,271
Ground resolution:	1.46 cm/pix	Projections:	2,037,105
Coverage area:	0.118 km²	Reprojection error:	0.691 pix

Camera Model	Resolution	Focal Length	Pixel Size	Precalibrated
ILCE-6000 (20 mm)	6000 x 4000	20 mm	4 x 4 μm	No
ILCE-6000 (35 mm)	6000 x 4000	35 mm	4.04 x 4.04 μm	No
ILCE-6000 (20 mm)	6000 x 4000	20 mm	4 x 4 μm	No

Table 1. Cameras.

Camera Calibration

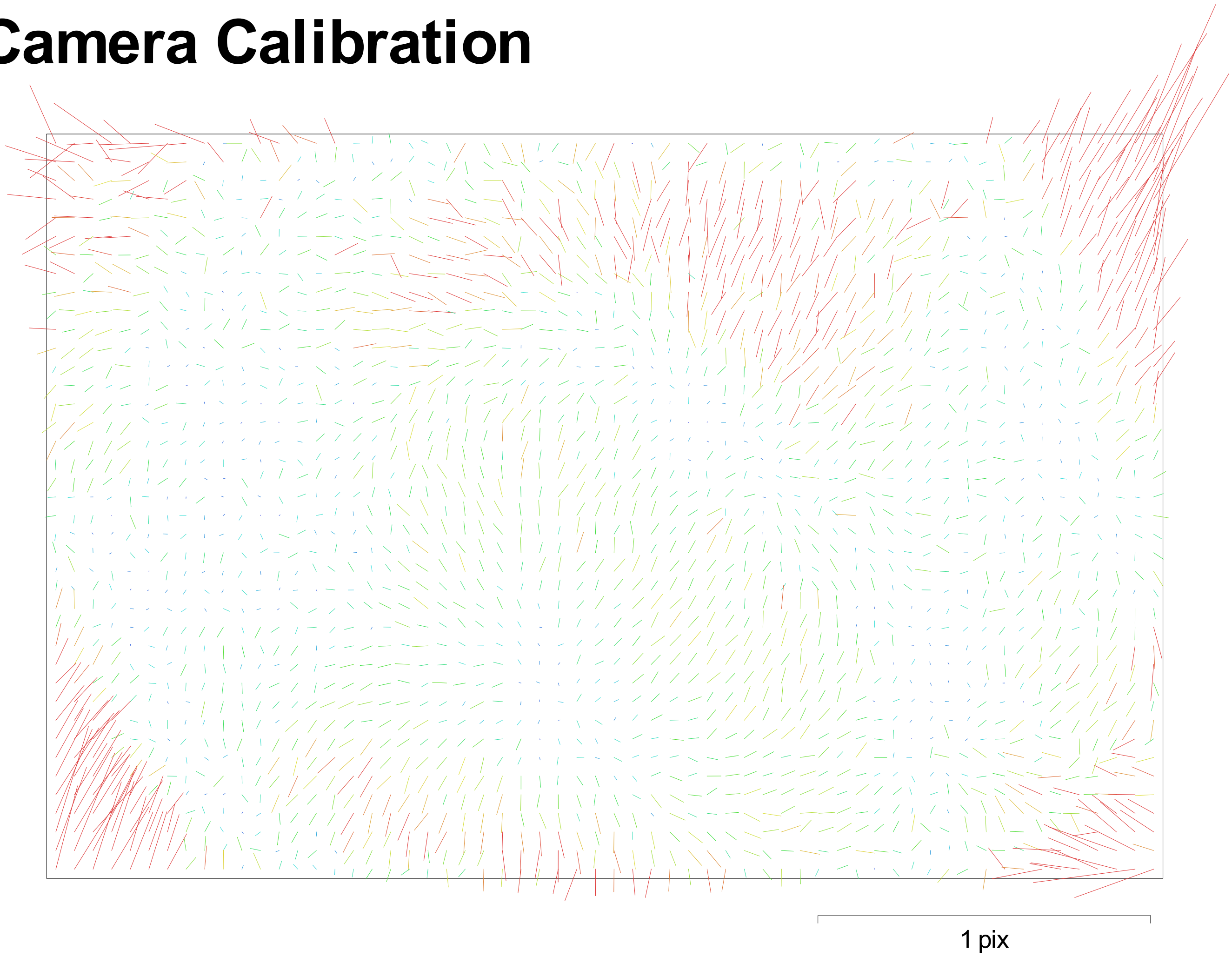


Fig. 2. Image residuals for ILCE-6000 (20 mm).

