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Abstract

Finite and decreasing landfill space on Army installations is a significant concern. Efficient waste management is essential for achieving resiliency and extending the lifespan of remaining landfills. The purpose of this demonstration was to conduct independent performance tests of small unmanned aircraft systems (sUAS) and their utility for providing landfill assessments in remote areas where physical presence is either dangerous or inefficient.

An active, near capacity construction and demolition (C&D) landfill at Fort Gordon, Georgia, was identified for the demonstration. The flights, data requirements, and outputs generated by the sUAS flyovers were analyzed for efficacy in detecting cell capacity and subsidence. Each flight took 1–2 hours for mobilization, ground marker placement, flight, and postflight analysis. Volumetric and topographic surveys were analyzed in less time than is typical for traditional surveying methods.

After initial setup of ground markers and rectification, sUAS flights save a significant amount of time. However, skilled individuals are required for flights and for processing and maintaining data. The technology is widely relevant to the Army, is commercially available, and offers an average of 30% cost savings in terms of manpower, repeatability, and equipment. The use of sUAS technology is recommended for monitoring and surveying Army landfills.

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Preface

This study was conducted for Headquarters, Department of the Army, Deputy Chief of Staff, G-9 (HQDA DCS G9) under "Comprehensive Waste Management & Landfill Facility Assessment," MIPR 11106470. The technical monitor was Svetlana O'Malley.

The work was performed by the Environmental Processes Branch of the Installations Division, US Army Engineer Research and Development Center (ERDC), Construction Engineering Research Laboratory (CERL). At the time of publication of this report, Mr. Jeffrey Burkhalter was chief, Environmental Processes Branch; Dr. George Calfas was chief, Installations Division; and Mr. Jim Allen was the technical director for Operational Science and Engineering, Office of Technical Directors. The deputy director of ERDC-CERL was Ms. Michelle Hanson, and the director was Dr. Andrew Nelson. The work was also performed by the Airfields and Pavements Branch of ERDC Geotechnical and Structures Laboratory (GSL). At the time of publication, Ms. Anna M. Jordan was chief, Airfields and Pavements. The deputy director of ERDC-GSL was Mr. Charles W. Ertle II, and the director was Mr. Bartley P. Durst.

Appendix A and Appendix B were prepared by Andrew B. Ward.

COL Christian Patterson was the commander of Engineer Research and Development Center, and the director was Dr. David W. Pittman.

1 Introduction

1.1 Background

The US Army owns and operates several on-post active municipal solid waste landfills and is required to continually maintain and monitor on-post closed landfills. Army Regulation 420-1 (Department of the Army 2012) and 40 CFR 258 set standards for operating, monitoring, and maintaining landfills. In addition, regulations require post-closure activities and care for 30 years after the date of closure (40 CFR 258, Subpart F). Physical monitoring of these sites is time consuming and potentially hazardous.

In the commercial sector, small unmanned aircraft systems (sUAS) are increasingly being used to take repeated images of landfills; this significantly reduces the time and potential physical constraints of regular monitoring. The images recorded by the sUAS can be used to calculate volumetric capacity and to identify subsidence or vegetation stress. In addition, sUAS are being used to monitor equipment and waste movement throughout the landfill facility, determine daily quantities, calculate the life of an active cell, estimate compaction and daily capping needs, and identify areas of concern.

Using sUAS to conduct assessments saves hours of labor in field collection, driving time, and data processing. In addition, the collected data are easily processed to determine current and future capacities. The use of sUAS in remote or inaccessible areas also reduces the risk to inspectors and to landfill caps.

Monitoring and determining the volume and locations of material, plotting fill elevations, and identifying signs of methane gas leaks by vegetation stress (i.e., color change and change in the Normalized Difference Vegetation Index [NDVI]) or methane sensors can be performed from a centralized site, out of the way of heavy equipment operators. On closed landfills, subsidence can be easily captured without driving or walking over the vulnerable cap. Much like landfill sites, ranges and training lands can be remotely and rapidly monitored for illegal dumping and to identify and optimize dumpster locations and collection. Augmenting waste management with sUAS can reduce labor, the need for vehicle maintenance, and fuel consumption, while improving data acquisition, data processing, and individual safety.

1.2 Objectives

The objective of this demonstration study was to demonstrate the use of sUAS to assess an active construction and demolition (C&D) landfill on US Army Garrison Fort Gordon. Using sUAS to assess landfills, particularly in remote areas or on training lands where physical presence is either dangerous or inefficient, could allow for the rapid determination of solid waste infrastructure needs across US Army installations.

1.3 Methodology

This demonstration study is the product of a collaboration between two labs within the US Army Engineer Research and Development Center (ERDC): Construction Engineering Research Laboratory (CERL) and Geotechnical and Structures Laboratory (GSL). CERL and GSL used untethered sUAS for data collection, following Army Aviation requirements. All Federal Aviation Administration (FAA) and US Army Corps of Engineers (USACE) required memorandums of understanding were followed, and the clearances and certificates needed to fly in both restricted and unrestricted airspace were obtained. The sUAS used in this demonstration study contained no parts, hardware, or software made in China.

This demonstration was initially derived from a feasibility assessment of sUAS technology to delineate parameters and the limits of the system for data collection to conduct site identification and mapping. Consequently, this report focuses on an active on-post landfill and a closed landfill that requires continual monitoring. These details are integrated into a final recommendation for consideration by Fort Gordon and higher echelon stakeholders to demonstrate a feasible option for optimizing waste management tasks that will keep resource costs low and provide environmental and economic benefits across US Army installations.

2 Feasibility Assessment

Ensuring that waste and recycling are collected efficiently is essential to achieving installation resiliency because they are the main drivers for waste diversion. An efficient, integrated solid waste management and recycling program not only reduces the amount of waste sent to the landfill, but it also maximizes the opportunities for collection and diversion of recyclable materials from the waste stream. Optimal material collection not only supports resiliency efforts but also reduces costs incurred in waste hauling contracts and increases revenue generated by the recycling of materials under the Qualified Recycling Program. Even though the US Army is moving toward waste reduction, it still owns and operates several active landfills and must monitor closed landfills. Installations have limited resources and too few personnel to complete the assessments required to comply with landfill regulations and to optimize waste management infrastructure. This study explores the feasibility of using sUAS to assess active and closed landfills.

2.1 Integrated Solid Waste Management Planning

Since 2014, researchers from ERDC-CERL have been conducting waste characterization studies and creating integrated solid waste management plans (ISWMP) for active duty and reserve component installations throughout the world. An ISWMP identifies planned reduction and contingency efforts related to solid waste and is required by DoDI 4715.23 (DoD 2016a) at all installations, including US Army Garrison Fort Gordon.

