RECLAMATION

Managing Water in the West

Unmanned Aerial System (UAS) Data Collection at Reclamation Sites

Research and Development Office
Science and Technology Program
Final Report ST-2019-7104-01

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

September 2019

Mission Statements

Protecting America's Great Outdoors and Powering Our Future

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Cover Photograph:

Operating a UAS at Hoover Dam.

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REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*
T1. REPORT DATE: SEPTEMBER 2019	**T2. REPORT TYPE:** FINAL RESEARCH REPORT	**T3. DATES COVERED**
T4. TITLE AND SUBTITLE Unmanned Aerial System (UAS) Data Collection at Reclamation Sites Research and Development Office, Science and Technology Program, Final Report ST-2019-7104-01		**5a. CONTRACT NUMBER** XXXR4524KS-RR4888FARD1803101 (8) **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER** 1541 (S&T)
6. AUTHOR(S) Matthew Klein (mjklein@usbr.gov), Jakeb Prickett (jprickett@usbr.gov), and David Salas (desalas@usbr.gov)		**5d. PROJECT NUMBER** ST-2019-7104-01 **5e. TASK NUMBER** **5f. WORK UNIT NUMBER** 86-68530, 86-68260, and 86-68260
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Matthew Klein, Principal Investigator Bureau of Reclamation, Technical Service Center Concrete and Structural Laboratory, 86-68530 PO Box 25007, Denver CO 80225-0007		**8. PERFORMING ORGANIZATION REPORT NUMBER**
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: Bureau of Reclamation DOI: U.S. Department of the Interior **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** ST-2019-7104-01
12. DISTRIBUTION / AVAILABILITY STATEMENT Final report can be downloaded from Reclamation's R&D Web site: https://www.usbr.gov/research/		
13. SUPPLEMENTARY NOTES		

14. ABSTRACT *(Maximum 200 words)* Using unmanned aerial systems (UAS) for data collection will help reduce the costs associated with data collection, improve data quality, and increase safety. It is estimated that by using UAS to transfer the data collection sensor from slow and restrictive ground-based control to a more fluid and spatially unrestrained platform, data collection times can be reduced between 50 and 75 percent. Data collection quality is improved by positioning the sensor in the exact position required and by the ability to access features that are nearly impossible for human entry without specialized equipment and procedures. Using UAS to collect data for these types of features greatly improves safety.

15. SUBJECT TERMS
Unmanned Aerial Systems, UAS, Data Collection

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**93**	**19a. NAME OF RESPONSIBLE PERSON** Matthew Klein
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	U		**19b. TELEPHONE NUMBER** 303-445-2368

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

BUREAU OF RECLAMATION

Research and Development Office
Science and Technology Program

Concrete and Structural Laboratory, Technical Service Center, 86-68530

Final Report ST-2019-7104-01

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Acronyms and Abbreviations

3D	three-dimensional
3DR	3D Robotics
ACE	Aviation Centered Education
ADSRB	Airworthiness Flight Safety Review Board
AGL	above ground level
APS-C	advanced photo system type-C
ASA	Aviation Supplies and Academics
ASCE	American Society of Civil Engineers
ATC	air traffic control
AUVSI	Association for Unmanned Vehicle Systems International
BDS	BeiDou Navigation Satellite System
BLM	Bureau of Land Management
BVLOS	beyond visual-line-of-sight
CAD	computer aided design
CBP	U.S. Customs and Border Protection
CEATI	Canadian Electricity Association Technologies International
CFR	Code of Federal Regulations
COA	Certificate of Waiver or Authorization
COTS	commercial off-the-shelf
CSL	Concrete and Structural Laboratory
DJI	Da Jiang Innovations
DOF	depth of field
DOI	U.S. Department of the Interior
DSM	digital surface model
EVLOS	extended visual-line-of-sight
F	Fahrenheit
FAA	Federal Aviation Administration
FCC	Federal Communications Commission

FRRB	Flight Readiness Review Board
FWS	U.S. Fish and Wildlife Service
GB	gigabyte
GCP	ground control point
GCS	ground control station
GIS	geographical information system
GLONASS	Globalnaya Navigazionnaya Sputnikovaya Sistema
GNSS	global navigation satellite system
GP	Great Plains
GPS	Global Positioning System
GPU	graphics processing unit
GS	ground station
GSA	General Services Administration
HD	high definition
HDMI	high-definition multimedia interface
IACRA	Integrated Airman Certification and Rating Application
IAT	Interagency Aviation Training
ILMF	International LiDAR Mapping Forum
IR	infrared
ISO	International Organization for Standardization
IT	Information Technology
kV	kilovolts
lbs	pounds
LC	Lower Colorado
LIDAR	Light Detection and Ranging
LiPo	lithium polymer
MAV	micro air vehicle
MOA	Memorandum of Agreement
mph	miles per hour
NACE	National Association of Corrosion Engineers

NAM	National Aviation Manager
NAMP	National Aviation Management Plan
NAS	National Airspace System
NCI	National Critical Infrastructure
NDVI	normalized difference vegetation index
NGS	National Geodetic Survey
nm	nanometer
NMSU	New Mexico State University
NOAA	National Oceanic and Atmospheric Administration
NOC	National Operations Center
NOTAM	Notice to Airman
NPS	National Park Service
O&M	operation and maintenance
OAS	U.S. Department of the Interior Office of Aviation Services
OPM	Operational Procedures Memorandum
OPUS	Online Positioning User Service
OTAO	Oklahoma-Texas Area Office
PAO	Provo Area Office
PIC	pilot-in-command
PN	Pacific Northwest
R&D	Research and Development
RAM	random-access memory
RAM	Regional Aviation Manager
RC	remote control
RCC	roller-compacted concrete
Reclamation	Bureau of Reclamation
RTK	real-time kinematic
S&T	Science and Technology
SJRRP	San Joaquin River Restoration Program
SSD	solid-state drive

sUAS	small unmanned aerial system/small unmanned aircraft system
TB	terabyte
TFR	Temporary Flight Restriction
TSC	Technical Service Center
UAS	unmanned aerial system/unmanned aircraft system
UAV	unmanned aerial vehicle
UC	Upper Colorado
U.S.	United States
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey
USSD	United States Society on Dams
VO	visual observer
VPS	vision positioning system
VTOL	vertical take-off and landing
WCAO	Western Colorado Area Office
Wi-Fi	wireless

Executive Summary

The Bureau of Reclamation (Reclamation) is faced with an increasingly aging infrastructure composed of many features and parts that require continual maintenance and inspection. There is a need throughout Reclamation to increase data collection quality while reducing costs in order to manage and maintain its facilities. However, collecting quality inspection data requires significant resources and can be costly in terms of time, money, and safety.

Unmanned aerial system (UAS) technology has many attributes that can benefit Reclamation. UAS technology could improve data collection methods for major areas such as condition assessments and inspections, geologic mapping and monitoring, and geographic information. Using a UAS can reduce the costs associated with data collection, improve data quality, and increase safety. A UAS can collect high-quality data more cost-effectively and safer than other alternatives.

Thus, a Reclamation Science and Technology Program research project was proposed to create a testing and evaluation platform that was wide ranging and would ultimately provide a robust synopsis of the technology. This project, spanning 3 years, essentially birthed UAS operations at Reclamation's Technical Service Center (TSC) by allowing personnel to research training and equipment, and conduct demonstrations to answer whether UAS is a tool that can used within Reclamation's mission.

During the first year, 6 personnel completed training requirements as set forth by the Federal Aviation Administration (FAA), the Department of the Interior's (DOI) Office of Aviation Services (OAS) and Reclamation. During this time, TSC also acquired several airframes, sensors and supporting equipment and completed a demonstration at Upper Stillwater Dam in Utah. While the demonstration was not successful, TSC gained invaluable experience and applied this towards future demonstrations including a return to Upper Stillwater Dam the following year. TSC also conducted monthly UAS meetings which included TSC UAS pilots and others throughout Reclamation interested in UAS, UAS technology and how it can be used to complete projects.

Through the second year, TSC's pilot pool dropped to three personnel but kept an aggressive schedule to gain more experience operating UAS for quality data collection. During this time, sixteen total missions were conducted in support of this and other projects. Collaborations were made across Reclamation including offices in Reclamation's Upper Colorado (UC) Region, Lower Colorado (LC) Region, and Great Plains (GP) Region. The projects included rock face monitoring, sedimentation mapping, structural movement monitoring, and seepage detection among others.

Finally, in the third year, TSC added four pilots to the team by developing a UAS pilot application process. The UAS team also investigated procedures for indoor use of UAS and conducted several test flights. The team attended and presented at UAS conferences within Reclamation, other Federal agencies and within industry. Due to the special close-range, high resolution UAS data collection techniques developed by TSC, it was recognized as a leader in the use of UAS for inspection, deterioration monitoring and conditions assessment. TSC capped the project off by purchasing new airframes, recently made available by DOI OAS.

While this project has demonstrated the invaluable contribution that UAS can make, there is still much more to be accomplished. UAS technology is rapidly evolving and new applications are discovered every day that can make data collection better quality, in less time and safer. It is the Reclamation’s responsibility to investigate and implement UAS to accomplish its mission.

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Introduction

The definition of a UAS is somewhat loose and can be used to mean unmanned aerial system, unmanned aircraft system, unoccupied aircraft system, small unmanned aircraft system (sUAS), unmanned aerial vehicle (UAV), micro air vehicle (MAV), or drone. The term "unmanned aerial system" or UAS typically refers to the airframe, controller and sensor and "unmanned aerial vehicle" refers to just the airframe.

Objectives

The objective for this Reclamation Science and Technology (S&T) Program research project was quite broad and was to demonstrate that UAS can be used to collect data better, cheaper and safer than traditional methods. Because the UAS can position a sensor at any point in the air, a data collection sensor can be optimized to provide the best possible data including areas that are not easily accessible. Due to the optimized positioning, the amount of data is greater than could ever be attempted by traditional methods. In addition, because of the autonomous waypoint navigation, data collection can be repeatable, further reducing the initial costs of creating flight plans. Finally, because the pilot remotely operates the UAS and can choose the location of operation based on safety, the data collection is inherently safer.

Background

Brief History of UAS at the U.S. Department of the Interior

The history of UAS within the DOI begins with OAS. OAS is responsible, in part, for providing policy, training, and airframe authorization for all aviation within DOI. Its first use of UAS began with a fleet of ex-military drones, operated mostly by the United States Geological Service (USGS). Some of the airframes available were a ducted fan vertical-take-off-and-landing, or VTOL, system called the T-Hawk and fixed-wing systems including the Raven and Super Bat (see Figure 1) [1].

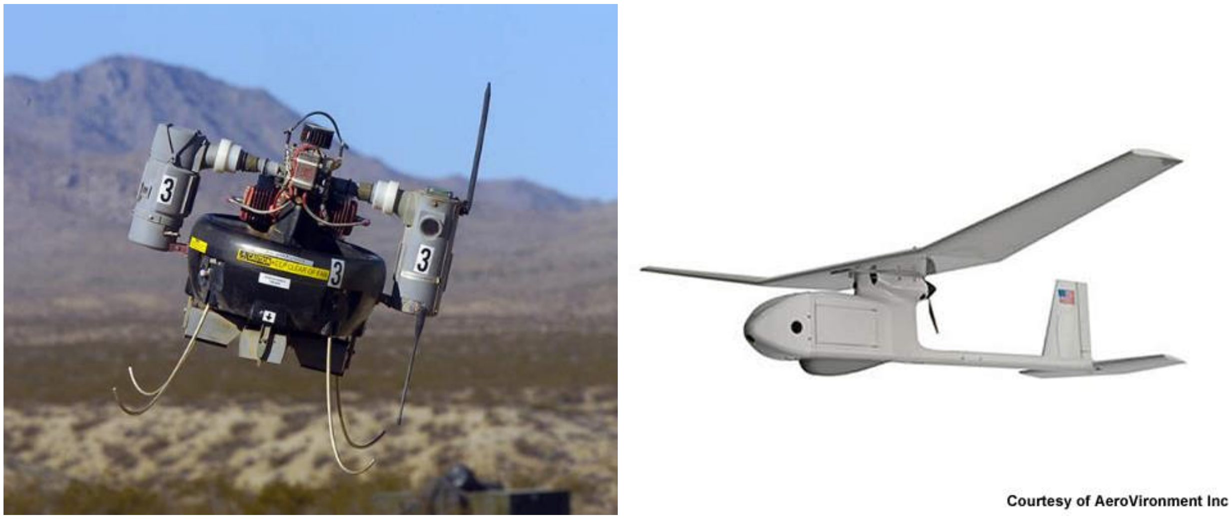

Figure 1.—Early DOI airframes: T-Hawk (left) [2] and Raven (right) [3].

Brief History of UAS at Reclamation

The UAS effort at Reclamation began in 2012 and was originally spearheaded by the Pacific Northwest (PN) Region's geographic information systems (GIS) group in Boise, Idaho. It also included efforts from TSC's Emergency Management and GIS Group (now the Geographic Applications and Analysis Group) in Denver, Colorado. The applications for UAS were fairly limited to river mapping and aerial media testing, though other applications were proposed [4].

More interest in UAS developed between 2012 and 2015 through the heavy commercialization of the industry and with advances in multi-rotor, lithium-polymer (LiPo), accelerometer and gyro-stabilized payload gimbals; lightweight/high-resolution digital sensors; and integrated flight controller technologies [5]. This made the cost of entry relatively inexpensive and allowed control of the UAS with minimal training and effort.

DOI authorized its bureaus to operate UAS upon satisfactory completion of in-house training and through cooperation of the agency with the FAA. DOI maintained a Certificate of Waiver or Authorization (COA), which allowed DOI employees the authority to operate UAS within the National Airspace System (NAS). In addition, in August 2016, the FAA legalized the use of commercial UAS through its 14 Code of Federal Regulations Part 107 rules (14 CFR Part 107). Shortly afterwards, DOI OAS updated its Operational Procedures Memorandum – 11 (OPM-11) to reflect the newer, less complicated rules. Accordingly, Reclamation updated its National Aviation Management Plan (NAMP) to allow its employees easier access to UAS training and airframe acquisition.

Proposal Development

In early 2016, several groups within Reclamation's TSC, with support from the PN Region, began discussing applications of UAS and how to implement the technology. The TSC groups represented included the Concrete, Geotechnical and Structural Laboratory (now the Concrete and Structural Laboratory (CSL)), Geographic Applications and Analysis Group, and the

Geology and Geotechnical Support Group (now the Engineering Geology and Geophysics Group), along with the PN Region's GIS Group.

The proposal team worked with Reclamation's S&T Program through the Research and Development Office (R&D Office) to develop a proposal that would initialize UAS acquisition, produce UAS pilots, and demonstrate UAS capability in a variety of applications, primarily within the TSC expertise, but also to share the knowledge and expertise with other Reclamation regions. In addition, the proposal also anticipated knowledge transfer outside of Reclamation to other Federal agencies and private companies with similar infrastructure and industries.

Previous Work

Scientists and engineers from the PN region conducted UAS operations several years prior, although TSC employees were actively collaborating with the PN region. The first UAS activities within Reclamation began in 2012 with the release of the first Reclamation Annual UAS Report [6]. The report documented the establishment and growth of the UAS Community of Interest.

In 2013, TSC released a report which reviewed applications of the aforementioned T-Hawk UAS [4]. This report also covered many of the details for operating a UAS at Reclamation and was intended, in part, as a resource for operating UAS commercially at Reclamation.

Also, in 2013, TSC collaborated with USGS, the National Park Service (NPS), and the Bureau of Land Management (BLM) to conduct a proof-of-concept study with the Raven fixed-wing UAS. The study monitored erosion of the Elwha River in Washington state and it was the first time a UAS-certified Reclamation employee operated a UAS in support of Reclamation's mission (see Figure 2) [7].

Figure 2.— Launch of a UAS at Elwha River, Washington [7].

In 2014, TSC's Geographic Applications and Analysis Group, along with the DOI Executive Aviation Subcommittee Work Group conducted a survey to review Reclamation's UAS needs and desired applications [8].

The TSC conducted another UAS airframe review in 2014. The airframe in this report was the MQ-9 Predator B, a much different UAS than proposed earlier. In this project, Reclamation submitted data collection requests to the U.S. Customs and Border Protection (CBP); however, the CBP denied all Reclamation requests without any comments [9].

In 2016, Reclamation's LC Region conducted a comprehensive evaluation of the feasibility and versatility of UAS to accomplish Reclamation's mission and thereafter published a report. The findings of the report concluded that acquiring training and airframes within DOI policy was a lengthy process (note that this was prior to the FAA's 14 CFR Part 107 rules) and that UAS adoption within Reclamation was risky [10].

In 2017, the UAS Community of Interest, which was initiated in 2012, transitioned into practical implementation of UAS technology [11]. In addition to maintaining an email distribution of interested parties throughout Reclamation and an online repository for UAS-related information, the UAS Community of Interest supported both training associated with UAS and knowledge transfer at prominent professional organizations.

Reclamation's Aviation Authority

Model aircraft and military UAS have been operated long before the FAA released UAS rules and required certification of UAS for-hire or commercial operators. However, since the FAA released its Code of Federal Regulation Title - Aeronautics and Space, Part 107 - Small Unmanned Aircraft Systems (14 CFR Part 107) rules, the process for operating UAS commercially is now defined and streamlined. These rules have also affected the way DOI and Reclamation can operate UAS.