ILCE-6000 (20 mm)

581 images

Resolution	Focal Length	Pixel Size	Precalibrated
6000 x 4000	**20 mm**	**4 x 4 μm**	**No**

Type:	Frame	F:	5238.84
Cx:	-43.6549	B1:	0.481752
Cy:	-16.8148	B2:	0.196163
K1:	-0.151307	P1:	-0.000553705
K2:	0.0811042	P2:	-0.00033149
K3:	0.15907	P3:	0.480021
K4:	-0.131059	P4:	1.61116

Camera Calibration

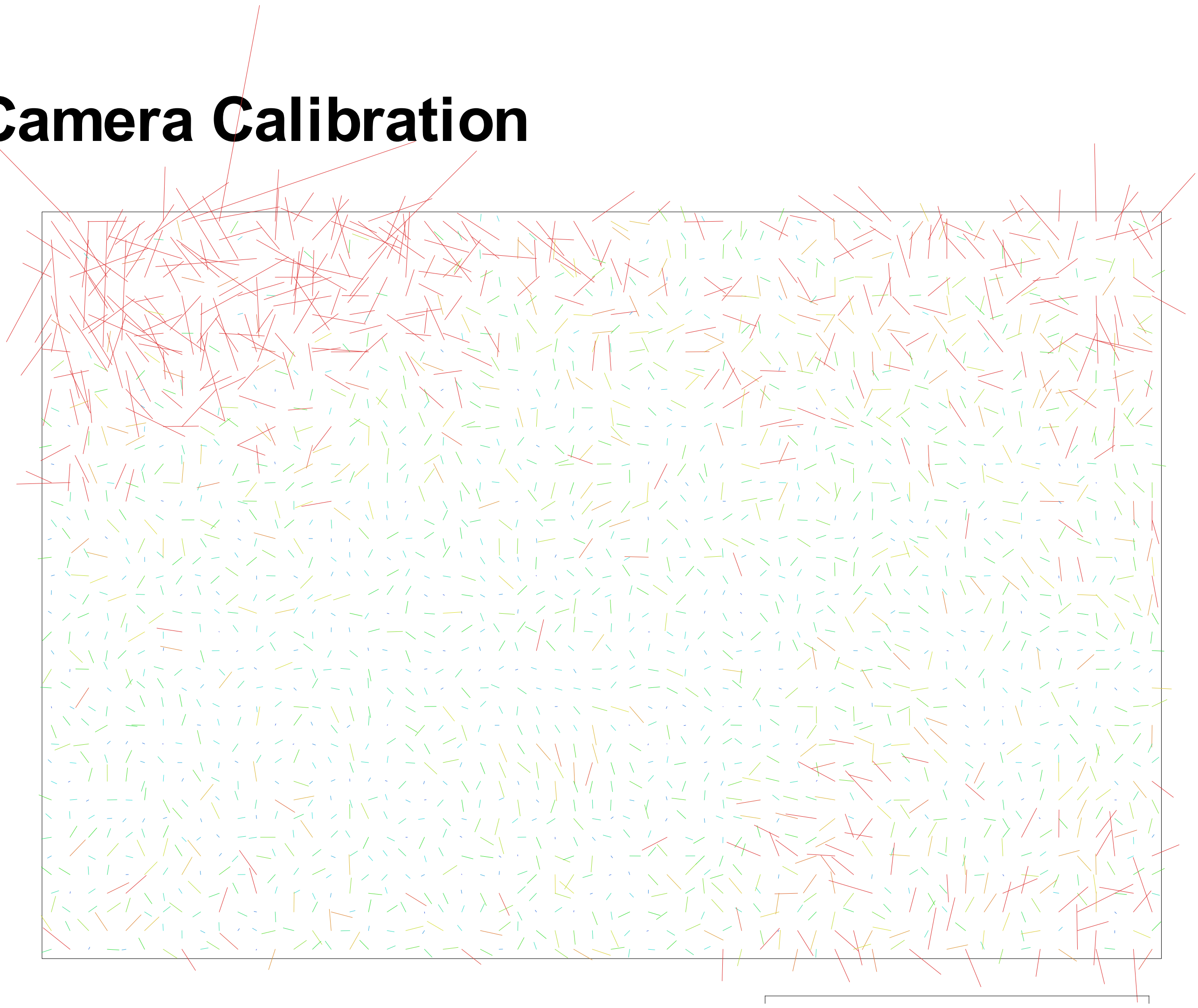


Fig. 3. Image residuals for ILCE-6000 (35 mm).

ILCE-6000 (35 mm)

112 images

Resolution	Focal Length	Pixel Size	Precalibrated
6000 x 4000	**35 mm**	**4.04 x 4.04 µm**	**No**

Type:	Frame	F:	9254.08
Cx:	-11.3098	B1:	-1.30774
Cy:	-53.7978	B2:	-1.98062
K1:	0.0695775	P1:	0.000352607
K2:	-0.56547	P2:	-0.00132682
K3:	2.44146	P3:	-2.49122
K4:	-5.92989	P4:	4.81535