2.2 Construction and Demolition (C&D) Debris Reporting

Based on the data collected from the ISWMP, Table 1 presents the C&D debris generated, disposed of, and recycled by Fort Gordon for FYs 2007 to 2016. C&D generation and diversion was higher for FY 2015 than for any other year. In FY 2015, there were several major construction projects, including updates to the Post Exchange and Command Support Center parking lots. This led to tons of concrete and asphalt waste being generated and diverted during the year.

Table 1. Reported construction and demolition (C&D) debris disposed of and diverted at Fort Gordon, FY 2007 to FY 2016.

FY	Generated (tons)	Disposed (tons)	Recycled (tons)	Diversion Rate (weight %)
2007	738	738	0	0
2008	872	872	0	0
2009	2,231	2,231	0	0
2010	1,734	1,734	0	0
2011	1,253	1,253	0	0
2012	1,205	1,163	42	3
2013	589	589	0	0
2014	517	517	0	0
2015	17,666	3,134	14,532	82
2016	3,388	1,660	1,728	51

2.3 Transition from Active to Closed Landfill

Landfill closure activities include monitoring and maintaining the waste containment systems and monitoring groundwater to ensure that leachate is not escaping and polluting the surrounding environment. When landfills transition from active to closed, and even when landfills are still active, there is often illegal dumping that occurs both within the perimeter of the landfills and on adjacent training lands. Identification of illegal dumping sites is a challenge for many installations and results in potential fines, pest nuisance, habitat degradation, and impacts to readiness.

3 Fort Gordon

3.1 Overview of the Installation

US Army Garrison Fort Gordon is primarily located in Augusta-Richmond County and partially colocated in Columbia, Jefferson, and McDuffie Counties in east central Georgia, just southwest of Augusta. It is approximately 140 miles east of Atlanta, Georgia; 80 miles southwest of Columbia, South Carolina; and 122 miles northwest of Savannah, Georgia. The installation covers approximately 56,500 acres of land.

3.2 Installation Mission

Fort Gordon is the home of the United States Army Cyber Center of Excellence, 7th Signal Command (Theater), 35th Signal Brigade, 513th Military Intelligence Brigade, the Regional Security Operations Center, and a host of other tenant units and organizations, including a multiservice community of Army, Navy, Air Force, Marines, and multinational forces.

The primary mission of Fort Gordon is to train, house, and support the Cyber Center of Excellence and tenant units. The multifaceted missions of the US Army Signal Center of Excellence and Fort Gordon encompass training, doctrine, force integration, and mobilization. Fort Gordon provides training for more military personnel than any other branch training center of the Army to ensure our Army's signal community remains the world's premier support force ready to win in a complex world.

3.3 Installation Population

Population data derived from estimates projected in 2018 by the Army Stationing and Installation Plan (ASIP) database (Department of the Army, n.d.) indicate that the installation's population is expected to remain steady through 2023, with approximately 14,400 military personnel, 9,500 civilians, and 1,300 reserve Soldiers. It is anticipated, however, that the increase in facilities over the next five years (i.e., the new campus for the Signal Regiment and the relocation of the Army Cyber Command headquarters from Fort Meade, Maryland to Fort Gordon) will bring an additional 25,000 personnel to the installation.

4 Waste Management and Existing Solid Waste Facilities

4.1 Background

Fort Gordon does not have an active sanitary landfill, but it has an active C&D landfill that is located at Gibson Road on the installation. Municipal solid waste is collected and transported from the installation to the local landfill, the Augusta-Richmond County Landfill, by a licensed waste management contractor. Recycling at Fort Gordon is first sent to the Recycling Center on the installation before getting distributed and picked up by various entities.

4.1.1 C&D Waste Management

Major construction, renovation, and demolition projects, currently totaling $1.2 billion, are planned at Fort Gordon. Between 2016 and 2027, the installation plans to demolish and reconstruct all buildings associated with the Signal Command School. Each planned facility will be 75,000 square feet, for 1 million square feet in total. In addition, the Army Cyber School relocated to Fort Gordon and will require an additional 500,000 square feet of space. Last, the installation plans to add an additional 400,000 square feet for the NSA (Department of the Army 2018b).

The last active landfill on post, Gibson Road Landfill, is estimated to have a remaining capacity of 140,785 cubic yards and an estimated fill date of 1 January 2167 (Department of Public Works [DPW] staff, pers. comm.). This landfill is reported to receive, on average, only four tons of material per day. To maintain this landfill's estimated lifespan, it is necessary to divert as much C&D debris from the on-post landfill as possible. It is important to give attention to C&D debris on an installation like Fort Gordon. According to installation personnel, the latest construction and demolition management plan was written in 2004 and is currently in the re-writing phase. It is recommended that an updated plan be written and followed to accompany the oncoming projects. C&D debris has a large potential for reuse, sale, donation, and diversion from landfills. This should be explained and pursued using the updated C&D management plan.

Generally, C&D debris is handled and disposed of by contractors, and diversion tonnage is reported by the project manager or the contracting officer representative (COR) to the DPW staff on the installation to enter into SWARWeb. SWARWeb is an online tool used for tracking, analyzing, and reporting information on the generation, recycling, and disposal of nonhazardous solid waste. Solid waste annual reporting (SWAR) for FY 2016 indicated that Fort Gordon generated a total of 3,388 tons of C&D debris (Table 1). Of this, 1,660 tons were sent to the landfill, resulting in a 51% diversion rate (i.e., less than the 60% goal set by the DoD's [2020] *Revision to Integrated Solid Waste Management Metrics* and Executive Order 13,514, signed in 2009). There is certainly room for improvement in terms of the C&D debris recycling and diversion tactics practiced at the installation.

As stated previously, C&D contractors most often haul, dispose of, and recycle generated materials themselves. This is especially the case when the generated concrete contains recoverable rebar. Fort Gordon recommends that contract officers require contractors to track the weights of C&D debris and their diversion percentage. To comply with the Unified Facilities Guide Specifications, a waste management plan that results in at least 60% diversion is required within 15 days of awarding the contract (DoD 2019).

To comply with Executive Order 13,514, signed in 2009, DoD (2020) mandates, and DoD sustainability goals, any C&D effort at Fort Gordon must ensure that the contractor diverts 60% of generated C&D materials by including recycling clauses stipulating the diversion of recyclable materials when feasible and when cost-effective for the United States government. C&D materials often include asphalt, concrete, sand and soil, metal, wood, brick, gypsum, plastic (e.g., ABS and PVC), and polystyrene (i.e., insulation).