DOI OAS was established in 1973 to increase efficiency and improve safety in aircraft activities [12]. To accomplish this, OAS also maintains a relationship with the FAA above the minimum requirements. These relationships, in the form of a Certificate of Waiver or Authorization (COA) and Memorandum of Agreement (MOA), allow for expanded UAS operational boundaries over the 14 CFR Part 107 rules.

14 CFR Part 107 - Small Unmanned Aircraft Systems [13]

The main objective of the 14 CFR Part 107 rules for Small Unmanned Aircraft Systems is safety [14]. Prior to 14 CFR Part 107, Section 333 of the FAA Modernization and Reform Act of 2012 governed UAS operations, and operators of UAS for commercial purposes had to apply for an exemption to Section 333 [15].

Some of the highlights from the FAA Summary of Small Unmanned Aircraft Rules (14 CFR Part 107) are shown in Table 1 [16].

Table 1.— Highlights of the FAA Summary of Small Unmanned Aircraft Rules (14 CFR Part 107)

Aircraft Requirements	FAA airworthiness certification is not required.[1]
	FAA registration and labeling of registration number on UAS
Pilot Requirements	Must hold a remote pilot certificate or operate under the direct supervision of a remote pilot certificate holder[2]
	Conduct preflight checks
Operational Limitations	UAS weight should be less than 55 pound (lbs)

[1]Note that airworthiness certification is required per OPM-11.
[2]OPM-11 requires that only a current DOI remote pilot manipulate the controls unless the employee is being evaluated or is attending UAS training.

	UAS should be operated within visual-line-of-sight (VLOS) of the pilot
	Operations are only allowed during daylight
	UAS must yield right-of-way to manned aircraft
	Operations only allowed in Class G airspace (without air traffic control [ATC] permission)
	Operations are not allowed over people not involved with the operations
	Altitudes are limited to 400 feet above ground level (AGL)

U.S. Department of the Interior Operational Procedures Memorandum - 11

In addition to the requirements set forth by 14 CFR Part 107, DOI provides policy for operations and management of DOI-operated UAS through OPM-11 (DOI Use of Unmanned Aircraft Systems [UAS]) [17]. It is within this document that the FAA and DOI agreements are detailed. These agreements allow for fewer operational limitations than 14 CFR Part 107, but also describe stricter requirements for the DOI UAS pilot.

The additional agreements outlined in OPM-11 include a MOA allowing UAS operations up to 1200 feet AGL and night operations if they are conducted at least 5 miles from the nearest airport [18]. It also includes a COA with special air traffic control (ATC) provisions for operating in extended visual-line-of-sight (EVLOS) and beyond visual-line-of-sight (BVLOS) [19]. Other agreements include provisions for emergency and standalone COAs for specific missions.

OPM-11 also gives the requirements for contracting UAS flight services or end product contracts. Contracted UAS flight services must adhere to the DOI Departmental Manual, Part 353 Chapter 1: Aircraft Contracting (353 DM 1) and OPM-35: Identification of End Product/Service and Flight Service Procurement [20] [21]. End product contracts allow for quick procurement of UAS services as long as DOI and Reclamation do not have operational control of the UAS. End product contracts are used to collect the data required for a project without specifying how the data are to be collected, that is, the DOI employee cannot imply any aviation operations related to the data collection.

A summary of OPM-11 rules pertaining to UAS, remote pilots, and operational limitations are given in Table 2.

Table 2.—Summary of OPM-11 Rules

Aircraft Requirements	Must be acquired through OAS only
	Must have a current OAS-36U DOI UAS Data Card
Pilot Requirements	Must possess FAA Remote Pilot Certificate
	Conducts preflight checks
	Must record flight time in OAS-2U
	Comply with training requirements, including evaluation by an OAS UAS Pilot Inspector or equivalent
	Must maintain flight proficiency and airframe currency
Operational Limitations	A Project Aviation Safety Plan (PASP) is required for each UAS mission
	Maximum altitudes are limited to between 400 (FAA COA and 14 CFR Part 107) and 1200 feet AGL (1200 ft AGL altitudes are based on the FAA/DOI MOA; requires a minimum 5 miles from an airport)
	Night operations without an FAA waiver (based on the FAA/DOI MOA and require a minimum 5 miles from an airport; requires DOI OAS approval)
	EVLOS and BVLOS operations (based on the FAA COA; requires DOI OAS approval)

Reclamation National Aviation Management Plan

Reclamation's NAMP is the next authority for Reclamation's UAS pilots and establishes Reclamations National Aviation Program [22]. The NAMP not only provides details related to UAS, but also to any aviation-related activity. With respect to UAS operations, the NAMP includes additional details related to Reclamation's mission over those required by the 14 CFR FAA Part 107 rules, one of the FAA/DOI COAs or MOAs, and OPM-11.

Additional major requirements include a Notice-to-Airmen (NOTAM) is required for each UAS mission, and that all UAS missions require a flight manager/Pilot-in-Command (PIC) and a visual observer (VO) who are both certified remote pilots. The NAMP also lists additional training requirements above the requirements of OPM-11 and 14 CFR Part 107.

The NAMP also specifies that each Reclamation region operating UAS develop a Mishap Response Plan and UAS Security Plan. The Mishap Response Plan features checklists of actions and a contact list to reference during an aviation accident. The UAS Security Plan gives details about UAS and UAS peripheral storage, transportation, and maintenance.

Reclamation manages several National Critical Infrastructure (NCI) facilities. DOI coordinated with the FAA to formally restrict UAS flights near these infrastructures in the fall of 2017 [23]. These Temporary Flight Restrictions (TFR) are described in the NAMP. Operations in these areas require approval from the FAA or from the facility superintendent.

The NAMP is periodically updated to represent changes in the way Reclamation interfaces with aviation. Refer to the updated NAMP for any changes not denoted in this report.

Reclamation Aviation Authority

The NAMP also establishes an order for Reclamation aviation authority (see Table 3). This arrangement is implemented, in part, to approval UAS flights at the appropriate risk level.

Table 3.—Summary of Reclamation's Aviation Authority.

Order	Position	Description
I	Commissioner	Responsible for the aviation management program
II	Director – Security, Safety and Law Enforcement	Oversees aviation policy
III	National Aviation Manager (NAM)	Liaison to OAS, conducts UAS asset management and verifies pilots
IV	Regional Aviation Manager (RAM)[3]	Coordinates UAS procurement, maintains regional aviation records, coordinates pilot training
V	Pilot Supervisor	Reviews PASPs and ensures compliance to policy
VI	Pilot	Conducts UAS mission planning and operations to meet client needs

[3]To be replaced by a Reclamation-wide Aviation Management Specialist.

Interagency Collaboration

Reclamation was one of the last DOI agencies to adopt UAS usage. Other DOI agencies and Federal departments have years of experience using UAS. This section outlines some of the interactions that Reclamation has had with some of these agencies, and the results.

U.S. Department of the Interior Office of Aviation Services

Reclamation's collaboration with DOI OAS has largely been in the form of policy, training and airframe acquisition. OAS is headquartered in Boise, Idaho, though some of its staff is located at the Denver Federal Center (DFC) in Denver, Colorado. While access to OAS is technically through the RAM and NAM, OAS is always ready to offer aviation-related assistance at any time.

Reclamation has also worked with DOI OAS to provide vendor demonstrations. Reclamation's infrastructure is a very challenging environment for UAS, and Reclamation personnel regularly research UAS that might have capabilities more suited.

Reclamation's more advanced UAS pilots have partnered with OAS and USGS to help provide advanced training courses to DOI employees.

U.S. Geological Survey

UAS experts, from the USGS National UAS Project Office have been the most instrumental in assisting Reclamation's TSC with establishing its UAS operations. The project office is also located at the DFC, making it convenient to work together. USGS UAS pilots established protocol for operating UAS at a test area at the DFC and acts as the contact for testing UAS procedures at nearby Jefferson County Open Space parks for several Reclamation projects.

In early spring of 2017, the USGS National UAS Project Office and USGS Science Coordinator hosted a meeting at their UAS laboratory to share USGS's capabilities and applications with Reclamation personnel interested in UAS, their supervisors, the TSC Director, and the R&D Office. Because of this initial collaboration, Reclamation and USGS regularly participate in trainings and capability presentations for each other's meetings and workshops.

Also, in the spring of 2017, USGS hosted the first annual Federal UAS Workshop in Mountain View, California at the National Aeronautics and Space Administration's (NASA) Ames Research Center. The workshop brought together all DOI bureaus as well as other federal agencies to discuss UAS and UAS operations. This workshop is also an extension of the monthly DOI UAS User Monthly Call/Webinars that are still curated by the USGS and feature updates from DOI OAS.

Because of USGS's advanced UAS equipment and capabilities, Reclamation has worked out opportunities to collaborate on data collection. In 2018, TSC contracted USGS to operate a single rotor UAS equipped with LIDAR (Light Detecting and Ranging) to collect data at Hart Mine Marsh in California.

Bureau of Land Management

BLM boasts the largest number of UAS pilots in DOI according to the *U.S. Department of the Interior Unmanned Aircraft Systems (UAS) Program 2018 Use Report* [24]. Reclamation has limited collaboration with BLM with the exception of BLM being largely responsible for establishing UAS data analysis methods to generate high accuracy data products and sharing the methods throughout DOI and other agencies. In addition, BLM also participates in Reclamation workshops to provide presentations on their agency UAS capabilities and applications.

U.S. Army Corps of Engineers

The U.S. Army Corps of Engineers' (USACE) Jacksonville District hosts an annual USACE UAS Community of Practice meeting in which Reclamation UAS pilots have been attending for the past two years, and with plans to continue. Through the UAS Community of Practice, Reclamation was able to connect USACE UAS operators with DOI OAS and its UAS policy.

In addition, Reclamation partnered with USACE in 2015 to test a UAS capable of conducting tunnel inspections at Glen Canyon Dam Penstock in northern Arizona. Reclamation has remained as a partner to provide feedback on the design of the UAS. Reclamation and USACE also collaborated to present annual updates at the USACE-USBR (U.S. Bureau of Reclamation) Research Collaboration Update Workshop.

Training

In order to receive certification for operating UAS within DOI and Reclamation, several training requirements must be met. Prior to signing up for training, however prospective UAS pilots must be nominated by the RAM and NAM.

UAS Pilot Nominations – Technical Service Center

Reclamation's NAMP gives the guidelines for pilot nominations. Currently, requests for UAS pilot training are approved by the RAM and NAM for forwarding to DOI OAS. According to the NAMP, requests for nomination must consider the number of pilots, UAS workload, and if the proposed UAS application has other non-UAS alternatives.

In 2018, TSC implemented a UAS Pilot Recruitment process that included an application by a prospective UAS pilot. The application process required information as to the applicant's intentions and how their work or group's work could benefit from UAS operation. The application also inquires as to the number of projects that the applicant has been team lead on as a metric to understand if the applicant can successfully manage all the different parts of being a UAS pilot. Three references are requested, as well as demonstration of approval by the group supervisor and division chief.

The TSC UAS Pilot Recruitment process was successfully employed in the nomination of an additional four pilots for the TSC. This process is currently being reviewed by the NAMP review committee as a process for all of Reclamation by inclusion in the NAMP.

Federal Aviation Administration Remote Pilot Certification

Prior to completing the DOI requirements for operating a UAS, the prospective pilot must obtain a 14 CFR Part 107 remote pilot certificate. The certification requirements are to pass the FAA UAS Remote Pilot Knowledge Test [25].

The 2-hour test covers many aspects of aviation including applicable regulations, airspace knowledge, and understanding aviation weather among others. There are third-party resources available to study prior to the test, such as the Aviation Supplies and Academics (ASA) Remote Pilot Test Prep study guides and online courses such as RemotePilot101.com. These guides/courses take between 8 and 12 hours to complete and typically offer sample exams.

The FAA UAS Remote Pilot Knowledge Test must be scheduled at an FAA Knowledge Testing Center. Once the test is completed satisfactorily, the prospective pilot must apply for a remote pilot certificate in the FAA Integrated Airman Certification and Rating Application (IACRA) system.

For current manned pilots, the process is simpler. A 2-hour, online training course – Part 107 small Unmanned Aircraft Systems ALC-451 – must be completed. The manned pilot then applies for the remote pilot certificate in the IACRA system.

U.S. Department of the Interior/Reclamation Remote Pilot Certification

While the FAA certification allows UAS pilots to operate UAS commercially, DOI and Reclamation have additional training requirements specified in OPM-11 and the Reclamation NAMP. These training requirements include coursework, webinars and classroom training as well as a week-long, in-person UAS instruction, demonstration and evaluation prior to obtaining the DOI OAS-30U Remote Pilot Certificate (see Table 4). In addition, the supervisors of the pilots (those responsible for approving PASPs and ensuring compliance) are required to take training as well.

Interagency Aviation Training

The platform for DOI training is the Interagency Aviation Training (IAT) Website [26]. Prospective DOI UAS pilots must create an account and associate their supervisor with their account. Then, the pilot will complete the listed requirements shown in Tables 4 and 5.

Table 4.—DOI OAS Initial Training Requirements (Adapted from [27])

IAT Course Code	Title	Format	Length
A-100	Basic Aviation Safety	Online: On-demand[4]	5 Hrs
A-110	Aviation Transportation of Hazardous Materials	Online: On-demand	2 Hrs
A-200	Mishap Review	Online: On-demand[3]	2 Hrs
A-203	Basic Airspace	Online: On-demand	3 Hrs
A-450-PWRK	Pre-Work: A-450 small Unmanned Aircraft System (sUAS) Basic Remote Pilot Course	Online: On-demand	0.5 Hrs
A-450	Small Unmanned Aircraft System (sUAS) Basic Remote Pilot Course	Classroom: On-demand/scheduled	32 hrs

[4]Other formats are available

Table 5.—Reclamation Initial Training Requirements (Adapted from [27])

IAT Course Code	Title	Format	Length
A-107	Aviation Policy and Regulations	Online: On-demand	1 Hr
A-116	General Awareness Security Training	Online: On-demand	0.5 Hrs
A-205	Risk Management I	Webinar: Scheduled	2 Hrs
A-302	Personal Responsibility and Liability	Webinar: Scheduled	2 Hrs
A-305	Risk Management II (requires A-205)	ACE Conference: Scheduled	4 Hrs
A-311	Aviation Planning (requires A-205 or equivalent experience)	Webinar: Scheduled	3 Hrs

In addition to most of the training being offered through the IAT Website, many courses are also offered at the Aviation Centered Education (ACE) conference held several times a year in different locations around the country. ACE is presented by DOI OAS trainers and bureau volunteers who have taken and completed trainer requirements.

Certification Renewal

Both the FAA and DOI remote pilot certifications must be renewed every two years. For the FAA, 14 CFR Part 107 pilots are required to complete the Part 107 Recurrent Knowledge Test, while 14 CFR Part 61 pilots will complete an online course to stay current. Studying for the test is recommended, which can take up to 8 hours.

DOI requires the A-452R, Small Unmanned Aircraft System (sUAS) Remote Pilot Refresher Training. The training is 2 hours long and is offered by scheduled webinar. Credit can also be given if the pilot has instructed in an A-450 course.

Additional Requirements and Recommended Training

UAS pilots are required to maintain flight proficiency every 90 days. Flight proficiency includes, at a minimum, three take-offs and landings. Operating within a UAS flight simulator is also accepted to maintain proficiency, however operating an actual airframe is preferred.

There are several approved airframes available to DOI UAS pilots. Pilots must be evaluated about the basic operation of each by a DOI UAS inspector prior to operating. Once the pilot has demonstrated knowledge on that airframe, the pilot must maintain proficiency by operating that airframe at least once every 12 months.

While the coursework listed gives a UAS pilot the authority to operate UAS, experience in mission planning and in-the-air operations is vital. There are several opportunities for DOI UAS pilots to expand their knowledge including webinars from vendors and non-Federal aviation education, as well as courses offered from OAS and other DOI bureaus.

U.S. Department of the Interior Advanced UAS Workshop for Project Planning

In response to the fact that newly minted UAS pilots do not have the skills required for advanced mission planning and operations, DOI OAS arranged a weeklong course to have students gain experience with all aspects of an advanced UAS mission [28]. Some of the topics covered are developing a PASP, flight planning using pre-programmed waypoints, understanding sensor setup and capture, geotagging and georeferencing data, processing UAS derived data, evaluating data quality, and creating basic UAS projects.

While DOI initially established the format for the course, bureaus have been encouraged to adapt it to their agency mission. The courses are scheduled on-demand and often employees from other agencies can join in on any scheduled course. To register for a course, applicants will need nomination from the NAM.

Photogrammetry Workshops

Photogrammetry is one of the main uses for UAS data within DOI. Because the UAS can be preprogrammed to collect digital images accurately and repeatedly, the data can be used to develop highly precise photogrammetric products. Photogrammetry leverages the concept of overlapping or stereo images to triangulate the three-dimensional (3D) position of each pixel. This information is used to generate 3D models, digital surface models (DSM), and mosaic orthoimagery.