Camera Calibration

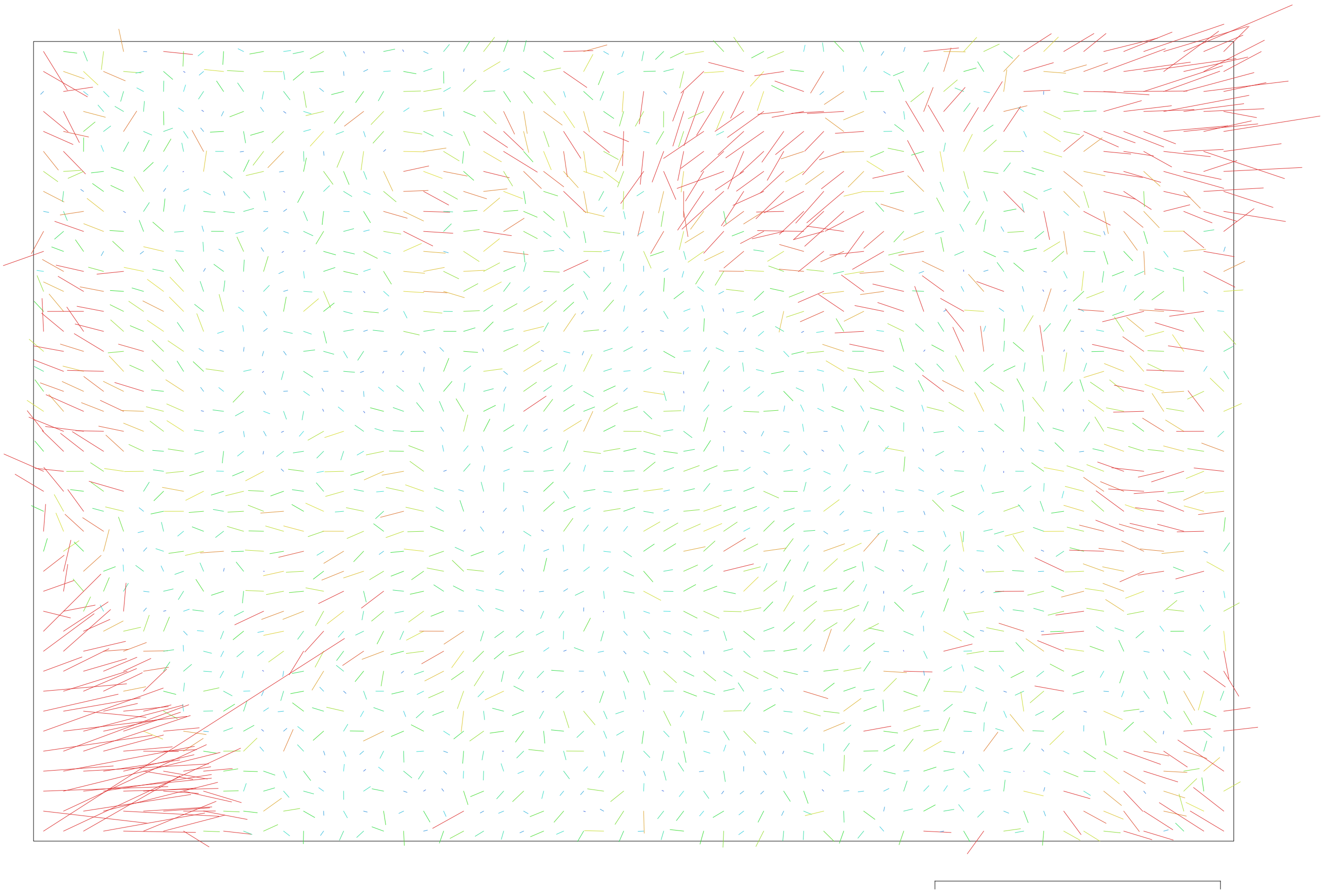


Fig. 4. Image residuals for ILCE-6000 (20 mm).

ILCE-6000 (20 mm)
581 images

Resolution	Focal Length	Pixel Size	Precalibrated
6000 x 4000	**20 mm**	**4 x 4 μm**	**No**

Type:	Frame	F:	5231.37
Cx:	-45.9845	B1:	0.1291
Cy:	-22.2776	B2:	-0.296472
K1:	-0.146496	P1:	-0.000751245
K2:	0.0475488	P2:	-0.000674231
K3:	0.249501	P3:	0
K4:	-0.217724	P4:	0