4.1.2 Policy and Guidance

Many opportunities exist for the successful diversion of construction materials. Construction contractors are increasingly aware of, and concerned with, the recovery of construction materials and their related savings. In areas where C&D disposal facilities are abundant, commodity prices are low, illegal dumping is common, or reuse culture is limited, there is a high likelihood that C&D debris will be mismanaged. It is important that installation personnel reinforce the importance of C&D

debris diversion and continually monitor the efforts of contractors. To do this, industry professionals must be aware of best practices for C&D sorting, recycling, and reuse. Further, contractors must truly understand how to report their waste diversion totals, making sure to report the tonnage of all waste types throughout the entire process of a construction or demolition project. Improper sorting, handling, and tracking often result in inflated diversion numbers and take value away from the importance of C&D diversion efforts.

An excellent review of C&D management policies and techniques (Napier 2016) can be found on the Whole Building Design Guide website, which is the official repository for DoD construction specifications. This review can help decision makers and contractors enhance current efforts to produce diversion practices with the most value.

In terms of the notable policies concerning C&D debris, a recent (FY 2016) DoD document, *Strategic Sustainability Performance Plan* (SSPP), calls for 60% diversion of C&D materials (DoD 2016b). Army policy echoes the SSPP but adds a net zero initiative that states that each installation is supposed to strive for continuous improvement toward net zero energy, water, and waste (Secretary of the Army 2014).

Unified Facilities Guide Specifications* (UFGS) is the primary database for all government agencies (i.e., tri-service military departments [Army, Navy, Air Force], defense agencies, DoD Field Activities, and NASA). It provides a set of contract language templates to be used in all types of construction (i.e., not just military). UFGS 01 74 19, *Construction Waste Management and Disposal* (DoD 2019), calls for a detailed construction waste management plan to be prepared by the contractor and submitted and approved before receiving notice to proceed. Most often, C&D debris is subject to local, state, and provincial laws and regulations that should be understood by project contractors and written into disposal and diversion plans. Ideally, the project COR would share the waste plan with the DPW solid waste manager for approval. This is an opportunity to inform the contractor of inhouse waste handling capability or perhaps of a need for certain materials, such as those used as fill or cover.

* http://www.wbdg.org/ffc/dod/unified-facilities-guide-specifications-ufgs

UFGS 02 41 00, *Demolition and Deconstruction* (DoD 2010), provides guidance on procedures for salvaging specific materials and administrative guidance on what party assumes title to salvaged materials.

4.2 Fort Gordon Gibson Road Landfill

Fort Gordon has one remaining active landfill on post, the Fort Gordon Gibson Road Landfill. This landfill is only for inert waste and is located at 33.368828, −82.24342. Inert waste is waste that is not chemically or biologically reactive and does not typically decompose. Inert waste is often generated from C&D projects. Common materials include furniture, concrete, and sand. According to DPW personnel, this landfill has a remaining capacity of 140,785 cubic yards and an estimated fill date of 1 January 2167 (DPW staff, pers. comm.). This landfill is reported to receive, on average, only four tons of material per day, resulting in the estimated fill date. There is a large amount of C&D planned at Fort Gordon. Thus, it is necessary to divert as much of this waste from the on-post landfill as possible to maintain the landfill's estimated lifespan. The Solid Waste Permit 121-014D (SL) issued by the Georgia Department of Environmental Regulation for the Fort Gordon Gibson Road Landfill is an active permit for C&D debris only.

4.3 Fort Gordon Closed Landfills

Fort Gordon has multiple closed landfill sites that must be monitored and maintained (Table 2). For the purposes of this project, one additional landfill site, Carter Road, was imaged to provide a static digital elevation model (DEM). The Carter Road DEM was used during processing to ensure data collection was accurate.

Table 2. List of closed landfills and locations at Fort Gordon, Georgia.

	Fort Gordon Landfills	Activity	Latitude	Longitude
1	3rd Avenue (East)	Closed	33.412083	−82.144194
2	3rd Avenue (West)	Closed	33.412517	−82.149977
3	8th Avenue	Closed	33.427670	−82.150951
4	17th Street	Closed	33.410518	−82.164373
5	19th Street	Closed	33.435312	−82.162423
6	Carter Road	Closed	33.373279	−82.155331

4.4 Landfill Monitoring

For both open and closed landfills, continual monitoring is necessary for maintaining safe operations and avoiding risks, such as structural collapse due to compaction. The USGS assessed the soil-gas and groundwater contamination levels for the Gibson Road Landfill in Fort Gordon (Falls et al. 2012). They found that volatile and semivolatile organic compounds, as well as polycyclic aromatic hydrocarbons, were contaminating the soil-gas and groundwater. Prior to the Falls et al. (2012) study, the landfill was permitted as an unlined landfill. In addition to the Gibson Road Landfill, closed landfills, such as those listed in Table 2 , must include a post-closure plan that effectively outlines maintenance of the final cover system, the leachate collection system, the groundwater monitoring system, and the methane gas monitoring system.

4.5 Illegal Dumping

Though Fort Gordon does not report struggling with illegal dumping, some installations do. Illegal dumping has been witnessed in multiple installations and could cost garrisons hundreds of thousands in additional disposal fees. For example, when refuse containers at administrative facilities are placed in main corridors, a higher degree of household refuse is found in the containers. This could be from staff or contractors bringing refuse onto the post.

5 Small Unmanned Aircraft Systems (sUAS)

5.1 Background

An sUAS is a UAV, or drone, that weighs less than 55 pounds, including all onboard attachments and equipment. It is flown without any direct human contact or intervention on the aircraft. To operate the sUAS, the remote pilot in command (PIC) must hold a Remote Pilot Certificate from the FAA. With a certificate, the PIC is authorized to fly the sUAS in the National Airspace System Class G, defined as within 400 feet above ground level and not to exceed 100 miles per hour. The PIC is also required to keep the vehicle within visual line of sight (VLOS) or to be in communication with a visual observer (VO) who has VLOS. The VO acts as the flight crew and assists the PIC in avoiding other air traffic or fixed structures on the ground.

5.2 UAV for Landfill Monitoring

Several studies have found that topographical and volumetric surveys may be safer and more economical with UAVs than with traditional surveying methods, and they are increasingly utilized by municipalities and the private sector to expediently image landfill areas that are difficult to access or are not accessed on a regular basis due to physical or time constraints (Filkin et al. 2021; Incekara et al. 2019; de Sousa Mello et al. 2022). Moreover, UAVs have been used to identify environmental issues in landfills that could harm surrounding areas. They can be used to monitor equipment and waste movement throughout the landfill facility, determine daily quantities, calculate the life of an active cell, make estimates on compaction and daily capping needs, and identify areas of erosion. They can also be used to improve waste hauling by optimizing routes, reducing pickups of dumpsters that are at a predetermined capacity, and identifying illegal dumping.