BLM’s National Operations Center (NOC) has long been recognized as a leader in highly accurate photogrammetric processing. In 2008, NOC published a manual on photogrammetry that includes methods for obtaining and processing quality data for accurate data products [29]. Since then, the NOC has established a weeklong training course to understand the process for photogrammetric processing. This course has been offered at several bureaus including USGS, the NPS, and Reclamation.

Reclamation Aviation Workshop

In response to the growing aviation community within Reclamation, the first annual Reclamation Aviation Workshop was introduced in the fall of 2018. The workshop is organized by the NAM and typically consists of policy updates, Reclamation staff presentations, technical demonstrations, facilitated aviation-related discussions, and training. The workshop is considered mandatory for all Reclamation personnel involved in aviation activities, including UAS, and is held in different locations each year.

Reclamation UAS Research Workshop

Early on, Reclamation's R&D Office, supported the growth and acceptance of UAS technology. Over the past decade, nearly $2 million of research funding through the S&T Program has been awarded in support of UAS capability and applications with respect to Reclamation's mission. In the spring of 2019, the R&D Office hosted a 2-day workshop in Denver, Colorado to bring together reports of UAS technological progress and brainstorm new applications (see Figure 3). It is expected that this workshop will continue annually.

Figure 3.—Demonstrating virtual reality (VR) at the Reclamation UAS Research Workshop.

Train-the-Trainer

DOI aviation training is assembled, and support provided by, OAS employees; however, DOI OAS relies largely on bureau volunteers to instruct the courses. Reclamation has not had representation in IAT in past years because its aviation program was dormant; however, with the growth of UAS in the bureau, Reclamation's involvement has been requested. Recently, Reclamation has committed several experienced UAS pilots to attend the IAT Train-the-Trainer (A-220) course to help fill the gap. Having Reclamation instructors will help facilitate specific DOI OAS training requirements outside of IAT and ACE and allow Reclamation to certify its own UAS pilots.

Equipment

It may be tempting to think of UAS as a toy, but the truth is that it is much more. The traditional components of an unmanned aircraft *system* are the controller, airframe and sensor. However, this report proposes that the *system* is actually the controller/airframe/sensor, the UAS crew, the ground control, flight planning software/hardware, crew communication equipment, aviation monitoring equipment, weather meters, mishap kit, etc. All of these require an in-depth knowledge of the specifications of each component in order to operate in the most efficient and safe manner. This section is not intended as an exhaustive review of all these components but rather to highlight some of the more important details.

Airframes

While there are currently dozens of commercial off-the-shelf (CTOS) airframes, DOI OAS is responsible for authorizing and purchasing airframes for DOI use. The criteria for selecting potential airframes requires coordination between the NAM and DOI OAS and is based on bureau needs. Once an airframe is nominated by a bureau, it may chosen by DOI OAS for evaluation by experts at the NASA’s Ames Research Center, according to criteria outlined in the Airworthiness Flight Safety Review Board (ADSRB) and the Flight Readiness Review Board (FRRB) Handbook [30]. The evaluation may also involve other Federal agencies as needed.

While many airframes may be of interest to each bureau, another responsibility of DOI OAS is to select airframes that can operate under a variety of missions and with a selection of payloads to keep the number of available airframes to a minimum. This way, standardized airframe training, proficiency, and tracking can be easily managed.

Airframes can be modified only with DOI OAS approval. If a modification is proposed, it must be tested before it can be implemented. Testing is coordinated with DOI OAS and other DOI bureaus with modification experience. Some of the modifications include range extending antennas, real-time kinematic (RTK) global navigation satellite system (GNSS) integration, third-party rotors, and leg extensions and strobe lights, among others.

The current DOI UAS fleet can be reviewed on the DOI UAS Website, and includes the Autel Robotics EVO, Parrot Anafi, Birds Eye View Aerobotics FireFLY6 PRO/S, 3DR Solo, and Pulse Vapor 55TM [31]. However, only the airframes that are being used at the TSC are described in this section.

3D Robotics Solo

The 3D Robotics (3DR) Solo is the workhorse of the DOI UAS fleet (see Figure 4). It was originally released in 2015 and was added to the DOI UAS fleet in 2016. In 2018, according to the *U.S. Department of the Interior Unmanned Aircraft Systems (UAS) Program 2018 Use Report*, there were 486 3DR Solos in the fleet, which represents over 90 percent of the total fleet. Reclamation has 26 3DR Solos and TSC has 6 of those. As of September 2019, TSC’s 3DR Solos have been operated a combined total of 90 flight hours.

Figure 4.—3DR Solo in flight.

The 3DR Solo quadcopter has been popular within DOI partly because it was the only airframe available that was affordable and could carry a sensor payload that was accurate and precise, but it is easy to operate and maintain too. It's reported range is approximately 0.5 mile, has a reported battery life of 20 minutes with a payload, a maximum speed of 55 miles per hour (mph), a maximum payload capacity of 420 grams, is about 10 inches tall, and has an approximate 18-inch square footprint [32]. The system is also able to transmit a 720p (720 pixels measured vertically, progressive scan) video signal to a connected mobile device running compatible software.

The observed battery life is about 10 to 12 minutes, or less, depending on the altitude. It has also been noted that about 25% of batteries fail to hold a charge during flights. Batteries with this rapid discharge phenomena are immediately removed from service.

The intended payload is the GoPro action camera using a 3DR removable three-axis mechanically-stabilized gimbal. This gimbal can power the camera and allows for control of the camera settings within the 3DR Solo mobile app. The gimbal can also be tilted. However, third-party and 3D printed fixed-gimbals have been developed that are compatible with a variety of payloads, including high-quality optical sensors, infrared (IR) thermal sensors, and multispectral sensors.

The 3DR Solo can be controlled by hand and is stabilized using GNSS so that it will hold its position if no commands are given by the operator. Because of the GNSS positioning, waypoints can be preprogrammed and loaded into the airframe flight controller for autonomous operation.

The 3DR Solo has several failsafe measures to prevent flyaways. If the airframe loses connection with the controller, it is programmed to return to the take-off position and land autonomously. If the airframe has lost GNSS positioning and connection with the controller, it will drift with any available wind and begin descending until it reaches the ground.

Parrot Anafi

The Parrot Anafi was tested in 2018 and joined the DOI UAS fleet in 2019. Its features include a small, portable, foldable quadcopter design with an integrated 4K (four thousand pixels measured horizontally) camera. It is also easy to operate and maintain. The range is 2.5 miles, has a battery life of 25 minutes, a maximum speed of 33 mph, is approximately 2-1/2-inches tall, and has an approximate 9-1/2-inch square footprint (unfolded) (see Figure 5). The folded size is approximately 9-1/2 by 2-1/2 by 2-1/2 inches. High Definition (HD) video is also transmitted at a resolution of 720p [33].

Figure 5.—The Parrot Anafi UAS.

The camera is integrated and cannot be swapped with other sensors. It is on a two-axis, mechanical-stabilized gimbal. The gimbal is unique in that it allows for a controlled tilt in a complete 180-degree movement (90 degrees upward and 90 degrees downward). As previously mentioned, the camera is 4K with a resolution of 21 megapixels and features a rolling shutter

[33]. The camera settings can also be set from the controller via the FreeFlight6 mobile application.

DOI OAS has also approved the thermal IR version of the Parrot Anafi. The resolution of the thermal IR sensor is relatively low, only 160 by 120 pixels.

The Parrot Anafi is GNSS-stabilized during flight and can be controlled with preprogrammed waypoint automation for photogrammetric data collection. In addition, the UAS features a downward facing vision positioning system (VPS) that allows it to operate in GNSS-denied environments and still hold its position without coasting or drifting.

Da Jiang Innovations (DJI) Mavic Pro and Matrice 600 Pro

According to a 2019 Forbes article, DJI is responsible for approximately 66 percent of the UAS global market [34]. While DJI UAS are feature rich and are affordable, DOI OAS has only just recently approved two of DJI's available airframe models.

One of the reasons for the delay in approval is due to alleged DJI cyber security concerns. These concerns led the U.S. Army to ban the use of DJI manufactured goods and software (which are made in China), as well as the Department of Homeland Security to issue a warning about "Chinese manufactured unmanned aircraft systems" and the risk they pose to national security [35] [36]. DJI did respond to both claims by offering to work with any organization to discuss cyber security issues and that customer data "is none of our [DJI] business" [37] [38]. Consequently, DJI released firmware updates that included a "private mode" on their commercially available equipment. This private mode did not allow the UAS, controller, or mobile device app to connect to the Internet [39]. In addition, in the summer of 2019, DJI released a Government Edition of its firmware/software app that ensures that UAS data is never transmitted from the UAS and is not shared with DJI [40]. DOI OAS followed up with a report summarizing 2 years of testing and evaluation that has allowed the use of certain DJI Government Edition solutions [41]. The approved DJI Government Edition UAS include the Mavic Pro and Matrice 600 Pro. However, the two approved UAS are only to be operated on non-sensitive projects.

The DJI Mavic Pro is a revolutionary quadcopter outfitted with vision positioning, acoustic sensors, and a collision avoidance system that is intuitive to operate (see Figure 6). It features a small portable, foldable design with 4K video recording, a range of 4.3 miles, a battery life of 27 minutes, a maximum speed of 40 mph, and is approximately 3-1/4 by 3-1/4 by 7-3/4 inches when folded. The DJI Mavic Pro transmits video at 720p or 1080p resolution depending on the distance from the controller [42].

Figure 6.—The DJI Mavic Pro UAS.

The DJI Mavic Pro camera is integrated. Its gimbal has three-axis mechanical stabilization and the tilt can be controlled to 90 degrees downward. The resolution of the still images are 12 megapixels and the camera settings can be adjusted in-flight using the controller or via a mobile device with the DJI Go 4 PE mobile application.

The Mavic Pro is GNSS-stabilized during flights and can be preprogrammed with waypoint navigation for highly accurate and repeatable operations. The downward facing vision positioning system is used to stabilize the UAS horizontally when there is no GNSS positioning such as in a building. An acoustic sensor also helps to provide vertical stability in the same conditions. These systems work together with forward facing optical sensors to provide forward and downward collision avoidance. The system can detect objects and will automatically brake the system to prevent a collision.

The DJI Matrice 600 Pro is the largest of the DOI-approved UAS capable of carrying up to 12 lbs additional payload. Its lift is generated from six 21-inch rotors mounted to a lightweight carbon-fiber frame with foldable arms. The range is 3.1 miles, battery life is 38-minutes[5], top speed is 40 mph, and measures approximately 2-1/2 feet tall and 5 feet in diameter, unfolded, and just under 2 feet tall and 1-1/2 feet in diameter when folded [43]. It can transmit a 720p to 1080p resolution video depending on the distance from the controller [44].

There is no camera that is integrated with the DJI Matrice 600 Pro. Instead DJI offers several gimbals that are compatible with several different types of sensors including a gimbal system that features a quick-release collar for rapid payload changes. Not only does DJI offer gimbal

[5]No payload, 5,700 milliamp hour (mAh) batteries

systems, but there are several third-party sensor and payload packages that are approved for use by DOI OAS including a thermal IR sensor, tethering options (for infinite flight time), a fire ignition system (for wildfire prevention operations), water sampling equipment, and a payload release system. Additionally, there is currently testing underway for a LIDAR payload system.

The positioning system for the Matrice 600 Pro is limited only to GNSS positioning though it is capable of preprogrammed waypoint navigation.

Batteries

Most UAS batteries are “smart” batteries, meaning that the internal circuitry has been designed to maintain the battery at the optimal storage level. Most LiPo batteries are best stored at 50% capacity and the smart battery will self-drain if left stored for an extended period, usually around 2 weeks. LiPo batteries should not be stored at levels below 50% or damage to the battery may occur. This is important because an operator may arrive at a project expecting the batteries to be charged but if they have been stored, they may, in fact, be only partially charged.

Many batteries are also designed to log vital battery information such as the lowest voltage reached on any cell and how many times the battery is charged. This information can be used to determine if a battery has reached its useful life.

Sensors

The main objective for a UAS is to carry or deliver a payload to an intended location that is difficult, unsafe, or cost-prohibitive by conventional means, such as an airplane carrying a camera at 200 feet above the ground. At this time, the payloads typically carried by Reclamation UAS are optical sensors for capturing digital imagery, thermal IR sensors, and multispectral payloads that feature multiple sensors on the same unit, filtering specific visible and non-visible wavelengths.

Payloads need DOI OAS approval before attaching to an airframe. The ideal payload sensor is one that can be controlled remotely, is under the UAS payload weight capacity threshold, integrates with a stabilized gimbal, and can transmit live video signals to the operator. The current list of approved payloads is accessible from the DOI UAS Remote Pilot Forum Website at https://sites.google.com/a/ios.doi.gov/department-of-the-interior--uas-operator-s-forum/?pli=1.

Optical

Optical sensors are the most familiar type. Advancement of the digital imaging electronics sector has allowed for high-quality, lightweight designs. Most optical sensors are used for simple photography and videography. When combined with a UAS, the photographer can set up unique perspectives. Inspectors use optical imagery to help describe problems or give context to an issue. Geographers use optical imagery to help identify features and develop maps.

Optical sensors are also used to collect data for photogrammetry. Photogrammetry is the science of using overlapping or stereo images to measure a scene or subject. When performed on digital imagery, the pixels can be located and assigned a position in 3D space to generate a point cloud. Multiple images can be used to develop 3D models of a subject and can provide digital surface models (DSMs) and contours.

Sensors used explicitly to collect data for photogrammetric purposes require specific features such as large pixel pitch, a global shutter and manual control over exposure settings. Pixel pitch is the size of each pixel on the sensor. The larger the pixel pitch, the more sensitive each pixel is to the light and the sharper the image is.

The global shutter or mechanical shutter controls how the sensor is exposed to the light. The global shutter exposes the entire sensor at one time. A rolling shutter moves across the sensor, exposing one end of the sensor at a different time than the other and causes distortion in the image. Rolling shutter distortion can be minimized by moving the UAS slowly.

For the photogrammetric software to solve positions of each pixel accurately, the shutter speed, aperture, ISO (International Organization for Standardization), white balance, and focal length should be the same throughout the dataset. These settings are set prior to the project and are unique to the lighting conditions at the subject area.

Blurry images during camera movement on the UAS are reduced by using a higher shutter speed but requires more light (large aperture). Aperture refers to the amount of light the sensor is exposed to and affects the depth-of-field (DOF). A small aperture will reduce light and increase the DOF to keep the foreground and background in focus; a large aperture will increase light and decrease the DOF with the result that the foreground and background will be out of focus.

The ISO refers to the sensor sensitivity to light. A higher ISO will allow the sensor to be more sensitive in low-light conditions but increases noise within the image. White balance is the camera’s interpretation of white color and the overall color temperature of a subject. Selecting an appropriate white balance will ensure the proper color saturation. For most photogrammetric data collection, the focal length is fixed so that the light rays entering the lens aren’t bent differentially throughout the data set. For subjects between about 30 to 50 feet or greater, the focal length is typically set to infinity to ensure all features are in focus. Check with the camera manufacturer specifications and instructions to ensure optimal settings.

The optical sensors that TSC uses are the GoPro Hero 3+, GoPro Hero 4, and the Ricoh GR II. The GoPro models integrate with the 3DR Solo through the stabilized gimbal. The integration allows for control of the GoPro remotely, including most of the camera settings, providing power to the camera and transmitting a live feed from the camera to the operator. The GoPro models feature a 12 megapixel sensor capable of 4K video through a fisheye lens (see Figure 7) [45] [46]. The integration and camera features are popular for aerial video and photography and can be used for photogrammetry though the results are not as accurate.

Figure 7.—Example of the fisheye lens on a GoPro (Brock Reservoir, California).

The Ricoh GR II is a lightweight, inexpensive, high-quality camera with an APS-C (advanced photo system type-C) sensor with a global shutter [47]. These features alone make it nearly perfect for photogrammetry. The images are sharp, and the camera offers manual control to dial in settings customized to the scene (see Figure 8). However, the camera can only integrate with the 3DR Solo using a third-party, 3D-printed, fixed gimbal. None of the camera controls can be accessed remotely through the UAS controller or ground control station. The camera settings and tilt must be set prior to flying. The camera can transmit a live video feed through the HDMI (high-definition multimedia interface) cable on-board the 3DR Solo.

Figure 8.—Aerial view of the outlet works at Red Willow Dam, Nebraska, from the Ricoh GR II.

Thermal Infrared

Thermal IR cameras have a sensor that can give the temperature of each pixel within a scene or subject. The applications are varied and often the results must be inferred to the situation. The FLIR Vue series are specifically for use on UAS due to their small size. The recommended IR cameras have higher resolution and radiometric functionality. Radiometric capabilities allow the camera to measure the actual global temperature of each pixel as opposed to the relative temperature of a single pixel [48].

TSC uses the FLIR Vue Pro R, which is a radiometric IR sensor capable of taking images that are 640 by 512 pixels [49]. Thermal IR images can also be processed photogrammetrically into 3D models and mosaiced orthoimagery for full site analysis.

The FLIR Vue Pro R integrates with the 3DR Solo using a third-party stabilized gimbal that is made by OEMcameras.com. The gimbal allows for tilt control and can offer limited remote camera control and live video transmission [50].