Ground Control Points

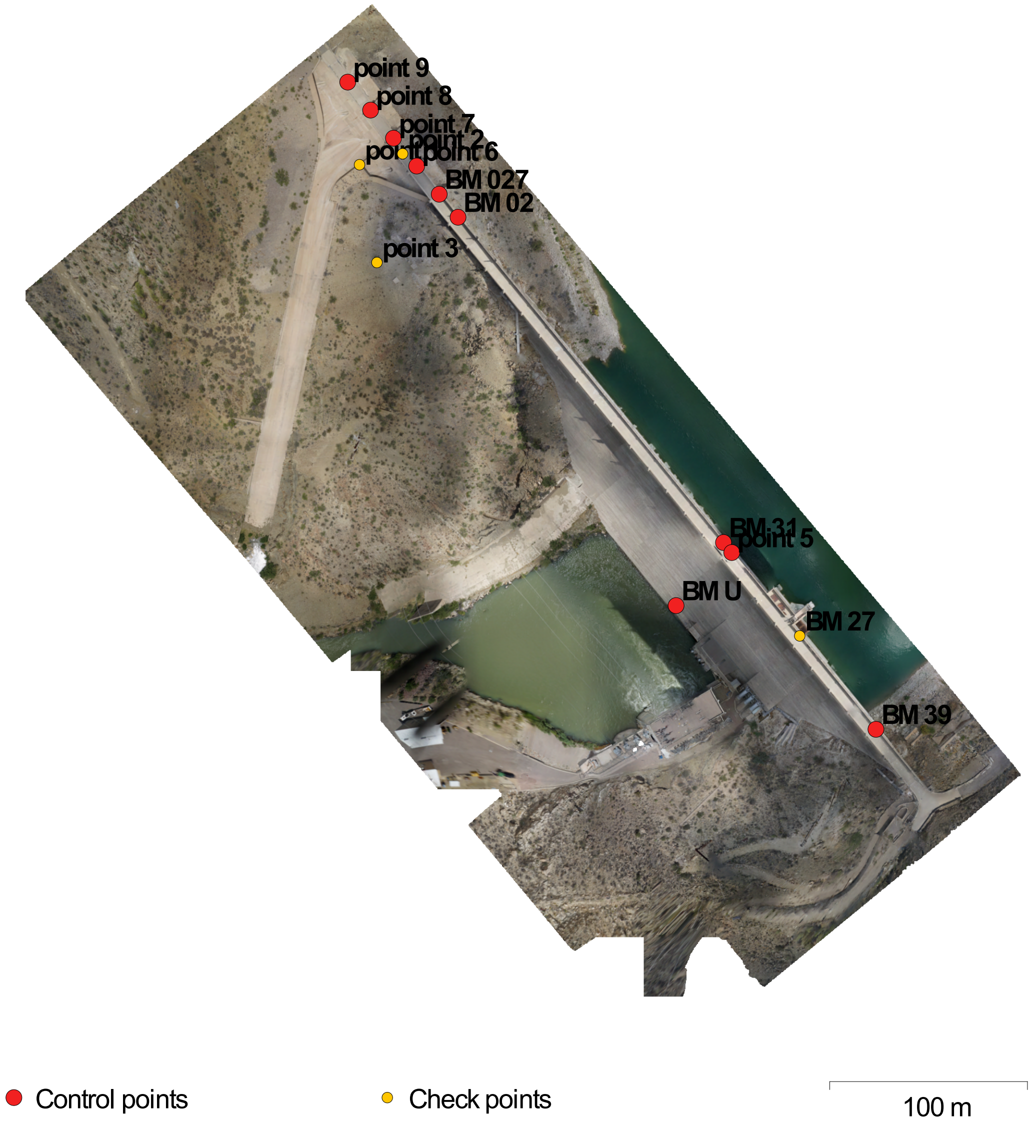


Fig. 5. GCP locations.

Count	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total (cm)	Image (pix)
10	1.19762	0.933742	2.02266	1.51861	2.52929	0.835

Table 2. Control points RMSE.

Label	X error (cm)	Y error (cm)	Z error (cm)	Total (cm)	Image (pix)
BM 39	0.583025	-0.764346	1.58644	1.85497	0.950 (14)
BM 027	-0.922697	1.01523	0.477954	1.45275	0.766 (24)
BM 02	-0.349913	0.519217	0.403245	0.744737	1.104 (28)
BM U	-2.08084	-0.0184317	-2.60181	3.33161	1.222 (19)
BM 31	0.529958	0.710346	-0.715891	1.13927	1.328 (22)
point 5	0.980829	0.692092	0.587514	1.33648	1.050 (33)
point 6	-1.68771	-0.688935	2.63463	3.20379	0.000 (12)
point 7	-0.0917459	-0.919514	1.51041	1.77067	0.000 (21)
point 8	1.42724	1.15336	-4.57394	4.9283	0.000 (29)
point 9	1.60085	-1.78884	0.482652	2.44859	0.000 (34)
Total	**1.19762**	**0.933742**	**2.02266**	**2.52929**	**0.835**

Table 3. Control points.

Label	X error (cm)	Y error (cm)	Z error (cm)	Total (cm)	Image (pix)
point 1					1.731 (34)
point 2					1.098 (49)
point 3					0.360 (38)
BM 27					1.632 (31)
Total					

Table 4. Check points.