Using a UAV to conduct assessments may save a significant amount of time in field collection, operation and driving, and data processing. UAVs can collect data in a matter of minutes, as opposed to the days required by traditional methods. By reducing the costs associated with traditional surveying methods, it is possible that more surveys can be conducted, which is particularly important when landfills (such as Gibson Road at Fort Gordon) are near capacity.

Additionally, use of an sUAS will allow for more expedient and detailed data collection, especially in remote or inaccessible areas. It will also reduce the risk of compromising capped landfills. Monitoring and determining the volume and locations of incoming material, plotting fill elevations, and identifying signs of methane gas leaks by vegetation stress (i.e., color change and change in NDVI) or methane sensors can be performed from a centralized site, out of the line of heavy equipment operators. On closed landfills, subsidence, an indication of liner breach, can be easily captured without driving or walking over the vulnerable cap.

Similar to landfill sites, ranges and training lands can be remotely and rapidly monitored to determine if illegal dumping has occurred and to identify and optimize dumpster locations and collection. Unlike landfills that generally cover hundreds of acres, training lands tend to cover tens of thousands of acres. Monitoring 8- and 30-cubic-yard refuse containers can take an individual an entire day or more. The implementation of sUAS for data collection, which can be performed more or less remotely and rapidly, will minimize impacts to the training mission and Soldiers.

5.3 Commercial Off-the-Shelf (COTS) sUAS for Surveying

Using a commercial off-the-shelf (COTS) sUAS to augment waste management can reduce required labor, vehicle maintenance, and fuel consumption while improving data acquisition, data processing, and individual safety. For the demonstration at Fort Gordon, the team went with a COTS sUAS that, at the time, met all Army Aviation requirements.

The Matrix-E by TurboAce (Figure 1*a*) used for this demonstration study uses a LiPo battery for propulsion and a Pixhawk autopilot flight controller and has a roughly 36-inch wingspan. The command and control communication system operates through a Futaba 14SG controller, operating at 2,404–2,480 megahertz for transmitting to and receiving spatial position data from the base station. The telemetry system operates at 915–928 megahertz, and the Connex video transmission link is 5,138–5,808 megahertz. The transmitter is powered at 0.5 watts, the telemetry is adjustable from 100 megawatts to 25 megawatts, and the Connex is 500 megawatts. The payload capacity of the forward-facing gimbal on the Matrix-E is limited to less than 1 pound. This allows for the use of smaller digital single-lens reflex (DSLR) cameras, such as the Sony Alpha 6000 (A6000), combined with smaller fixed-focus lenses. The A6000 is a COTS electro-optical camera equipped with a 24.3 megapixel full-frame sensor. It collects imagery at a resolution of 6,000 × 4,000 square pixels. Most important, at the time of flight, the Matrix-E complied with cyber and information risk mitigation procedures.

In addition to the Matrix-E, a fixed-wing vertical takeoff and landing sUAS was used for some higher-altitude flights: the BirdsEyeView Aerobotics FireFLY 6 PRO (Firefly; Figure 1*b*). The Firefly featured a similar control scheme to the Matrix-E and had a wingspan of roughly 60 inches. The fixed-position, bottom-mounted gimbal of the Firefly was capable of a slightly larger payload than the Matrix-E and was flown with a Sony DSC-RX1R (RX1R) DSLR camera with a fixed 35 millimeter prime-focus lens. The Rx1R is a COTS electro-optical camera equipped with a 42.4 megapixel full-frame sensor. It collects imagery at a resolution of 7,952 × 5,304 square pixels.

Figure 1. Matrix-E and FireFLY 6 PRO small unmanned aircraft systems (sUAS). (*Left* image is from Drones Users Manuals, n.d.; *right* image is from PrecisionHawk 2018. Public domain.)

a) Turbo Ace Matrix-E

b) FireFly 6 PRO

6 Approach

6.1 Background

Two visits were scheduled, approximately three months apart, in June 2018 and October 2018. The initial collection, which took place in June, involved multiple passes over Gibson Road Landfill and over maneuver and training lands near cantonment. The October visit included multiple passes over Gibson Road Landfill, Carter Road Landfill, and maneuver and training lands near cantonment. Figure 2 shows an image of the Gibson Road Landfill at Fort Gordon, and Figure 3 is a photograph of the flight crew taken by the sUAS in 2018.

Figure 2. Google Earth image of Gibson Road Landfill site at Fort Gordon. The launch point for the sUAS flight is indicated. (Satellite image from Google Earth 2018.)

Figure 3. Image of flight crew as seen from the sUAS. (Photograph taken by R. C. Strange in 2018.)