Multispectral

Multispectral imagery consists of a set of images taken at the same time. Usually 4 or more sensors are involved, and each sensor is wavelength limited. Often a full optical sensor is also triggered for context. Multispectral imagery is often applied to vegetation analysis to determine plant heath or to identify plant species although many of the results can be deduced for other types of applications.

One of the multispectral cameras used by DOI scientists and engineers is the MicaSense RedEdge-MX. It features one more targeted band instead of the optical sensor: 475, 560, 670, 720, and 840 nanometers (nm) [51]. A previously used multispectral camera was the Parrot Sequoia. It features an optical sensor and four additional sensor bands in the visible and non-visible range of 550, 660, 735, and 790 (nm) [52]. However, this camera is not favored due to distortion in the optical sensor. Figure 9 shows the optical image and Figure 10 shows all other bands.

Figure 9.—An example image from the Parrot Sequoia optical sensor (Strawberry Canal, Utah).

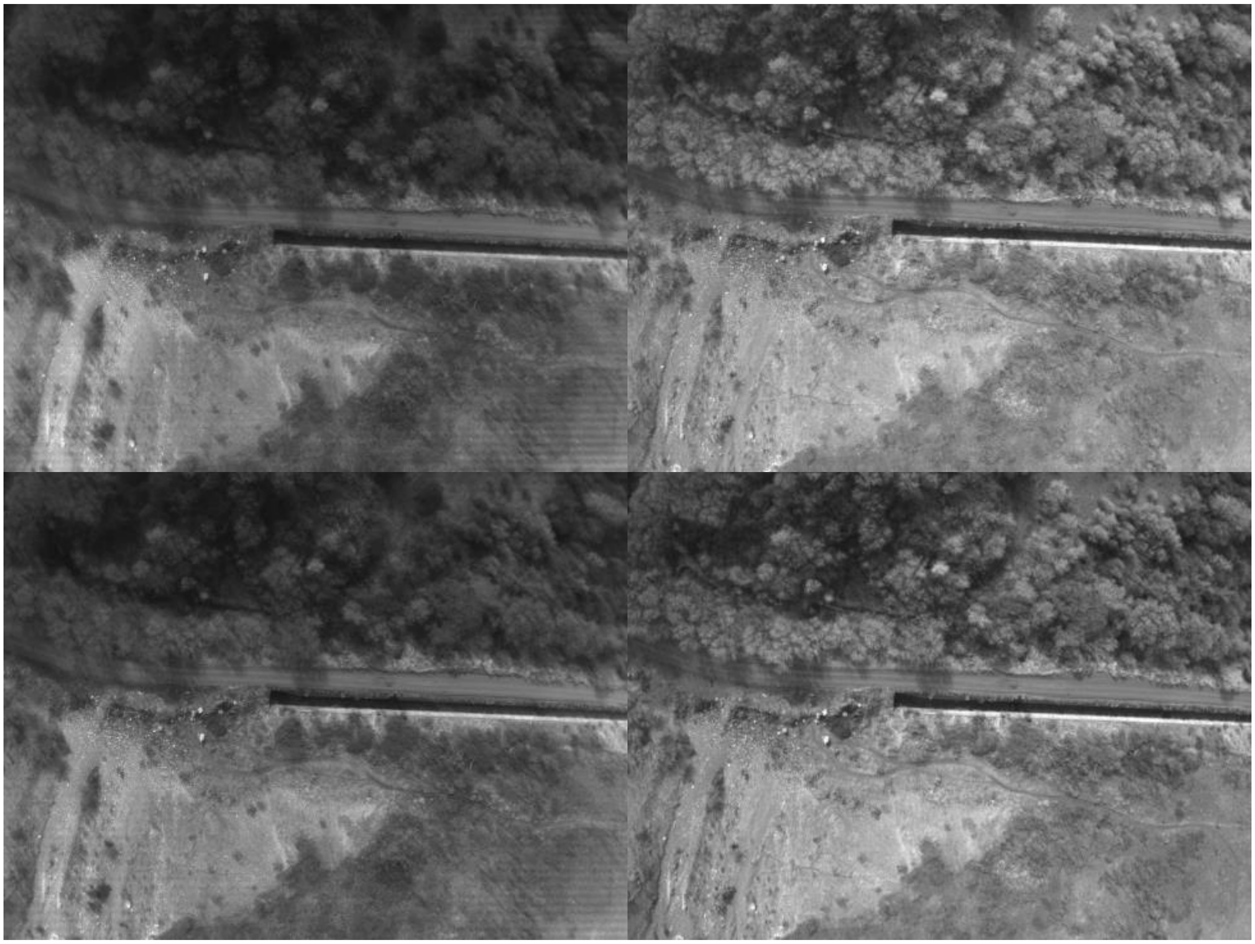

Figure 10.—The same exposure as Figure 7, but from different light bands: 550 nm (top left), 660 nm (top right), 735 nm (bottom left), and 790 nm (bottom right).

Ground Control

Most UAS data products require georeferencing or at least at a minimum, scale. All the DOI airframes can geotag images either directly or by merging the UAS flight log with the images based on time. However, geotagging is only accurate to about 30 feet unless third party RTK payloads are attached.

In order to get a high level of accuracy from UAS data products, ground control is placed throughout the UAS subject area prior to collecting data. The ground control points (GCPs), or targets, are usually placed large enough to detect from the imagery. Typically, between 5 to 10 targets are placed per project, though more points may be needed for larger projects. Depending on the site layout, targets should be placed approximately 500 to 1,000 feet apart, at each corner and at major vertical discontinuities (see Figure 11).

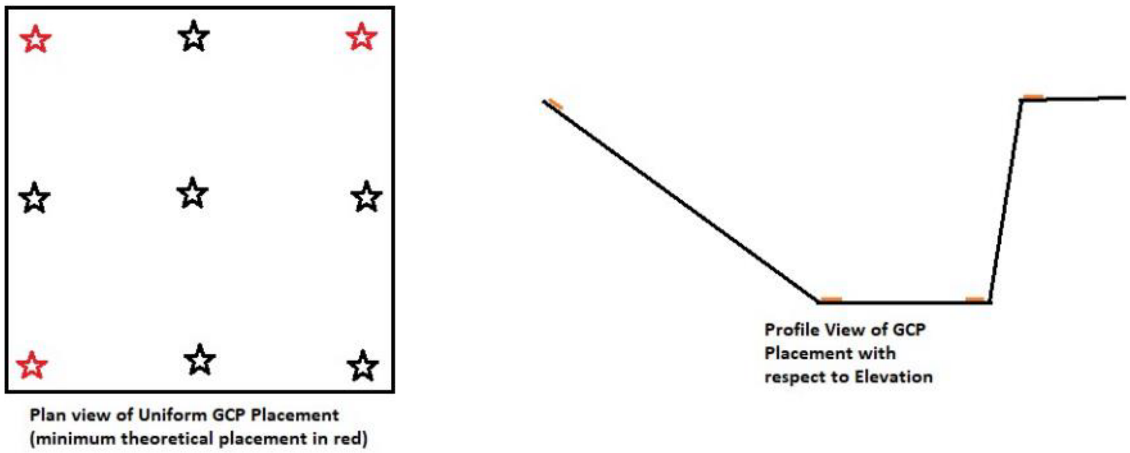

Figure 11.—Optimal layout of GCPs in a plan view (left) and a profile view (right) [53]

Coded Targets

There are many types of GCPs that can be used for georeferencing UAS data. Some can be as simple as round bucket lids or painted crosses. Some photogrammetry software will automatically detect targets. The targets can be coded so that they can be automatically numbered as well. Coded targets have been used often by TSC UAS pilots for this reason (see Figure 12). The targets can be exported digitally and reproduced by a sign printer for a durable, long-lasting solution that can be mounted on any surface.

Figure 12.—Example of a coded target (Upper Stillwater Dam, Utah).

Online Positioning User Service Global Positioning System

Once the GCPs have been placed, their position is surveyed. The coordinate system used is typically the client's choice and may even be a local coordinate system not tied to a global one. The GCPs can be tied to a local established survey control point or use a separate survey. When a separate survey is used, an OPUS (online positioning user service) point is established for the base station position or for each control point. OPUS is a free service maintained by the National Geodetic Survey (NGS) within the National Oceanic and Atmospheric Administration (NOAA) to compute coordinates based on files collected from the United States (U.S.) Global Positioning System (GPS) [54]. GPS and GNSS differ in that GNSS is any collection of the worlds global positioning satellite systems whereas GPS is a GNSS. For example, the BeiDou Navigation Satellite System (BDS) is operated by the Chinese, Galileo is operated jointly by the European Union and Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS) is operated by Russia [55].

An OPUS receiver is typically set up over the point and collects GPS data for a minimum period, usually between 15 minutes and 4 hours. Then, the data file is uploaded to the OPUS Website for corrections. The processing can take up to 24 hours, approximately. OPUS surveying is only accurate to about 1/2 inch horizontally and between 1 and 1-1/2 inches vertically [54]. TSC's

OPUS receiver is the X90-OPUS though it is currently no longer manufactured and has since been replaced by the iG3s [56] [57].

Real Time Kinematic System

In addition to the OPUS system, Reclamation’s TSC also has an RTK system. RTK refers to the correction of the position using an established control point or an OPUS solution for the base station during a survey. The base station communicates with a rover to collect additional points. The additional points are post-processed to correct the entire survey to the base station point. An RTK system takes more time to set up initially, but only requires a couple of seconds to establish each point thereafter. The basic RTK system consists of Trimble R10 GNSS receivers (one for the base station and one for the rover) and a Trimble TCS3 controller to set up and log points in the survey [58] [59].

Global Navigation Satellite System Enabled Ground Control Points

A novel idea is to integrate the GCP and GNSS together. This was the idea behind Propeller AeroPoints, a portable, reusable GCP system. It is a 2-foot-square foam pad with a tiled pattern to indicate the center (see Figure 13). They are battery operated capable of recharging using an integrated solar panel and includes a GNSS receiver. One set of 10 points must be left in position for a minimum of 45 minutes. Once collected, the data from each point is uploaded for correction. Usually, the processing is complete within 24 hours and the points are accurate up to 1-inch horizontally and 2-inches vertically depending on the correction method used [60].

Figure 13.—A 3DR Solo on the Propeller AeroPoint GCP.

Supporting Equipment

In addition to the airframe, controller, and payloads, there are a multitude of other equipment required to successfully complete a mission. The main components are described below.

Ground Control Station

Most UAS require an addition of a third-party mobile computing device in order to deliver enhanced flight information to the operator and allow for the adjustment of mission settings. The controller is usually able to relay critical information about the flight (see Figure 14). In addition, the computing device, whether a laptop, tablet, or smartphone, is a platform to conduct advanced features including autonomous navigation and is referred to as the Ground Control Station or GCS.

Figure 14.—3DR Solo controller with GCS. Note the flight information on the controller screen and video display on the GCS.

If a tablet or smartphone is used, often the pilot can attach the device directly to the controller, however, in some cases it is advantageous for the visual observer to operate the mobile device, freeing the pilot to focus only on the UAS flight. For this reason, the mobile device is paired with a rugged case with a carrying strap and hand loop for better handling.

The computing device system requirements are relatively basic. Most updated laptops, tablets, and smartphones can run the software and mobile application without any trouble. In some cases where there are a significant number of waypoints, the software and mobile applications may run better with a faster processor and ample RAM (ready access memory). Battery life and screen brightness are major factors. Also note that some UAS mobile applications are only compatible with specific operating systems. Connectivity is important as well since the GCS connects to the UAS controller via wireless radio. In addition, the GCS will need Internet access in order to download basemaps. Many GCS only have wireless (Wi-Fi) capability requiring basemap caching before arriving onsite where there may not be any Internet connectivity either by wireless or cellular.

TSC operates its UAS mainly with the Samsung Galaxy Tab A 10.1, although the Samsung Galaxy Tab Active2 is currently being evaluated for increased brightness [61] [62].

Aviation Radios

Aviation radios are required to monitor potential manned traffic in the area of any UAS operations. UAS pilots are not allowed to transmit on an aviation frequency without having a Federal Communications Commission (FCC) airband license. In addition, Reclamation has rules regarding the purchase of radios. Typically, the purchase must be approved by the Radio Program Manager. This approval accompanies an IT (information technology) charge card purchase request. Only approved radios can be purchased from the mandatory use contract for radios. The models that TSC currently operate are the Icom A6 and Icom A25N airband radios [63] [64].

Weather Meter

Weather meters are used to review, verify, and log the local weather conditions prior to any UAS operation. Aviation weather is covered during the FAA remote pilot's knowledge test, including minimum weather visibility. Other weather factors that may influence the UAS performance can be found in the manufacture's specifications. Verifying weather conditions such as wind speed, temperature, humidity, and density altitude prior to operations will help with understanding the UAS performance during flight. TSC uses the Kestrel 5500 Weather Meter, which features an anemometer and can measure wind speed, temperature, humidity, and density altitude [65]. The types of weather that can affect UAS flight are described below.

Visibility is a key factor in avoiding a potential collision. FAA requirements include minimum weather visibility of 3 miles and an offset from clouds and fog at 500 feet below and 2,000 feet horizontally [66].

Wind affects battery life and can cause airframe instability if it is high enough. Most UAS adapt to the wind, especially if they are using GNSS positioning. If the satellite positioning is lost, however, the UAS will drift with the wind requiring corrective action to stay on course and makes take-offs and landing more challenging. UAS manufacturers usually specify the maximum speed of the UAS. As a rule of thumb, the maximum wind that a UAS can safety operate at is half the maximum speed. In addition, taking off and landing with the operator positioned downwind can make the operation smoother.

Extreme temperature typically affects the LiPo batteries adversely. Cold temperatures below freezing requires either battery warmers or keeping the batteries warm until they are to be used. The ambient temperature is typically well within LiPo batteries operating range, however, hot temperatures, due to discharge and recharge, can reduce the life cycle of the LiPo battery [67].

Humidity is a less monitored weather phenomenon, but many electronic specifications give a maximum humidity. The impacts from humidity include condensation forming on the electronics especially when the UAS temperature has not acclimated to the ambient temperature [67].

One of the major overlooked impacts to UAS operation, particularly in the mountains, is density altitude. Density altitude or apparent altitude is an altitude that is corrected based on the location's temperature [68]. In hotter temperatures, the air is less dense and the UAS rotors must generate more lift. Many UAS have a maximum altitude ceiling where they can operate, and the density altitude can affect this maximum ceiling.

Landing Pads

Landing pads are used for a variety of reasons - to prevent dust and debris from blowing and getting into the UAS motors, airframe, and sensors; to take-off and land from grassy areas by flattening vegetation; to create a level area; and to protect the sensors/payloads from uneven ground and penetrating rocks. There are a variety of commercially available landing pads. The recommended features include a foldable design, 4-foot or greater diameter, and a durable fabric that will withstand thorns, sharp rocks, and uneven ground. Additionally, landing pads can be as simple as a 4-foot by 4-foot sheet of plywood (see Figure 15). Rigid materials like plywood allow the operator to take off from areas or slopes that are uneven by propping up one side.

Figure 15.—Use of a rigid landing pad in a grassy, sloped area.

Mishap Response Kit

The NAMP requires that each region have a Regional Mishap Response Plan. TSC's plan, called the UAS Mishap Response Guide and Checklist, has general information with a contacts section that is filled out for each mission. The UAS Mishap Response Guide and Checklist details steps to be taken in the event of flyaway, loss of GPS signal, or if there is a mishap that damages property, etc. For the flight crew to respond to the mishap as quickly as possible, a Mishap Response Kit is also required to be onsite with the flight crew. The Mishap Response Kit includes:

1. First Aid Kit
2. Class D Fire Extinguisher
3. Folding Shovel
4. Camera

5. Permanent Black Marker
6. Small Plastic Bags
7. Large Plastic Bags
8. Latex Gloves
9. Leather Gloves
10. Notebook
11. Pens
12. Caution Tape
13. Duct Tape
14. Flashlight

Battery Charging

Battery management is a key factor in UAS mission planning. Many missions require several flights and can take days to collect all the data. Autonomous missions must be designed around the battery capacity although some mission planning apps allow the operator to pause and resume a mission for a battery change. Batteries can last anywhere from 8 to 30 minutes depending on the weather, payload weight, and efficiency of the UAS. Oftentimes, either enough batteries need to be transported to the project site or an onsite battery charging plan should be considered.

When planning to charge batteries onsite, the number of battery chargers must be considered including the time required to completely charge a battery before it is ready to be used again. Many manufactures recommend cooling the battery before charging. In addition, the power source for the chargers should be considered and may include a generator. As previously mentioned, smart batteries may need to be charged prior to arriving at the project site due to the self-discharge storage feature.

Software

Usually a UAS manufacturer has developed a mobile application or computer software that is unique to their product (see Table 6). The manufacturer-developed mobile application is typically the main method to introduce, via a mobile device, firmware updates to the remote control (RC) transmitter (controller) and the flight controller onboard the airframe though the firmware can sometimes be updated vie computer software.