Digital Elevation Model

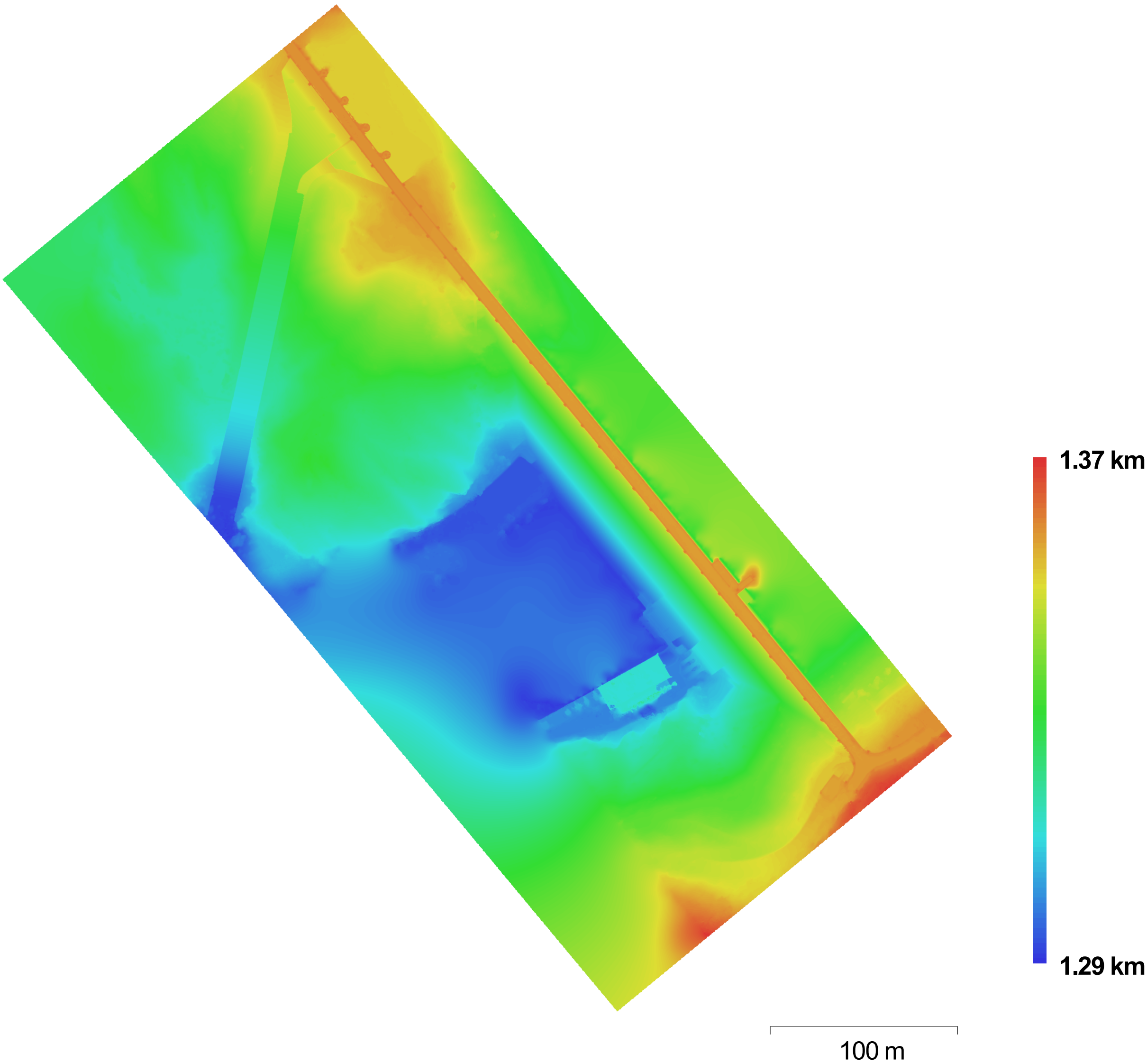


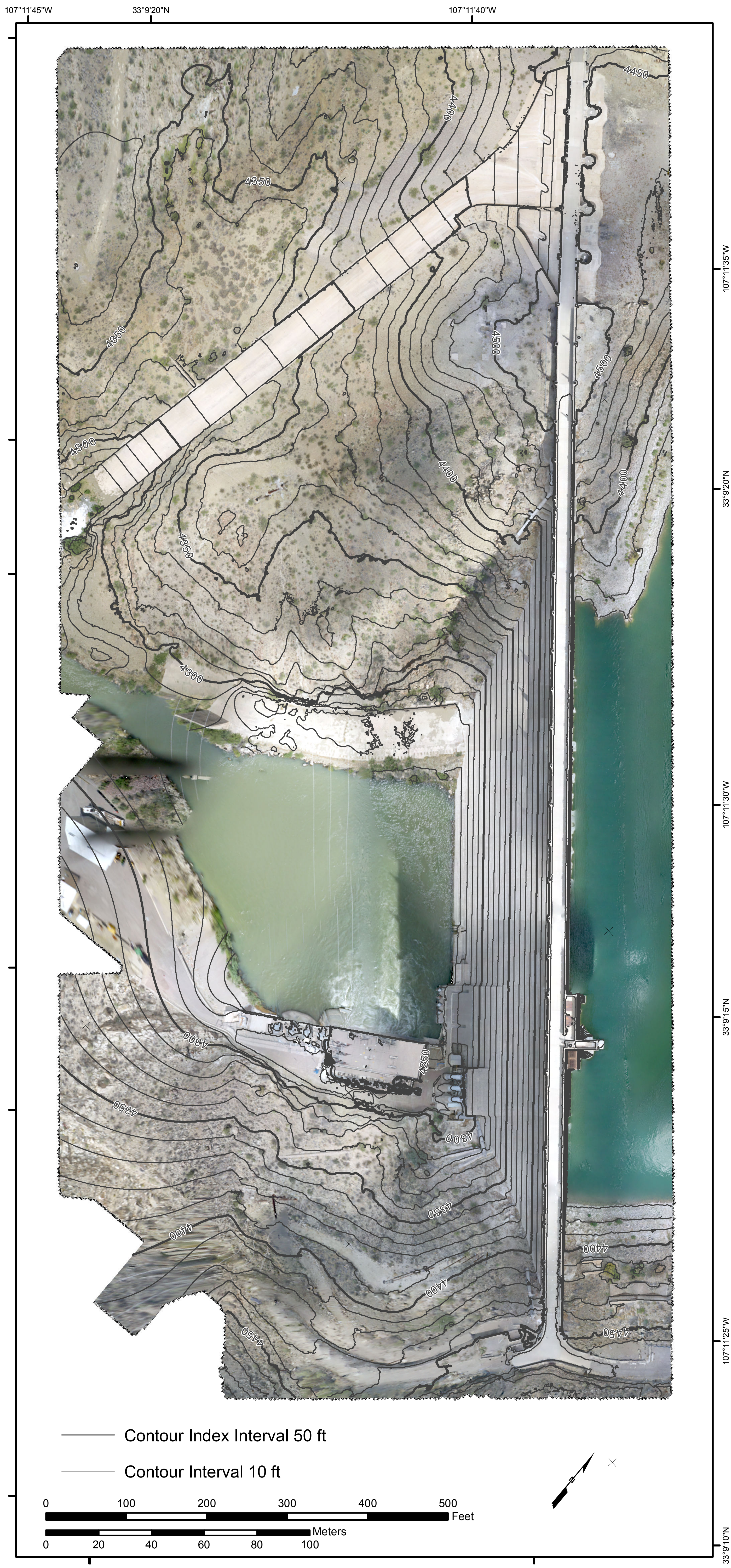
Fig. 6. Reconstructed digital elevation model.

Resolution:	5.84 cm/pix
Point density:	293 points/m²

Processing Parameters

General	
Cameras	1386
Aligned cameras	692
Markers	14
Coordinate system	NAD83(2011) / New Mexico West (ftUS) (EPSG::6533)
Point Cloud	
Points	423,271 of 3,735,196
RMS reprojection error	0.134684 (0.69143 pix)
Max reprojection error	0.486971 (16.4852 pix)
Mean key point size	4.46305 pix
Effective overlap	4.11021