6.2 Analysis

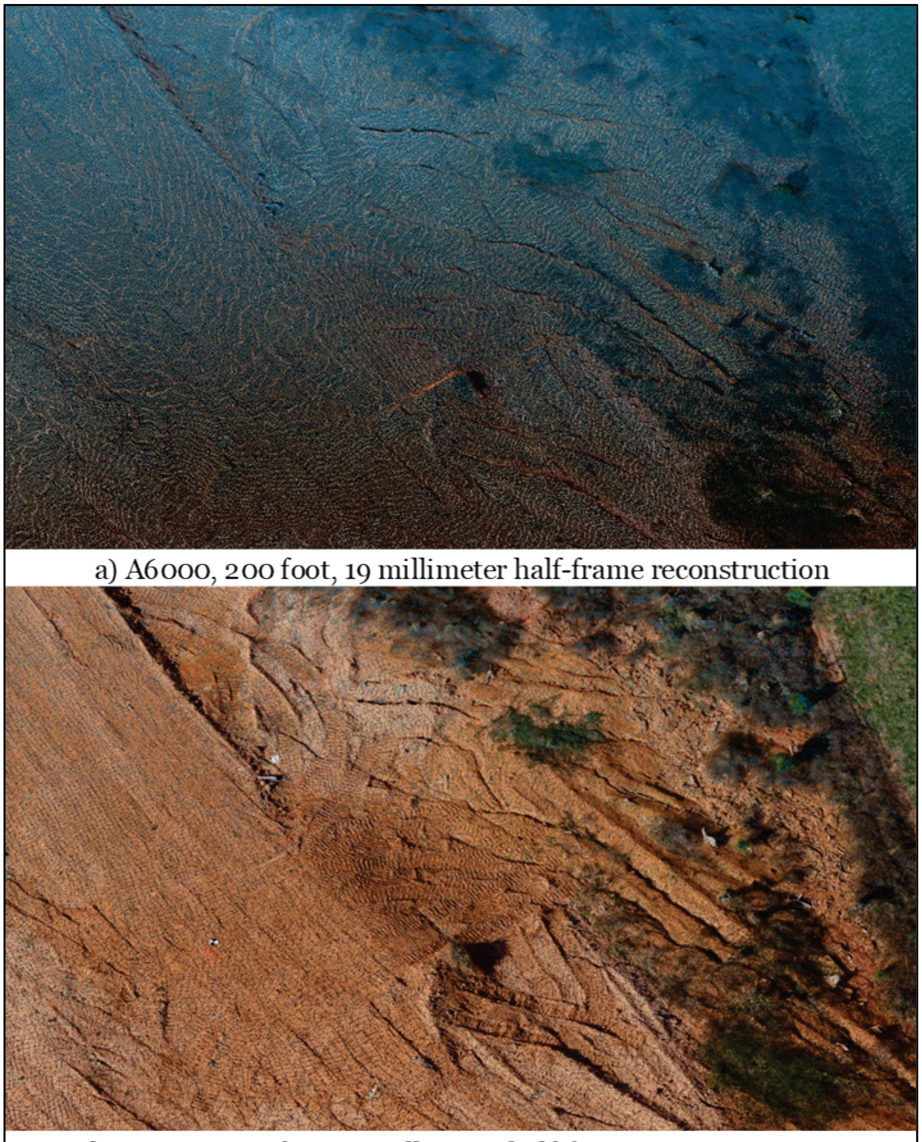
During the June collection period, several parameters were tested, including altitudes of 100, 150, 200, 250, and 300 feet. More than 4,000 images were collected. Figure 4 shows an image of the active cell from 150 feet above ground. All images were processed on a per-run basis in a COTS photogrammetry software called Agisoft PhotoScan. The imagery collected by the COTS sUAS and optics platforms referenced in Chapter 5 do not contain any geospatial information. To georeference and improve mosaic quality, ground control points (GCPs) were collected on site using a Trimble base and rover system. Base station data points were processed through a correction service called Opus. These centimeter-accurate GCPs allowed not only for an abbreviated image stitching process, but also for all imagery to be exported as georeferenced image files. The coordinate system used for the GCPs was NAD83 UTM Zone 17N. Following the initial stitching process, a dense 3D reconstruction of the area of interest was performed using PhotoScan. This resulted in a dense, georeferenced, 3D point cloud of the landfill being tested. This point cloud was then processed through ESRI ArcMap to generate a DEM. These DEMs were then subjected to difference analysis to report volume changes. See Appendix A and Appendix B for more details on each pass, including alignment time, dense reconstruction time, resolution, point density, DEMs, orthomosaic maps, and so on.

Figure 4. Image of an active cell at the Gibson Road Landfill, as shown from 150 feet above ground with a 35 millimeter lens. (Photograph taken by R. C. Strange in 2018.)

Point density has a direct impact on the variety of feature changes that can be detected. Very high point density (i.e., thousands of points per square meter) allows for minute changes in scenery to be detected but requires longer processing time. In contrast, lower point densities (i.e., hundreds of points per square meter) allow for the detection of mostly large-scale feature changes but require shorter processing times. In addition, the PhotoScan software allows for half-frame or full-frame reconstruction; that is, images can be artificially downsampled prior to 3D reconstruction to allow for faster processing times. Considering these processing times prior to mission planning allows end users to consider appropriate altitudes and lens focal lengths to meet mission objectives. For example, the A6000 at a 200-foot altitude and with a 19-millimeter lens generates a half-frame reconstructed point density of 465 points per square meter

(Figure 5*a*) and a full-frame reconstructed point density of 1,923 points per square meter. The same camera and lens at a lower elevation of 100 feet produces a half-frame reconstructed point density of 1,890 points per square meter (Figure 5*b*) and a full-frame reconstructed point density of 7,926 points per square meter.

Figure 5. Reconstructed 3D point clouds derived from images collected with the A6000 camera.

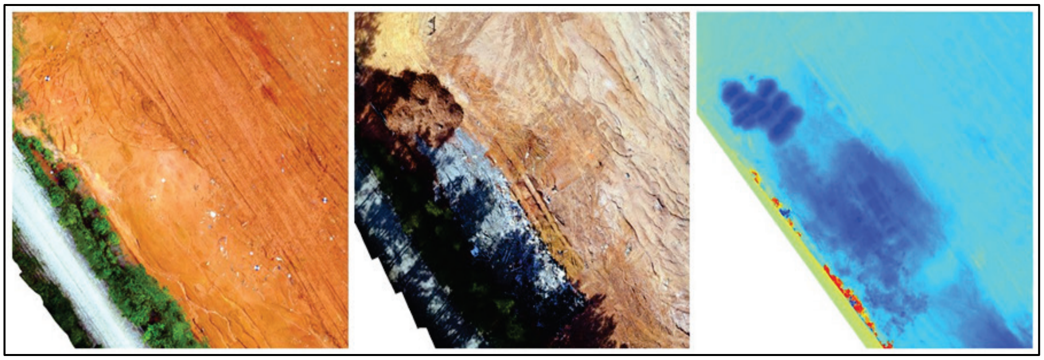


a) A6000, 200 foot, 19 millimeter half-frame reconstruction

b) A6000, 100 foot, 19 millimeter half-frame reconstruction.

The three sets of images that follow (Figures 6, 7, and 8) are stills taken of the 3D reconstructed point cloud from the active cell and indicate the measurements taken in June (left), the measurements taken in October (middle), and their elevation difference (right). The images on the right are from a difference map created using the June and October DEMs. The colorization of the difference map reflects changes in elevation, where dark blue indicates an increase in elevation from June to October, dark red indicates a decrease in elevation from June to October, and yellow and light blue indicate little to no change between the images.

Figure 6. The images are from June (*left*), October (*middle*), and elevation difference (*right*) and feature a portion of the active cell at Gibson Road Landfill, as seen from the northern direction.



The images in Figure 7 better illustrate the significance of the colors. Two bulldozers were photographed. The first image was taken in June, and the second was taken in October. The June image on the left shows a large dozer, and the October image in the middle shows a smaller dozer. In the difference map on the right, the large dozer is dark red, and the small dozer is dark blue (i.e., the smaller dozer indicates an increase in elevation because there was not a dozer in that specific location in the June image). In addition, two large dirt piles in red can be seen next to the dozers. The dark blue points in between the two piles indicate that they were likely plowed to cover waste in that area. Changes such as these allow base differences to be detected and provide a measure of forensic information on how volumes on the landfill are distributed over time and their likely purpose.