Table 6.—Summary of Manufacturer-Developed UAS Control Mobile Applications[6]

Airframe	Mobile Application Name	Operating System
3DR Solo	3DR Solo	Apple, Android [69] [70]
Parrot Anafi	FreeFlight6	Apple, Android [71] [72]
DJI Mavic Pro/DJI Matrice 600 Pro	DJI GS[7] Pro DOI [41]	Apple
DJI Mavic Pro, DJI Matrice 600 Pro	DJI Pilot Private Beta [41]	Android

[6] Updates to these apps, and their names and versions, may have occurred prior to publishing this report. Consult with DOI OAS for the latest approved mobile applications.
[7] Ground Station

The manufacturer-developed UAS control mobile application offers basic flight control functionality and control with telemetry data, such as battery levels, flight altitude, and airspeed. It also will feature camera controls, live video feedback, as well as advanced controls unique to the airframe, like collision avoidance. Some of the manufacturer-developed mobile applications also have autonomous control, either for specialized image and video effects or for data collection, though the additional functionality may cost extra.

In addition to the manufacturer-developed UAS control mobile applications, several manufacturer and third-party mobile applications and computer software are available for enhanced control and autonomous navigation of some of the UAS. Many of the mobile applications and computer software available are not approved by OAS. Approved mobile applications and computer software are listed on the DOI UAS Approved Payloads, Sensors, and GSC Software/Applications shared spreadsheet [73].

Processing UAS Data

While this report has mostly dealt with UAS and the immediate equipment required to support UAS missions, it is also worthwhile to touch on processing UAS data as it should be something UAS pilots, or those interested in UAS should understand. While UAS are operated to collect aerial imagery and video, data collection from UAS is usually associated with photogrammetry. Photogrammetry typically processes hundreds or thousands of images to solve pixel positions and the processing and storage required to support the photogrammetric processing is usually much greater than the standard-issue or workstation-level laptop or computer specifications.

Field Laptop

The field laptop is used to manage data collected from the UAS sensors. Situations occur where the sensor storage will fill up or the UAS is being operated over a particularly risky area such as water and the sensor removeable memory is replaced periodically. The laptop is used for data redundancy instead of replacing the memory card with an empty one. In addition, the field laptop can be used to integrate with some UAS like the 3DR Solo for autonomous flight control. Finally, the field laptop is often used to verify the data. Verifying data in the field is invaluable because it saves the potential return trip to collect mission data.

The field laptop should be a balance between portability and processing capability although the former is usually sacrificed. Many photogrammetry processing software, including the popular Agisoft PhotoScan/MetaShape leverage computing ability from the graphics card. The field laptop specifications should include a large, bright display, as much RAM as possible, a fast, multi-core processor, a large capacity SSD (solid-state drive), and discrete graphics (as opposed to integrated). Battery life should also be considered if the laptop is to be used without a power supply. Having a removeable battery that can be exchanged with a charged battery could be useful.

High-End Computing

Once UAS data collection is complete, and the equipment is returned from the project site, data are copied to one of several custom high-end computers at the CSL’s Center for 3D Condition Assessment at the TSC. The computers were designed and built specifically for photogrammetric processing and feature liquid-cooled, over-clocked, multi-core processors, 128 gigabytes (GB) of RAM, multiple discrete graphics processing units (GPUs), and several terabytes (TB) of storage.

Once a project is completed, it is transferred to an archive server. The archive server supports opening and viewing of the completed files but does not process them. The server has redundant large-capacity drives. None of the processing or data storage computers are connected to the Internet in order to protect the data.

Demonstrations

A major objective of this 3-year research project was to investigate the application of UAS by demonstrating capabilities while conducting actual projects. The following summaries are projects that were fully or partially funded by this research project thus to explore UAS usage. Some of the considerations reviewed during the demonstration were ease of use, benefits of the UAS over traditional methods, and lessons learned.

Upper Stillwater Dam

Upper Stillwater Dam was the first TSC UAS project. The objective of the project was to test the concept that high-resolution photogrammetric data could be used to monitor deflections of dams. In order to measure that type of movement, close-range data would need to be collected. Close-range meant 30 to 50 feet, as opposed to the standard maximum altitudes (400 feet) that UAS were permitted to operate at. Collecting data at 30 to 50 feet meant that thousands of images would be collected and processed.

Upper Stillwater Dam is located about 31 miles northwest of Duchesne, Utah, on Rock Creek. It is a roller-compacted concrete (RCC) gravity dam that is over 2,500 feet long and about 300 feet tall and was built in the 1980s [74] (see Figure 16). Given the simple cross-section and dimensions, it was determined that Upper Stillwater Dam would be a good project to test the effects of hydraulic loading on the deflection of the structure. The plan was to collect UAS close-range, high-resolution data of the entire structure and process the data into a high-resolution point cloud using photogrammetry. This would be done when the dam was at low and high pools. Then, the point clouds would be compared to one another and analyzed for deflection.

Figure 16.—Upper Stillwater Dam, Utah.

The first trip to Upper Stillwater Dam was conducted on July 18, 2017 at the time when the reservoir would be the most full (high pool). The project was conducted jointly with the Provo Area Office (PAO) in Reclamation's UC Region and the Central Utah Water Conservancy District. During this trip, the 3DR Solo was paired with the Ricoh GR II and about two-thirds of the downstream face of the dam was collected. On the last flight of the day, the UAS lost lift and collided with the dam and fell into the stilling basin. Because the cause of the crash was unknown, further flights were postponed. A mishap investigation was conducted by Reclamation officials soon after.

During the mishap investigation it was determined that the cause of the crash was a combination of density altitude and a condition called settling with power. Settling occurs when the rotors are engulfed in their own turbulence and are unable to generate lift and typically happens during descent [75]. During the data collection the UAS was operated manually in vertically sloped transects, following the contour of the downstream face of the dam. During the uncontrolled descent, the operator was already descending at a steady rate when the operator noticed a loss of control that contributed to the collision with the dam. So, due to the higher density altitude at the end of the afternoon and because the UAS was already in a descent, the settling phenomena occurred resulting in a loss of control.

The results of the mishap investigation changed two major approaches to close-range data collection: 1) everything should be done to avoid the conditions of settling, including descending straight down and 2) the flight should be controlled autonomously. Because most autonomous flight planning software is focused on collecting data in horizontal transects, the TSC pioneered a method to alter the horizontal transect waypoint generation to create sloped or vertical waypoints. This type of waypoint planning was dubbed “waypoint stacking” and was employed the following spring during the return trip to Upper Stillwater Dam.

In 2018, TSC pilots returned twice to Upper Stillwater Dam – once at low pool on April 30 and a second time at high pool on July 31 – and collected about 15,000 images each time to process the 3D model (see Figure 17). These flights, which were funded by the Dam Safety Technology Development Program, successfully demonstrated waypoint stacking, waypoint repeatability, and horizontal transects. At the time of publishing this report, the results are not yet available.

Figure 17.—Screenshot of the Upper Stillwater Dam, Utah, point cloud.

Altus Reservoir

In February 2018, TSC UAS pilots traveled to Altus, Oklahoma at the request of the Oklahoma-Texas Area Office (OTAO) in Reclamation’s GP Region. The purpose of the mission was to perform an aerial survey of Altus Reservoir using a UAS. The objective of the mission was to create a 3D point cloud file and digital elevation model (DEM) of the ground surface using aerial imagery and photogrammetric processes. The data were intended to be combined with bathymetric data to create a complete 3D surface model of the reservoir to determine its capacity.

In preparation for the mission, the TSC UAS team reviewed aerial imagery of the portion of the reservoir north of the OK-9 State Highway bridge. The team communicated with OTAO regarding conditions at the site. Aerial video collected near the bridge by OTAO UAS pilots was also reviewed (see Figure 18). The pre-mission assessment concluded that the AOI was mostly dewatered and moderately vegetated with short grasses, reeds, trees, and other riparian vegetation. Vegetation appeared sparse enough to provide sufficient open-views of bare ground from above allowing for proper photogrammetric data collection.

Figure 18.—Aerial view of Altus Reservoir, Oklahoma, looking north.

On February 13th, the TSC UAS team arrived onsite. They were joined by personnel from the OTAO's Oklahoma City Field Office. Onsite conditions at the north end of the reservoir were found to be highly complex, as vegetation density was much greater than near the bridge. Specifically, the area was covered with thick and matted, earth-tone, wide-blade grasses. Following the setup of the GPC's, an RTK system was used to collect ground control data and the UAS data collection flights commenced, using a the 3DR Solo paired with the Ricoh GR II camera. In total, seven flights were completed on the north end of the reservoir, which provided sufficient coverage to build a cursory photogrammetric 3D model.

The cursory photogrammetric data model showed that vegetation coverage at the north end was in fact too dense, and contained little-to-no areas of exposed bare-earth. Due to the density of the matted grasses, the modeling process was not able to distinguish ground versus vegetation, thus, determining volume capacity from the data model was not possible (see Figure 19). With this limitation in mind, the TSC UAS team and OTAO concluded that further data collection was not warranted. While initial expectations were not met, this project provided valuable feedback to the TSC UAS team, concerning the limitations of aerial photogrammetric modeling and ground/vegetation condition considerations.

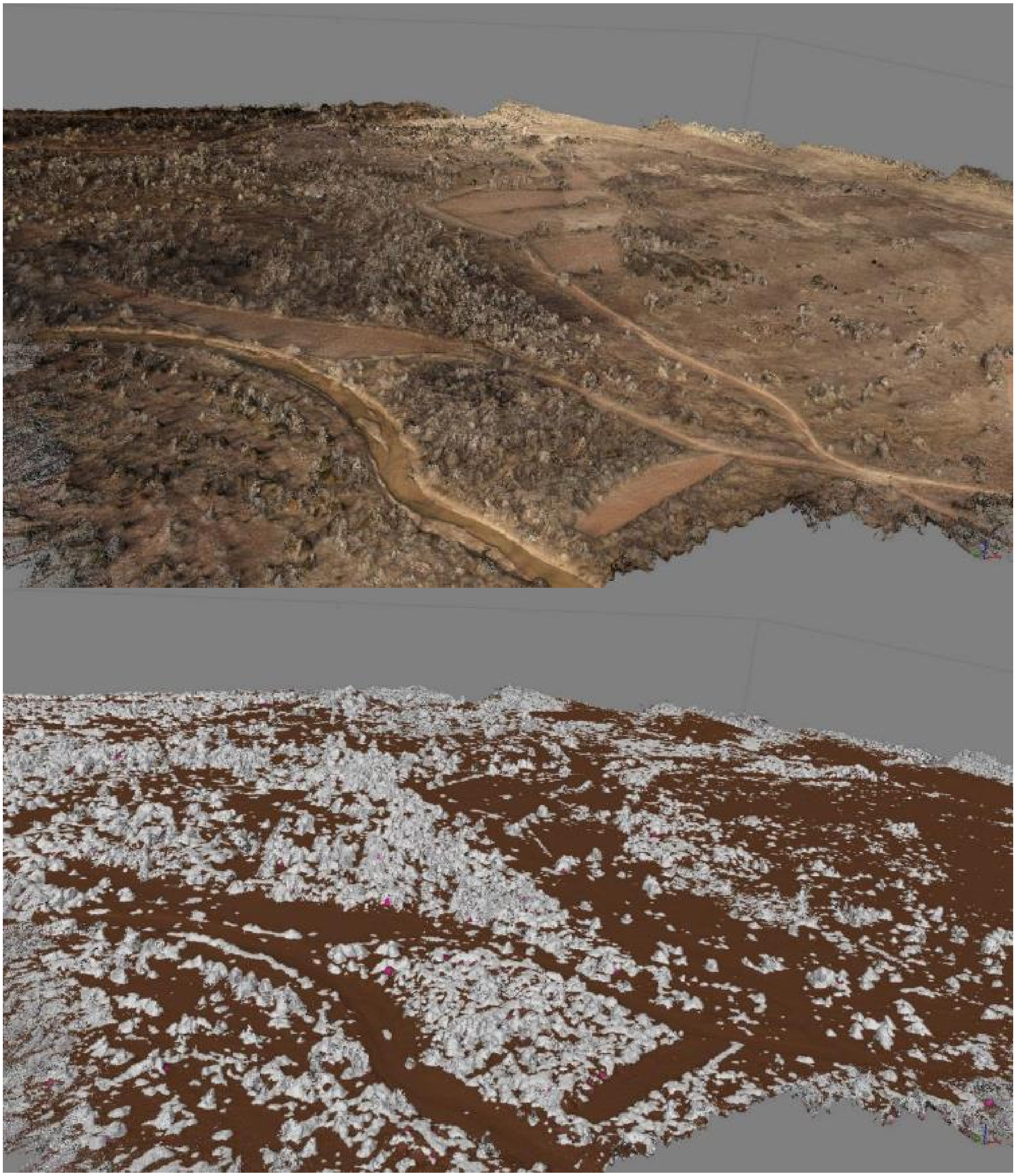

Figure 19.—Screenshots of the photogrammetric point cloud showing vegetation (top) and ground classification (bottom). The white points in the ground classification are calculated as vegetation and the brown points are estimated as ground surface.

Hart Mine Marsh

Located on the southern end of the Cibola National Wildlife Refuge, about 20 miles south of Blythe, California, Hart Mine Marsh was initially created by historic overbank flood flows from the Colorado River. With changes in the river system, including water operations and management, the dynamic processes that once maintained this marsh have been all but removed. Hart Mine Marsh has instead been managed by using drainage waters from the refuge's agricultural fields. Until recently, the marsh had no outlet, resulting in poor water quality and highly saline areas mostly dominated by invasive saltcedar shrubs.

By enhancing the ability to manage water on the site and by maintaining water levels and providing appropriate vegetation, suitable habitat for other marsh species could be created in this location. Hence, Reclamation and the U.S. Fish and Wildlife Service (FWS) entered into a long-term agreement under the Lower Colorado River Multi-Species Conservation Program to reconstruct the area. Mechanical treatment of the area was used to remove decadent marsh vegetation to promote new growth in order to provide improved habitat for endangered secretive marsh birds.

UAS was used to help evaluate the efficiency of the mechanical treatment to reset succession of native marsh habitat in two ways – LIDAR and optical data for photogrammetric processing. LIDAR data collection and analysis was conducted by the USGS through an interagency agreement with Reclamation. USGS owns and operates the Pulse Vapor 55 (now owned by AeroVironment), which is a DOI-approved heavy-lift, single-rotor UAS capable of carrying a LIDAR scanner (see Figure 20) [76]. Reclamation pilots operated a 3DR Solo with a Ricoh GR II optical sensor and managed the photogrammetric processing.

Figure 20.—USGS's Pulse Vapor 55 at Hart Mine Marsh, California.

LIDAR data were collected using the Yellowscan Surveyor (Velodyne VLP-16 laser scanner and Applanix APX-15 GNSS inertial positioning) onboard the Pulse Vapor 55 UAS platform (see Figure 21) [77]. The LIDAR scans were conducted in four separate flights (center, east, north, and south) and merged into a single point cloud file at a point density between about 15 and 50 points per square foot. The flights were collected at 100 feet in altitude between March 13 and 15, 2018.

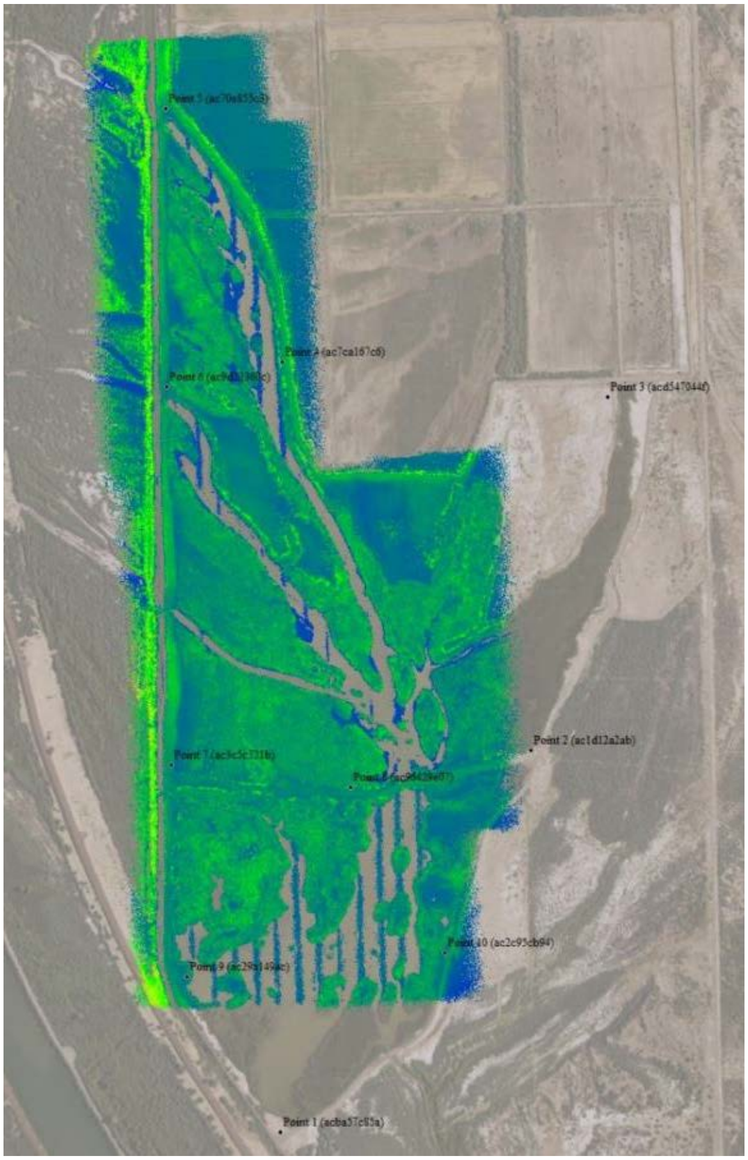

Figure 21.—The Hart Mine Marsh (California) LIDAR model. GCPs are also identified by the text.