Dense Point Cloud	
Points	45,367,337
Reconstruction parameters	
Quality	Medium
Depth filtering	Aggressive
Model	
Faces	8,041,409
Vertices	4,030,220
Texture	16,384 x 16,384 x 2, uint8
Reconstruction parameters	
Surface type	Arbitrary
Source data	Dense
Interpolation	Enabled
Quality	Medium
Depth filtering	Aggressive
DEM	
Size	8,709 x 9,275
Coordinate system	NAD83(2011) / New Mexico West (ftUS) (EPSG::6533)
Reconstruction parameters	
Source data	Dense cloud
Interpolation	Enabled
Processing time	1 minutes 34 seconds
Orthomosaic	
Size	34,599 x 36,943
Coordinate system	NAD83(2011) / New Mexico West (ftUS) (EPSG::6533)
Channels	3, uint8
Blending mode	Mosaic
Reconstruction parameters	
Surface	DEM
Enable color correction	No
Processing time	25 minutes 50 seconds
Software	
Version	1.2.6 build 2834
Platform	Windows 64 bit

Appendix C: Topographical Map


107°11'45"W
33°9'20"N
107°11'40"W
107°11'35"W
33°9'20"N
107°11'30"W
33°9'15"N
107°11'25"W
33°9'10"N
4450
4400
4350
4300
4500
4250
Contour Index Interval 50 ft
Contour Interval 10 ft
0
100
200
300
400
500
Feet
Meters
0
20
40
60
80
100