Figure 7. Another portion of the active cell at Gibson Road Landfill, as seen from the northern direction. The image on the *left* was taken in June, the image in the *middle* was taken in October, and the image on the *right* shows the differences in elevation between the first two images.

The volume of the active cell was calculated by laying a flat plane over the 3D reconstructed surface and measuring the volume enclosed. The highest elevation in the active dumping area was approximately 154 meters, so that was chosen as the height of the flat plane. The volume of the active cell as measured in the June flights was 89,923.701 cubic meters, and the volume of the active cell as measured in the October flights was 73,568.984 cubic meters. The volume difference was 16,354.717 cubic meters. As noted, the recorded volume was lower on the second collection pass. This is because volume, as measured in this context, is not the volume of the surface contents but, rather, the volume of the air enclosed by the artificial plane height and the surface. In this formulation, a lower volume indicates that less air exists below the plane height, and therefore, it can be surmised that more surface elevation exists. A variety of factors, including added or subtracted waste, soil compaction, and soil erosion, can cause these changes in elevation. While this measure of volume may seem counterintuitive, it allows volume changes to be calculated on areas with an unknown reference surface (i.e., an unknown original elevation). Should a landfill be scanned from its empty state to a future state, then volume changes from the base elevation map can be calculated in a more intuitive manner.

Figure 8. Another portion of the active cell at Gibson Road Landfill, as seen from the northern direction. The image on the *left* was taken in June, the image in the *middle* was taken in October, and the image on the *right* shows the differences in elevation between the first two images.

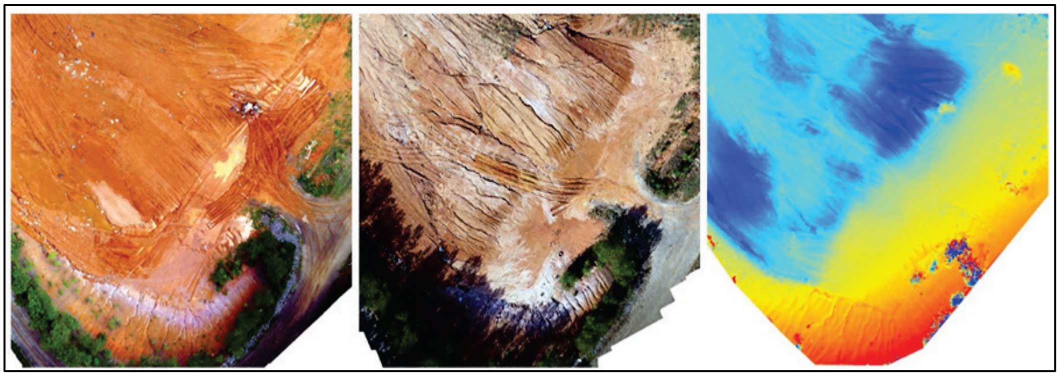
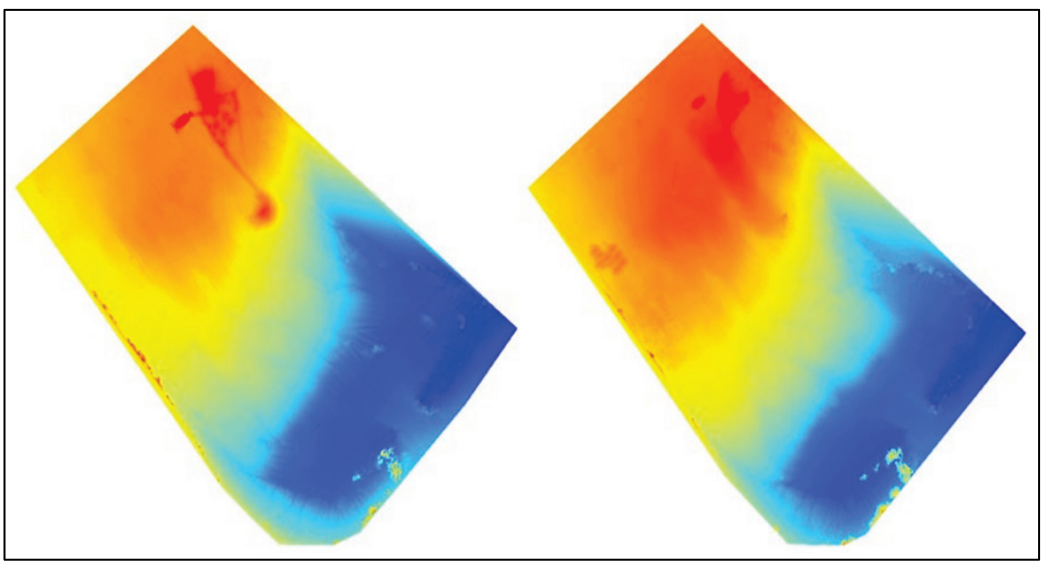