The optical aerial data collection was intended to create a high-resolution orthomosaic of the entire marsh. Although the data collection was successful, the photogrammetric processing yielded poor results due to much of the area being covered in water. Bodies of water that are featureless do not allow for the photogrammetric software to discern enough tie-points to create a seamless orthomosaic.

Strawberry Canal

Canal seepage is difficult to measure and is the subject of much research. One of the ideas for detecting canal seepage is to use UAS aerial IR thermography and multispectral normalized difference vegetation index (NDVI) to identify potential areas of seepage. The theory is that water-saturated ground will transfer heat at a different rate than dry ground. In addition, plants should thrive in areas with sufficient water supply.

On March 19, 2018, TSC collected thermal IR and multispectral data at a 2-mile section of Strawberry Canal near Payson, Utah with assistance from nearby PAO. During that time of the year, the canal was dry so that the data collected would produce a baseline of the water conditions. If water was detected along the canal during this time, it could not be from canal seeping.

The data collection plan called for two thermal IR datasets and one multispectral dataset. The thermal datasets had to be collected just after the sun started warming the ground in the morning and again at night just after it started cooling. Multispectral data are best when collected at midday. Resolution of the data was considered sufficient when operating the UAS at the maximum altitude of 400 feet AGL.

The 2-mile length of the canal was divided into seven sections, each about 1,500 feet long. Flights were conducted autonomously and consisted of eight longitudinal transects with the IR sensor and four longitudinal transects with the multispectral sensor. The IR data were collected in the morning and multispectral data were collected midday. The 3DR Solo was paired with the Flir Vue Pro R 336 thermal camera and the Parrot Sequoia multispectral for data collection.

Eight GCPs were placed along the access road adjacent to canal. The ground control consisted of red spray-painted crosses and were located near each of the ends of the seven sections. Positions were established using a Trimble RTK setup consisting of R10 GNSS receivers for the base station and rover and a TSC3 controller.

To operate the UAS at night, TSC pilots had to get the night operations endorsement on their remote pilot certificate including reviewing night time operations and conducting a check ride with DOI OAS inspectors prior to conducting the mission. The endorsement was also subject to a 90-day proficiency period, after which the endorsement expired.

During the setup for the night operations, the gimbal for the thermal camera failed. Despite contacting the manufacturer for troubleshooting steps, it was determined that the gimbal was irreparable, and the night data collection was not conducted.

Data were processed at TSC and the result of the multispectral data of one of the sections is shown below in Figure 22. Although, interpreting and analyzing were not completed (due to staff leaving) many lessons were learned during this demonstration. The lessons learned included:

- Photogrammetry should be conducted with a minimum 640-pixel resolution.
- The thermal and multispectral camera field of views should be selected so that flight plans can be interchanged between the two cameras.
- Backup equipment should be onsite in the event of equipment failures. The cost of the extra equipment is usually less than the cost of returning to the site.
- The thermal camera settings may require additional training. Pilots should review settings and complete training prior to collection thermal data.
- Data collection transects along linear features should be set up perpendicular to the feature to reduce flight complications.
- GCPs should be black, not red, for thermal imaging, as they are easier to identify.

- Some sensors are lower quality and research should be conducted among other camera owners to determine the correct equipment.

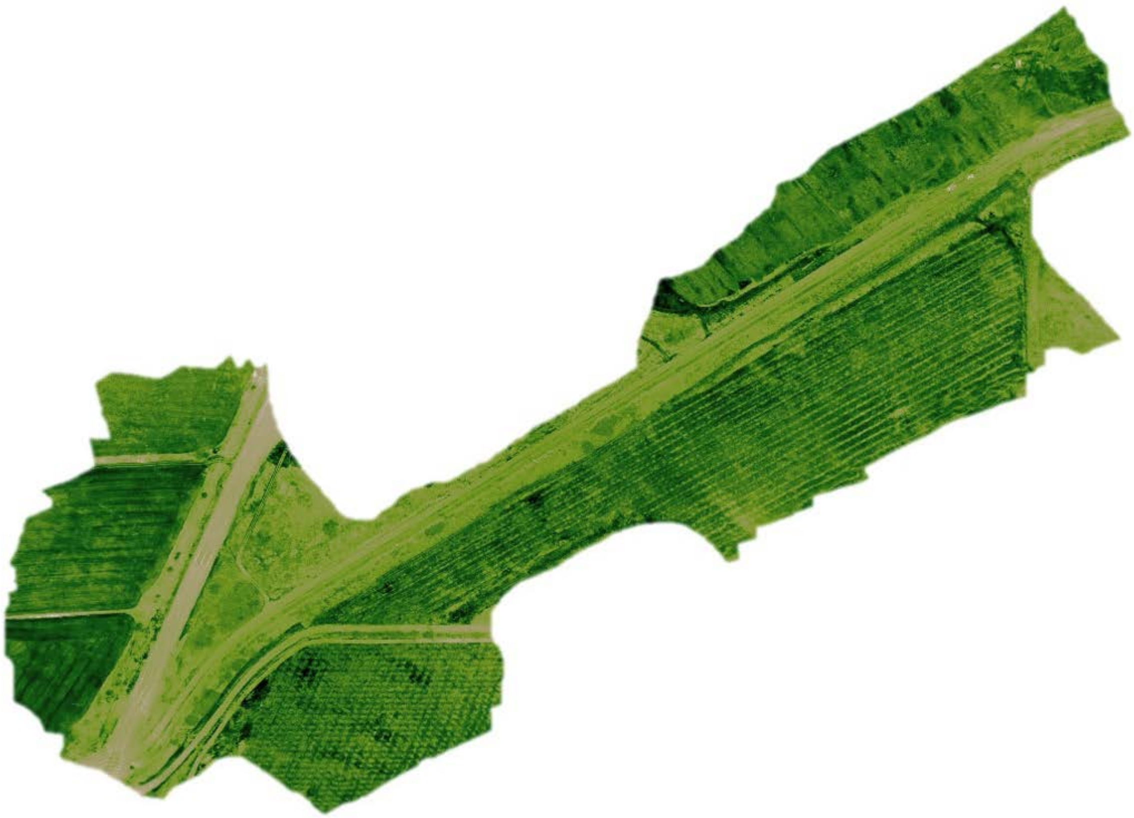

Figure 22.—Multispectral NDVI composite image of a section of Strawberry Canal, Utah.

Ridges Basin Dam

Early in 2019, employees from the Western Colorado Area Office (WCAO) - Durango in Reclamation's UC Region and the Animas-La Plata Operation Maintenance and Replacement Association observed a bare strip of ground on the north-facing right abutment of Ridges Basin Dam, Colorado, after several inches of snow had accumulated on the surrounding ground. During the observation, ground temperatures and gas monitoring measurements were made to try and determine the cause of the bare ground. Temperatures were taken of the snow, the bare ground and 3 inches under the ground using an IR thermometer. The conditions at the time were overcast with light snow and a temperature of 35 degrees Fahrenheit (°F). The snow nearby the bare earth was 16 °F, the bare earth measured 34 °F and the dug-out area measured 91 °F [78].

WCAO contacted TSC pilots to conduct an IR aerial survey of the right abutment to better understand the context of the bare earth for their investigation. On March 5, 2019, TSC pilots flew the 3DR Solo and the Flir Vue Pro R 640 and collected images of several areas on the right abutment per the request of onsite WCOA employees. Then, flights were conducted to collect both IR and optical photogrammetric data of the right abutment and the entire dam respectively, (see Figure 23).

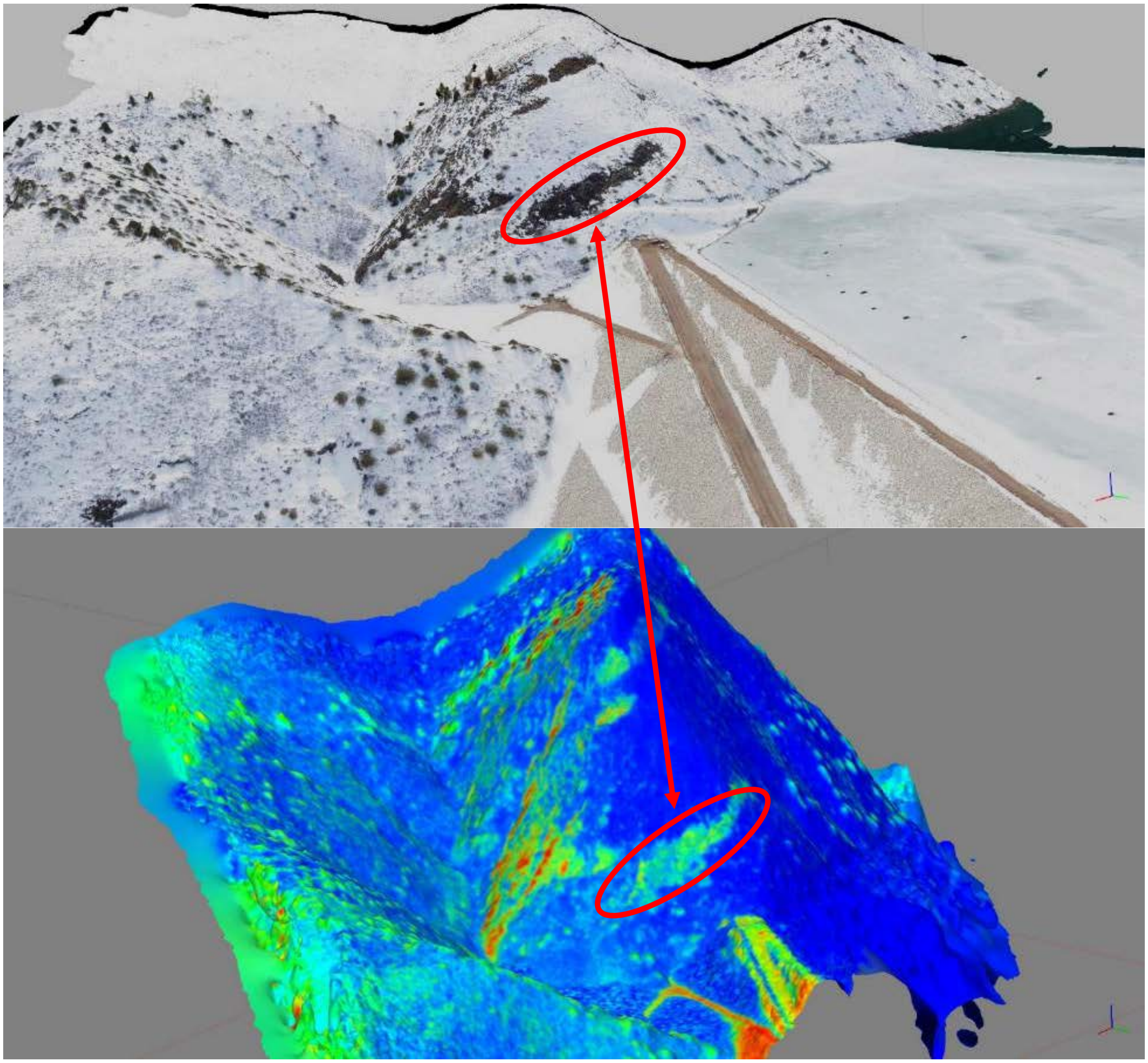

Figure 23.—Comparison of the optical (top) and IR (bottom) 3D models of the north-facing, right abutment at Ridges Basin Dam, Colorado. Note the bare earth and correlating hot spots.

The weather conditions during the flights were clear with temperatures in the mid- to high 30s. Ground temperatures were measured from the IR camera between 35 °F, from the snow, to 80 °F, on some of the exposed rock in the sunlight. Temperatures at the bare earth areas were between 51- and 76-°F.

This project demonstrated the practical use of aerial IR imagery, and that the images can be used in photogrammetric products to help provide context and overall analysis of a larger area at a higher resolution than could be obtained by a single image. The cause of the warm ground is still under investigation.

Elephant Butte Dam

In 2016, TSC and El Paso Field Division in Reclamation's UC Region – with the assistance of DOI OAS and Reclamation's R&D Office (separate from this project) – contracted UAS specialists from the New Mexico State University's (NMSU) UAS Flight Test Center and Leptron/Geotech to conduct an aerial survey of Elephant Butte Dam, New Mexico (see Figure 24). However, due to safety concerns by NMSU and Leptron/Geotech, the desired resolution of the inspection was not achieved [5].

Figure 24.—The Leptron Avenger UAS at Elephant Butte Dam, New Mexico, in 2016.

In 2018, shortly after TSC acquired UAS capabilities of its own, TSC UAS pilots (funded by a separate S&T Program research project) returned to Elephant Butte Dam to implement and demonstrate close-range, high-resolution data collection for the purpose of deterioration mapping and inspection (see Figure 25). Flights were conducted autonomously from June 26 to 29, 2018. Onsite weather conditions were most clear with temperatures between 90- and 115-°F. A total of 38 flights were flown using waypoint stacking and sloped flight plans to keep the UAS sensor between 30 and 50 feet from the surface. Ground control was provided using four 12-bit coded targets that were georeferenced using the OPUS system. A total of nearly 26,000 images were collected, though only 14,477 were required for the final data product.

Figure 25.—Reclamation UAS at Elephant Butte Dam, New Mexico, in 2018.

The final product was four orthoimages created by stitching together the collected images. The four areas highlighted by the high-resolution orthoimages were the upstream face, downstream face, crest and spillway. The final resolution of the orthoimages was between 0.15 and 0.17 inch. An example of the orthoimage resolution is shown in Figure 26 below. Once the images were generated, they were imported into a CAD (computer aided design) program for deterioration mapping. Deterioration mapping included identifying and marking cracks and areas that had some type of damage where the aggregate was exposed, such as spalls or erosion.

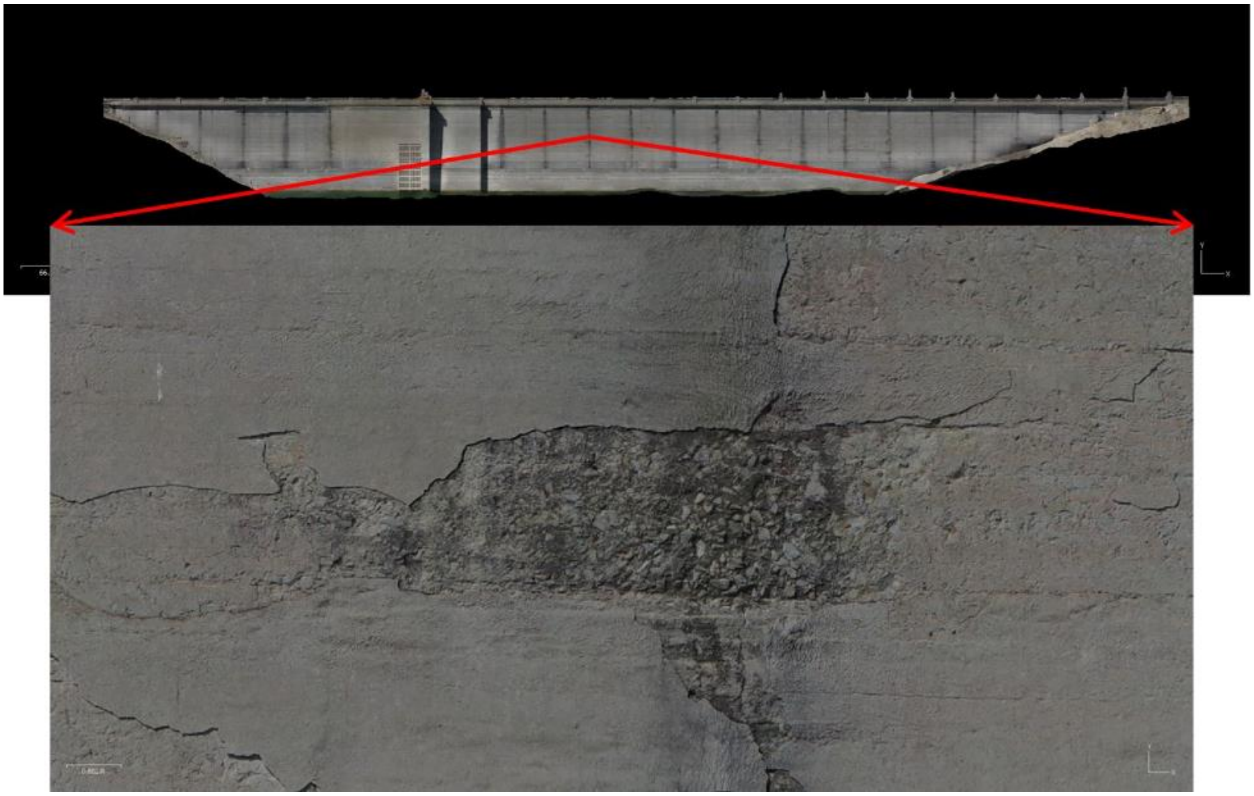

Figure 26.—Elephant Butte Dam, New Mexico, upstream face orthomosaic (above) and example of resolution. Note the aggregate visible in the spall that is approximately 3 feet long (inset).

Several conclusions were made from the successful UAS data collection and processing including that autonomous navigation can be used for accurate and repeatable data collection, DOI UAS can reliably operate in extreme high temperatures, photogrammetric data processing can be used to generate 3D models and orthomosaics and the orthoimages have high enough resolution to identify surface defects [79].

Brantley Dam

Brantley Dam is an earthen embankment dam that was constructed in the 1980s north of Carlsbad, New Mexico, on the Pecos River [80]. During construction, several hundred sinkholes were identified, though most of them no longer exist. However, for the remaining sinkhole depressions, yearly monitoring is required. Personnel from the Albuquerque Area Office in Reclamation’s UC Region contacted TSC in late 2018 to see whether aerial data could be used to provide a sinkhole monitoring baseline and if an efficient workflow could be developed to improve the monitoring over the current method.

On November 6, 2018, TSC and PN region pilots collected data for an aerial survey of the left abutment of Brantley Dam, which included about one square mile total centered on dam crest. About 13 flights were conducted to collect just over 2,000 images using the 3DR Solo and Ricoh GR II optical sensor. Ground control was provided by setting out all 10 Propeller AeroPoints over the square mile. An OPUS solution was used to solve point positions, although one of the

Propeller AeroPoints was set up over a local survey monument. Weather conditions were calm and clear with temperatures between 50- and 75-°F.

The data were processed photogrammetrically at TSC. A 3D point cloud and DSM with contours was derived and exported into a CAD program to generate drawings of the site (see Figure 27). Algorithms to remove the vegetation were run on the model, however, the same process that removed the vegetation also removed the sinkholes. In 2019, a Dam Safety Technology Development Project proposal was submitted to further investigate sinkhole monitoring using change detection and if funded, the results should be available in the fall of 2020.

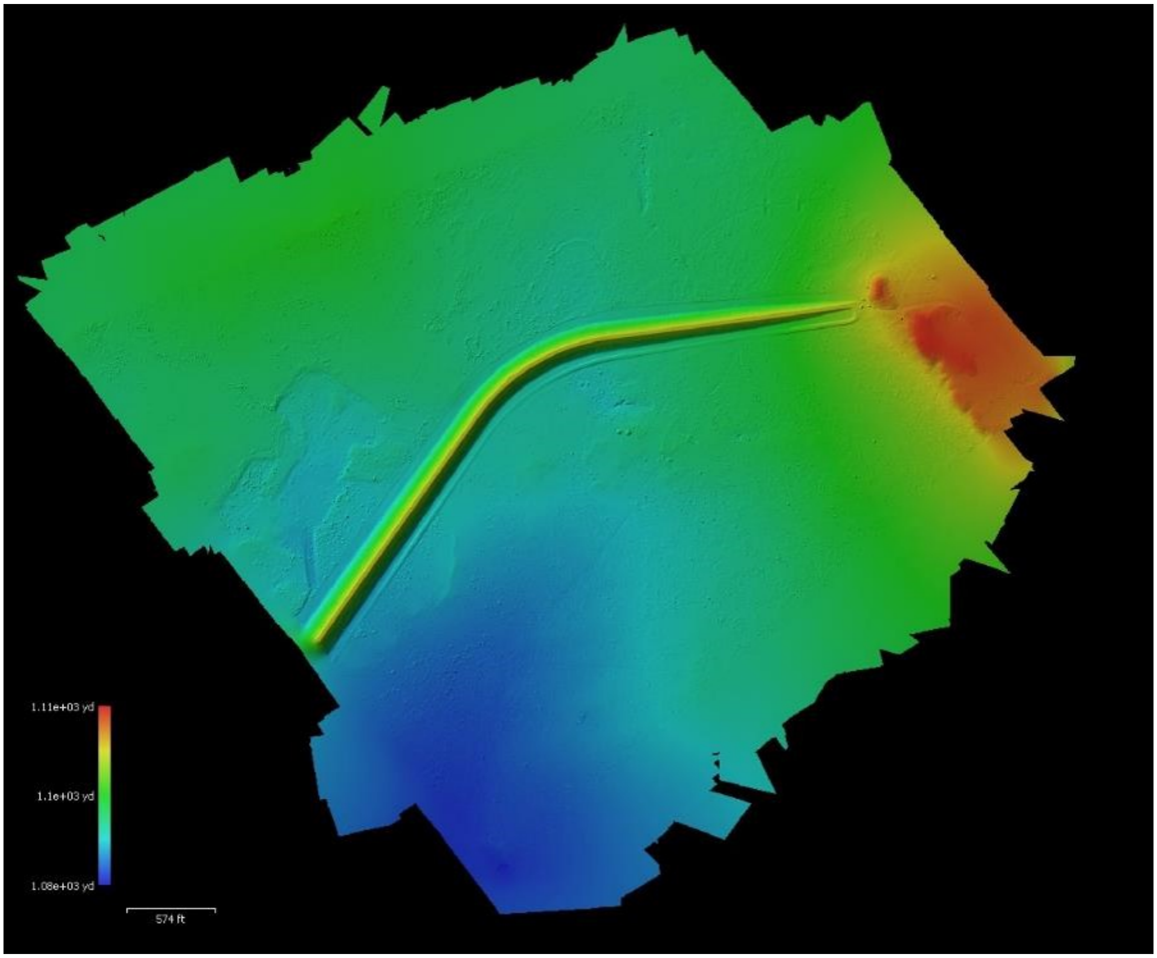

Figure 27.—Digital surface model of the left abutment of Brantley Dam, New Mexico, to investigate the use of UAS for sinkhole monitoring. Red is a higher elevation and blue is the lowest elevation.

Hoover Dam Rockface

LC Regional Office and Hoover Dam personnel contacted TSC pilots and geologists to conduct a survey of the rockface above the dam's visitor center and parking garage. This endeavor is funded by a separate S&T Program research project in which the objective is to explore the feasibility of using UAS for rockface monitoring as a supplement to, or alternative for, traditional methods. The traditional method of rockface monitoring at Hoover Dam is by rope access.

The first step in operating UAS for this purpose at such a high-profile facility such as Hoover Dam is to conduct several tests in order to ensure reliability and safety. After developing vertical waypoint stacking for projects like Upper Stillwater Dam in Utah, the same procedure was envisioned for Hoover Dam. An added hazard was the prevalence of 230 kilovolt (kV) transmission lines intersecting the data collection areas. The most obvious hazards are tourists and, to a lesser extent, helicopter tour traffic (lesser because the UAS is not expected to operate more the 50 feet from any surface and the helicopters maintain a perimeter around the dam as well as operate several hundred feet from the ground).

Prior to operating UAS at Hoover Dam, TSC conducted several test flights using autonomous waypoint stacking at a vertical rockface at a nearby quarry in Denver, Colorado. The tests demonstrated repeatability and reliability in the autonomous flight setup and operations. In fact, the tests proved how powerful the data collection could be. In Figure 28, the top image shows the comparison between data collected at two different times, 1 month apart. Blue points are those in which little or no change has occurred. Red points are those with the highest relative changes. At the middle of the screenshot, near the top of the model, an area with movement is observed by the green points. Upon further inspection of the images for that area, it was discovered that a 3-foot-long rock had fallen out of its position (the lower left image shows the rock face before and the lower right image shows the rock face 1 month later).

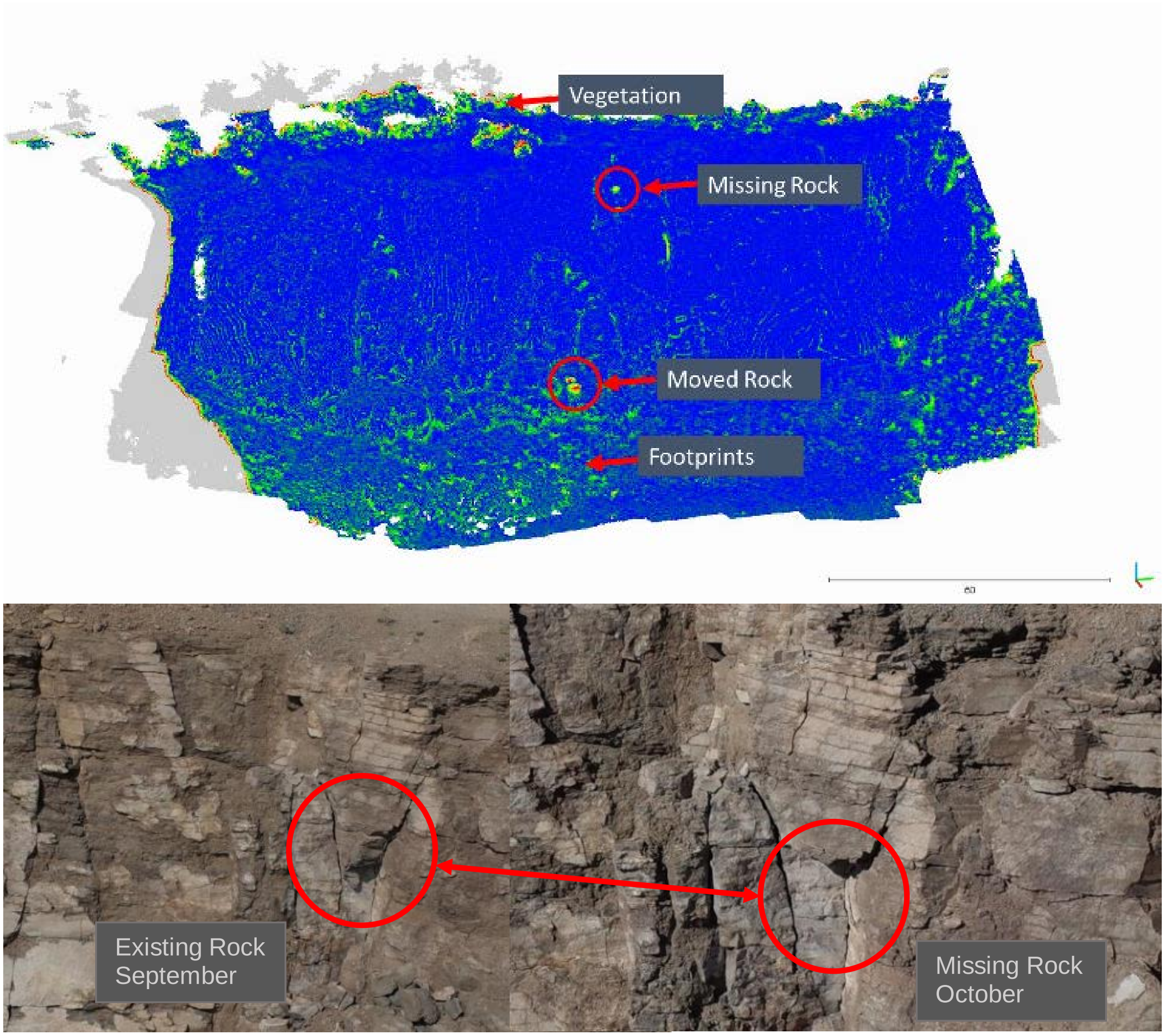

Figure 28.—Series of images showing a comparison of two models of rockface data collected a month apart, where blue shows points with no movement and red points have the most movement (top). The lower images show the rockface before and after a rock fell out of its position.

At the same location, after obtaining permission from the powerline owners, a high-voltage test was successfully conducted within 50 feet of a 230-kV transmission line. The 50-foot offset was recommended by Reclamation's high-voltage electrical engineers after conducting non-aerial proximity tests with the UAS. During the test, no abnormal behavior was observed from the UAS and autonomous waypoint navigation executed as expected.

Three tests were conducted at Hoover Dam to ensure that everything was prepared for the rockface data collection. The tests were conducted on January 17, 2018 – one at dawn, one at mid-day, and one at the end of the day. Only one flight plan was executed during each test at the same area. The temperatures varied from 45 °F at sunrise to around 60 °F at midday and afternoon. Skies were clear and winds were calm-to-light.

The onsite tests served two purposes – the first looking at the effect of light on the photogrammetric results and, the second, to determine the level of collaboration required between Hoover Dam operations, security, and the public. From the data processing perspective, the time of day had little effect on the model error and noise. From the coordination standpoint, the earlier flights had little to no effect on tourist behavior, which led to the conclusion that morning flights are preferred.

Nearly a year after the test flights, TSC pilots returned to Hoover Dam to conduct a total of 28 flights during the week of January 21, 2019. Flights were only conducted between sunrise and 9:00 a.m. in the morning to avoid tourist foot and vehicle traffic. Weather conditions were clear and cool with temperatures between 35- and 50-°F, with higher winds during the early part of the week. A total of 5,524 images were captured and used on the resulting point cloud (see Figure 29).

Figure 29.—Point cloud model of the rockface above the visitor center and parking garage at Hoover Dam, Nevada/Arizona.

The point cloud is currently undergoing further analysis by TSC's geologists to determine areas of the rockface that have potential for deteriorating. A report with the findings from the rockface team is expected to be completed in 2020.

Indoor Flights

Interest in indoor use of UAS has identified several applications unique to Reclamation. The foremost of which is for inspection of so-called inaccessible features. These are areas or components of water control structures that are difficult to access without special equipment, such as penstocks, draft tubes, and other water conveyance tunnels. Other examples include use of UAS to inspect large open areas like powerhouses or at Reclamation's Hydraulics Laboratory in Denver, Colorado.

Indoor flights are not governed by the FAA or DOI OAS because the aircrafts are not operated in the NAS. However, until recently or only by special consideration, indoor operations of UAS was prohibited within Reclamation. When the NAMP was updated for the use of UAS in 2016, a provision was made for indoor flights where the same processes and approvals for outdoor flights were applicable.

Glen Canyon Penstock Inspection

As part of collaboration research between Reclamation and USACE, a custom-designed UAS was operated in Unit 2 penstock at Glen Canyon Dam, Arizona. The flights were conducted during a 3-day period beginning July 21, 2015. The UAS was designed and built by the University of Pennsylvania's robotics laboratory and was used as part of their ongoing test and evaluation of the suitability of the airframe for tunnel inspections.

Approval for the indoor flight was provided by the UC Region's power manager, RAM, and Regional Director.

The UAS was a custom, six-rotor or hexacopter design and carried on-board processing, two LIDAR scanners for navigation and collision avoidance, four cameras oriented around the body of the airframe to view the entire circumference of the tunnel simultaneously, and lighting to view features within the unlit tunnel. During their time at the Glen Canyon Dam penstock, the University of Pennsylvania researchers tested their positioning features for autonomous navigation (see Figure 30) [81].

Figure 30.—Testing a tunnel inspection UAS at Glen Canyon Dam, Arizona.

Reclamation employees provided and continues to provide feedback to USACE and the University of Pennsylvania in terms of the inspection data that are required. This feedback has continued to drive feature implementation for the future completion of the autonomous tunnel inspection UAS for USACE and Reclamation. University of Pennsylvania researchers recently presented progress of the UAS design at the Reclamation UAS Research Workshop.

Reclamation Hydraulics Laboratory

The Reclamation Hydraulics Laboratory develops and tests scaled/physical models of water conveyance structures from simple gate flow tests to large recreated topographical representations of flood plains and dams. While the models are designed using CAD software, oftentimes changes are made that require updating. To do this, a digital model of the As-built conditions is required. Thus, the application of indoor operation of UAS to collect photogrammetric data of the models is a natural solution.

In December 2018, two indoor flight tests were conducted using DOI-approved airframes. The two tests were designed to demonstrate the indoor capabilities of the UAS and to determine any appropriate mitigations and recommendations for indoor operations of UAS. The tests were approved and observed by the pilot supervisors, the RAM, the NAM, and the Safety, Security and Law Enforcement Deputy Director.

The first test was conducted on December 11, 2018, in closed-access warehouse space in the event of unexpected behavior. The test was performed by two TSC pilots and consisted of several take-offs and landings and non-payload and payload-attached flights down warehouse corridors. The UAS used for the demonstration was the 3DR Solo with the Ricoh GR II payload. When operating the 3DR Solo indoors, the airframe is unable to use GNSS positioning and will drift in air currents caused by its own rotors. In addition, once the UAS is operating in any single horizontal direction, it will continue to coast in that direction unless an input is made to stop or reverse the direction of movement. The first test was successful and demonstrated that the 3DR Solo can be operated indoors; however, operation of the UAS without positioning capabilities can be challenging to inexperienced pilots.

The second test was conducted on December 12, 2018, in the Hydraulics Laboratory over the San Juan River Restoration Project (SJRRP) model. The Hydraulics Laboratory has a nearly 1-acre area, a ceiling that is 24 feet high and is divided by columns spaced approximately 30 feet apart. The SJRRP model was about 46 feet wide and 92 feet long (See Figure 31). The laboratory area is open to all building tenants, outside of Reclamation, and required General Services Administration (GSA) coordination to keep people safe and out of the immediate flight area.