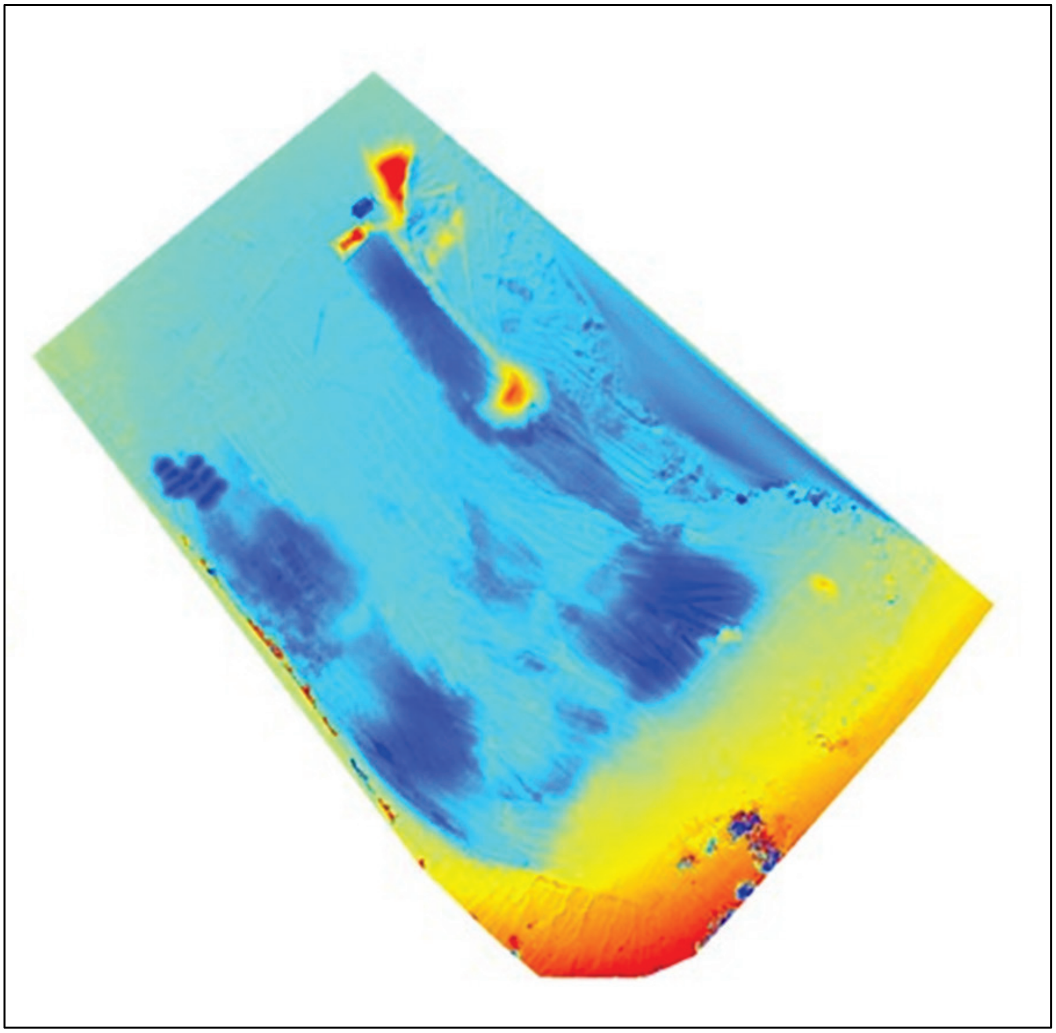
Figure 9 shows two images of the active cell of the Gibson Road Landfill. The dark blue, again representing higher elevation, indicates that the active cell shown in the southwest quadrant reduced in volumetric size.

Figure 9. Images indicate the volumetric data difference. The June pass (*left image*) notes greater volume than the October pass (*right image*).



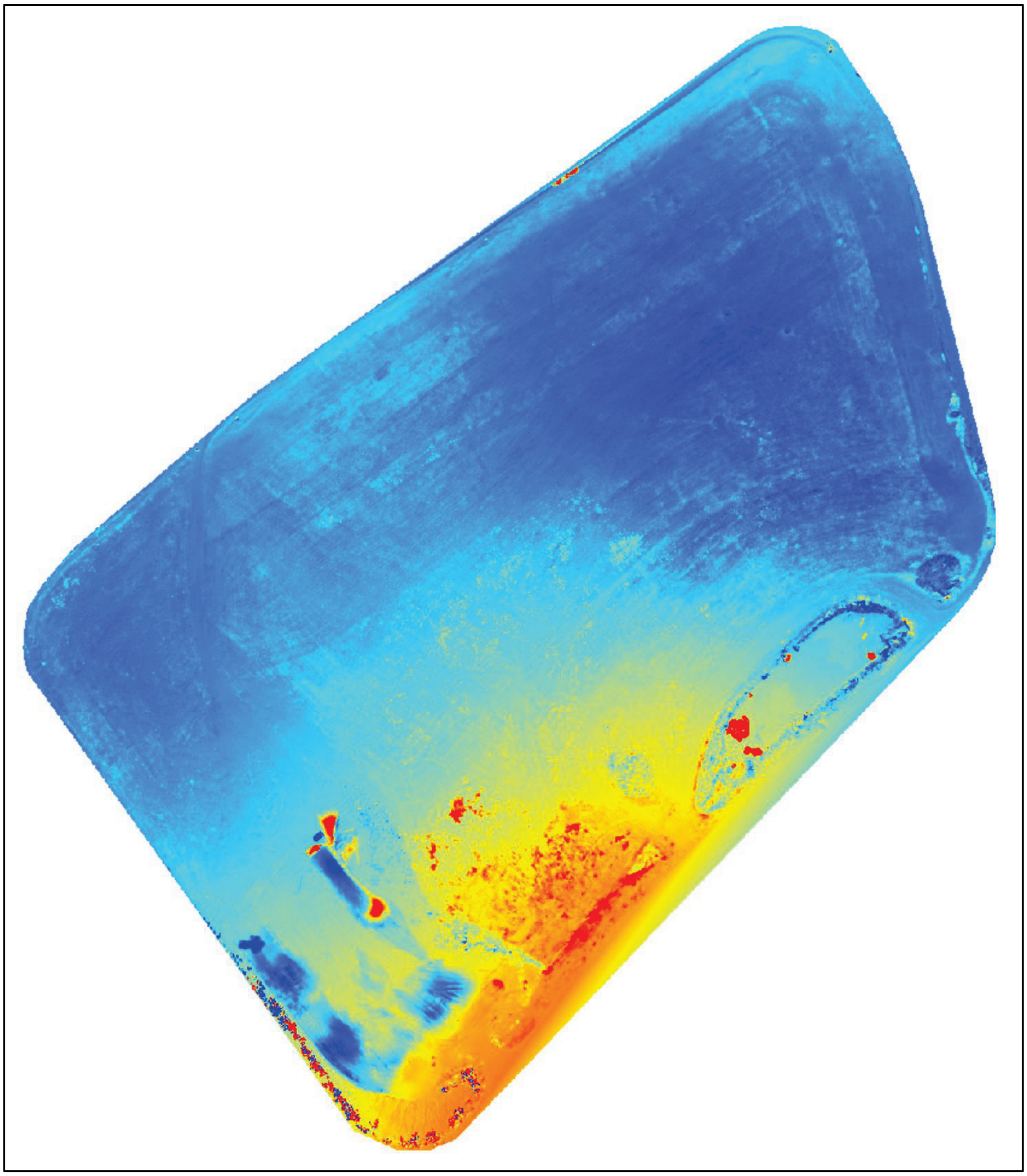
The differential image in Figure 10 is of the active cell at the Gibson Road Landfill. The dark blue indicates all the locations where activity took place after the June pass. Utilizing a data product like this would allow end users to locate hotspots or areas of high or low waste activity and to locate and remediate soil erosion, as seen on the bottom left edge of the difference map in Figure 10.