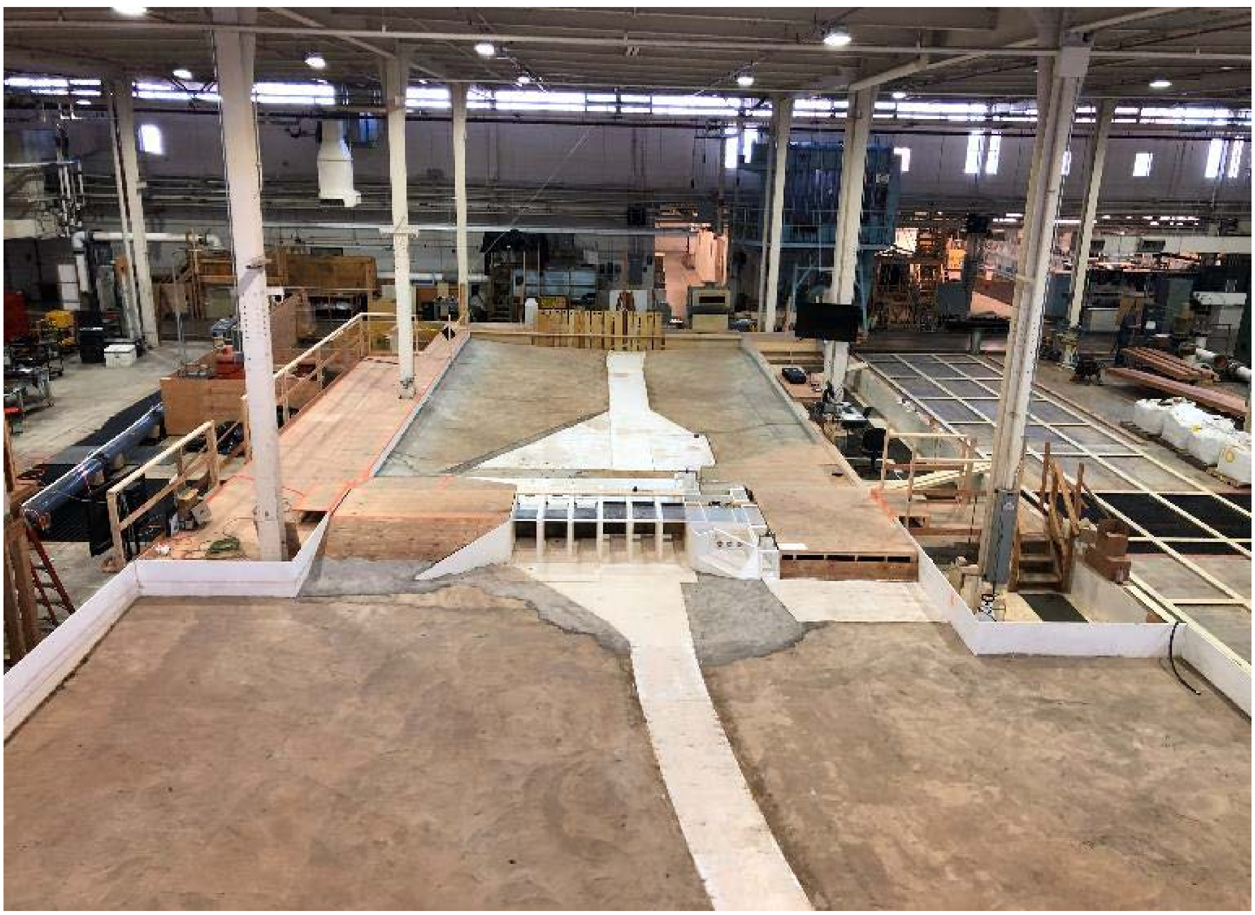

Figure 31.—SJRRP scaled/physical model at the Reclamation Hydraulics Laboratory in Denver, Colorado.

This flight was conducted to test the ability and quality of indoor UAS data collection for photogrammetry. The test was also conducted by two TSC pilots and featured a large flight crew. Temporary barriers were placed along common walkways, and ingress to the flight area was staffed by Reclamation personnel to prevent accidental encroachment to the UAS flight path. Spotters were used along the sides and end of the model to watch for proximity to the columns. The data collection flight consisted of four transects and lasted just under five minutes. A total of 341 images were collected and processed into a point cloud and orthoimage of the model area (see Figure 32).

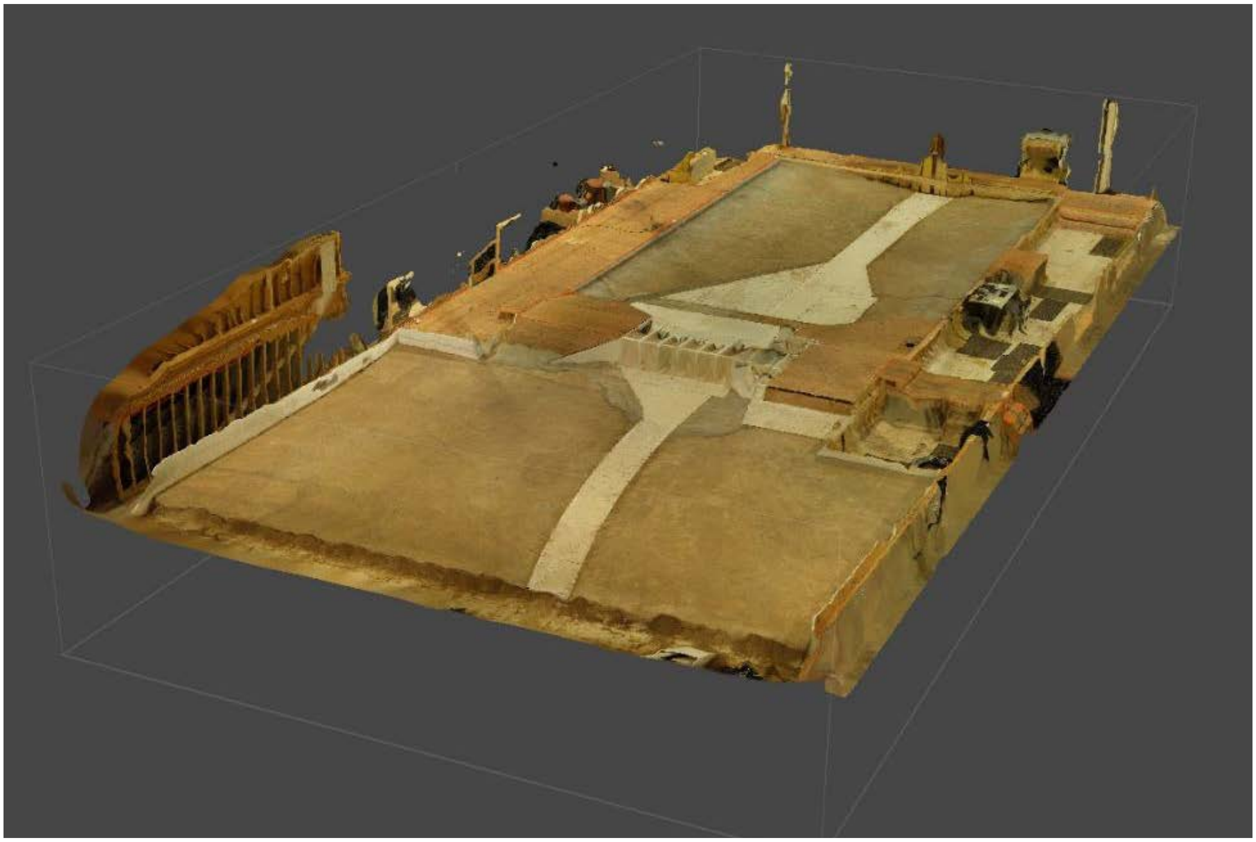

Figure 32.—Photogrammetrically textured mesh of the SJRRP model.

The indoor tests demonstrated that using proper notifications and hazard mitigation, along with operating in relatively open areas can lead to the successful operation of UAS indoors. Improvements to the process would be to limit UAS operations to after-hours to limit exposure to other non-participating personnel and, identify technologies such as vision positioning and collision avoidance to help improve data collection flight lines and prevent collision with obstacles and obstructions.

Airframe Evaluation/Demonstration

While the benefits of UAS have been demonstrated throughout this report, there is always room for improvement specifically with respect to Reclamation's mission and unique infrastructure. If an approved airframe is unable to perform an ability required by a project, or to operate safely and efficiently in a given application, there are mechanisms in place to evaluate and demonstrate the capability of another manufacturer's UAS. This process may help DOI OAS adopt other airframes that serve functions outside of its core fleet.

The process involves close collaboration with DOI OAS and gives DOI OAS operational control over the demonstration relieving any Bureau of the risks and responsibilities. Typically, the demonstrations are not purchased, as the vendor should be responsible for advertising their own equipment capability. Demonstrations should be simple as to keep costs low and should not perform work for the agency that would be done otherwise. DOI OAS is the liaison between any Bureau and vendor.

Intel – Arrowrock Dam

In January of 2018, Intel conducted a demonstration of the Intel Falcon 8+ UAS. The demonstration was performed in cooperation with DOI OAS, PN Region and TSC UAS pilots, and Arrowrock Dam, Idaho (see Figure 33). The Falcon 8+ UAS is a V-shaped octocopter that can carry about 1.75 lbs. and has a flight time between 16 and 26 minutes. The size of the UAS is about 30 inches square by 7 inches tall. It features a dual battery setup for redundancy. Its maximum speed is 40 mph and can hold its position using the GNSS network. It is equipped with an HD video downlink. The payload is configurable and can be integrated for live view from the camera [82]. Another advertised feature is the vision positioning system for collision avoidance and the ability to maintain an offset hold when inspecting vertical surfaces. The claim was also made that objects are identified during flight and spatial reference to those objects are retained to prevent collisions [83].

Figure 33.—Intel's Falcon 8+ UAS collecting inspection data at Arrowrock Dam, Idaho.

The demonstration was conducted on January 30, 2018. The demonstration party met at DOI OAS headquarters in Boise, Idaho, and then reassembled at Arrowrock Dam about 20 miles west. At the dam, safety plans were reviewed as well as a discussion of the work to be performed. Intel demonstrated photogrammetric data collection and collected images over the top and downstream face of the dam. The Falcon 8+ UAS was paired with a Sony A7 full frame camera; the collision avoidance and offset hold features were not demonstrated. The data Intel collected was transferred to Reclamation for processing. The results are shown below in Figure 34.

Figure 34.—The meshed model of Arrowrock Dam, Idaho, with a photorealistic texture captured by Intel's Falcon 8+ UAS.

After reviewing the results, Reclamation determined that the Intel UAS offers the same functionality as demonstrated in DOI's current fleet, and that further investigation into the airframe as configured was not required. Reclamation continued communication with Intel in an attempt to test the collision avoidance and offset hold, but additional demonstrations never occurred.

Center – UAS

The Center for UAS (C-UAS) is an assembly of academic and industry UAS research partners funded by the National Science Foundation [84]. The partners work by proposing UAS research topics to voting members that would like to advance research that meets their needs. The assembly meets twice a year – once for presenting proposals and updating progress and the second for approving new proposals.

Reclamation has a voting membership based in PAO; however, in February 2018, TSC staff also participated in a biannual meeting. At the meeting, several projects were identified that would meet Reclamation's mission, including "small-UAS-Based Infrastructure Monitoring: Multi-Scale Flight Optimization" and "Autonomous Navigation and Photogrammetry of Bridges for Inspection".

The sUAS-Based Infrastructure Monitoring: Multi-Scale Flight Optimization is a project that looks to target areas of interest during an inspection and provides only high-resolution in that area to optimize the completed model. This allows for a reduction in processing loads making it faster and more efficient. This work is being led by researchers at Brigham Young University in Provo, Utah [85].

Autonomous Navigation and Photogrammetry of Bridges for Inspection is a project focused on providing non-GNSS based navigation algorithms for close-range inspection and data collection of bridges where GNSS signals are known to degrade especially under the structure. The UAS flight controller relies on LIDAR for proximity placement and for systematic data collection. This project is headed by researchers at Virginia Polytechnic Institute and State University in Blacksburg, Virginia [86].

Knowledge Transfer

Over the course of this project, team members had several opportunities to participate and spectate in several UAS knowledge transfer activities including workshops, conferences, forums and symposiums. Table 7 below summarizes the activities.

Table 7.—Summary of UAS Knowledge Transfer Opportunities

Venue	Location	Date	Description
Commercial UAV Expo	Las Vegas, Nevada	October 2016	Attended presentations, investigated vendors
Reclamation TSC Technical Tuesday	Denver, Colorado	February 2017	Presented: “Elephant Butte Dam Inspections using UAS”
International LiDAR Mapping Forum (ILMF)	Denver, Colorado	February 2017	Attended presentations, investigated vendors
2nd Federal UAS Workshop	Mountain View, California	March 2017	Presented: “Unmanned Aircraft Systems: Reclamation Summary”
United States Society on Dams (USSD)	Anaheim, California	April 2017	Presented: “Elephant Butte Dam UAV Data Collection and Photogrammetry”
Reclamation Facility Review Workshop	Bend, Oregon	April 2017	Presented: “Drones – The good, the bad and the ugly” and “Drones for Survey and Inspection - Elephant Butte Dam”
National Association of Corrosion Engineers (NACE) Concrete Service Life Extension Conference	New York, New York	June 2017	Presented: “UAS Inspections: Elephant Butte Dam”
American Society of Civil Engineers (ASCE) Congress on Technical Advancement	Duluth, Minnesota	September 2017	Presented: “UAS Data Collection at the Bureau of Reclamation’s Elephant Butte Dam”
Center – UAS	Menlo Park, California	February 2018	Reviewed UAS academic and industry research
USACE Jacksonville District Annual UAS Meeting	Jacksonville, Florida	February 2018	Presented: “Bureau of Reclamation UAS Summary, February 2018”
Reclamation Associated Facility Review Workshop	Rancho Cordova, California	April 2018	Presented: “Bureau of Reclamation UAS Summary, April 2018”
DOI Dam Safety and Security Training	Rancho Cordova, California	May 2018	Presented: “Bureau of Reclamation UAS Summary, May 2018”

Venue	Location	Date	Description
Power O&M Workshop	Nellis Air Force Base, Nevada	May 2018	Presented by proxy: “Hoover Dam Rockface Analysis using UAS”
Association for Unmanned Vehicle Systems International (AUVSI) Xponential	Denver, Colorado	May 2018	Attended presentations, investigated vendors
Wyoming UAV Symposium	Laramie, Wyoming	May 2018	Attended presentations
Commercial UAV Expo	Las Vegas, Nevada	October 2018	Presented: “What is a UAS?” and “UAS Unintended Consequences”
USACE UAS Community of Practice	New Orleans, Louisiana	November 2018	Presented: “Reclamation UAS TSC Activities”
Reclamation Aviation Workshop	Boise, Idaho	November 2018	Training, networking
Canadian Electricity Association Technologies International (CEATI) Workshop on Coatings and Linings of Penstocks	Vancouver, British Columbia	December 2018	Presented by proxy: “UAS Inspections”
Reclamation Dam Operators Training	Durango, Colorado	March 2019	Presented: “UAS Applications at Reclamation”
3rd Federal UAS Workshop	Mountain View, California	May 2019	Training, networking
Reclamation TSC Technical Tuesday	Denver, Colorado	June 2019	Presented: “UAS Research Applications”

Conclusions

Conclusions

Over the past 3 years, UAS team members have worked to demonstrate that UAS can collect data faster, cheaper, and safer than traditional methods. Funded in whole, in part, or in collaboration with this project, a total of nine demonstrations were conducted. Also, during this period, the TSC conducted a total of 39 UAS projects resulting in nearly 100 hours of UAS flight time (recall that a 3DR Solo battery only last for about 10 minutes; 100 hours is around 600 total flights).

When processing the data from the UAS projects, it became apparent that the data collected were both higher quality and in greater quantity than what had been collected with previous methods. Cracks can be detected to 1/8 inch or better, topographical maps can be generated to 1-foot contours, and IR data (at 400 ft AGL) can be resolved to a resolution of 9 inches per pixel compared to satellite imagery that is around 36 inches per pixel.

The demonstration projects discussed herein showed that the typical photogrammetric project required about 2 to 3 weeks to complete, from flight planning to data collection to data processing. For example, photogrammetric data collected by hand requires 3 days whereas the data collected by UAS on the same area can be completed in about 3 hours. Faster data collection is cheaper data collection. However, it is pointed out that the cost savings is often not very apparent, when training and equipment costs are factored in. Nonetheless, the cost per data is significantly cheaper. Consider collecting a point cloud via UAS with 64 points per square inch (1/8-inch resolution at four-hundredths-inch error) by a surveyor collecting each point individually. Even a terrestrial LIDAR scanner cannot provide the same results because the terrestrial LIDAR scanner cannot be positioned as consistently as the UAS.

Finally, the safety aspect of operating a UAS is substantial. Because the UAS can access areas that are difficult to access, requires specialized equipment and training, or are impossible to reach, human hazard mitigation is reduced. There is no way to place a cost on this factor.

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