Figure 10. Difference map generated from the June and October passes in Fig. 9. *Dark blue* reflects greater activity.



Finally, given sufficient equipment, flight time, and processing time, overflights of entire landfills can be conducted to make broader landfill assessments. Such analyses, while time and cost prohibitive using standard survey techniques, are fundamentally the same as the active landfill analyses referenced in this section, requiring only longer processing times for 3D reconstruction, difference analysis, and flight planning. An example of one such analysis can be seen in Figure 11, where the entire Gibson Road landfill area was scanned and a difference DEM was presented. This difference DEM was derived from June and October flights, from a 200 foot altitude, using the Matrix-E and A6000 with a 19 millimeter lens.

Figure 11. Difference map from June and October flights over the entire Gibson Road landfill.



6.3 Challenges

One of the greatest challenges for the team in conducting this demonstration study was the delay in getting approval for the flight plan. Citing cybersecurity concerns, the Department of the Army (2018a) issued an order (EXORD 075-18) that all COTS sUAS were to be grounded until security risks could be mitigated. The team was able to acquire a temporary waiver, but evolving guidance for sUAS use on military lands continued throughout the study timeframe. This challenge was mitigated by coordinating with the installation's Range Control and Air Traffic

Control and by ensuring compliance with the standards and operating procedures set by Army Aviation and USACE Aviation and Remote Systems.

Unforeseen hazards contained within and around landfills posed challenges to the remote flight crew. These hazards included heavy equipment operations, debris, topography, uneven surfaces, and potential exposure to asbestos and other hazardous materials. These challenges were mitigated by developing adequate safety briefings for personnel not familiar with landfills.

Last, the processing of 2D electro-optical imagery into dense, 3D-reconstructed point clouds and DEMs requires not only specialized software packages (e.g., Agisoft PhotoScan and ESRI ArcMap) but also the expertise to operate the software. An investment in software and training would be required to perform these tasks in-house.

7 Recommendations

Multiple flights were successfully conducted over the Gibson Road Landfill at Fort Gordon to determine topographic and volumetric measurements of the active cell. They required minimal time for collection. Flights detected erosion on capped cells. Flights were also conducted over maneuver and training lands near cantonment areas, but no illegal dumping was found.

Approximately 200 (24 megapixel) images were processed, from image import to DEM creation, in 15 minutes. This was a significant reduction in time compared to the hours it would have taken to collect and process images using the traditional survey method. In addition, the sUAS allowed personnel to avoid the safety risks associated with traditional surveys.

While this demonstration was limited in scope, sUAS technology was found to provide rapid analysis of landfills and can be used for monitoring both active and closed landfills. Future studies involving multiple installations and both active and closed landfills would provide more insight into the benefits of sUAS monitoring. Additionally, it would be useful to include installations that have identified a challenge with illegal dumping in future studies.

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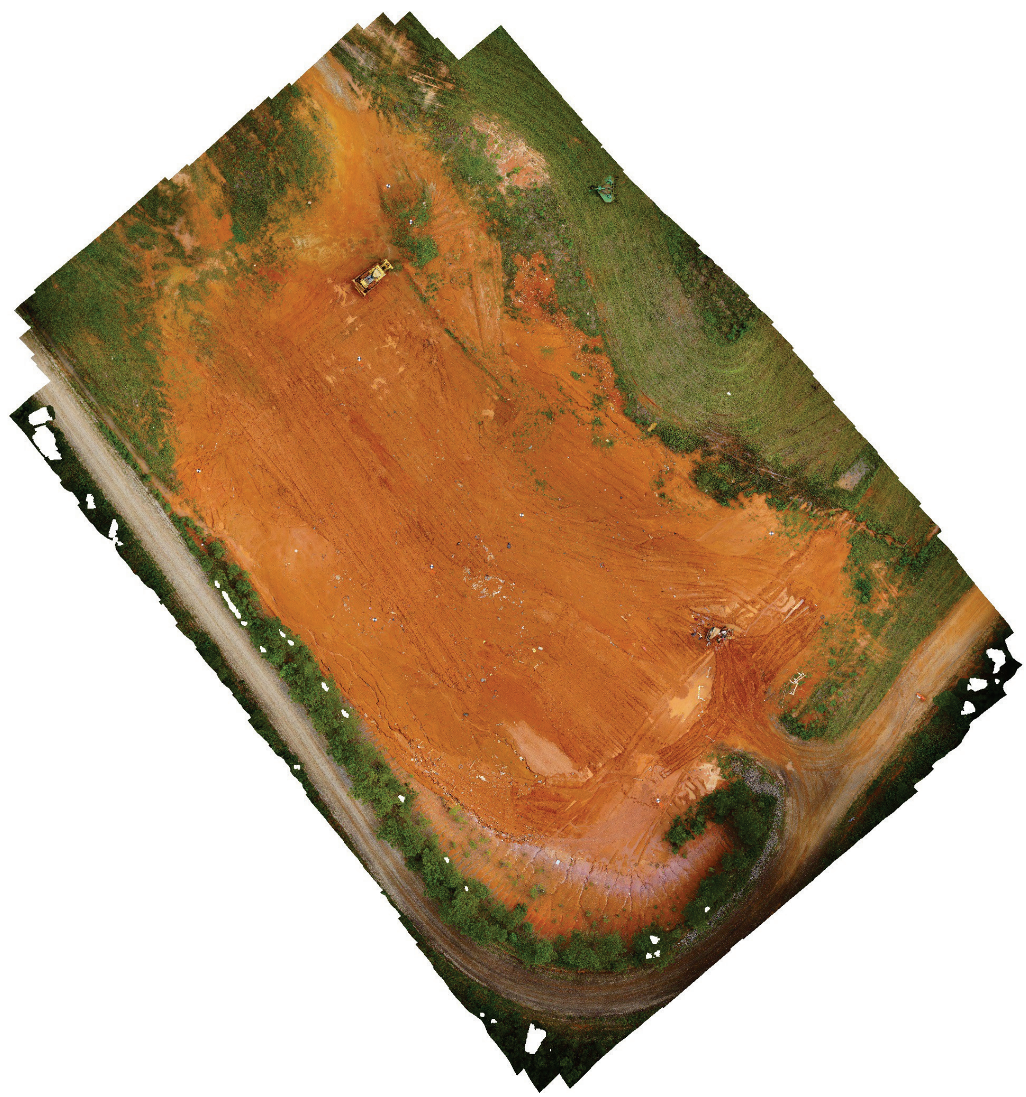
Appendix A: June 2018 Reports

Ft Gordon 100ft 19mm Report

Processing Report

03 July 2018



Survey Data

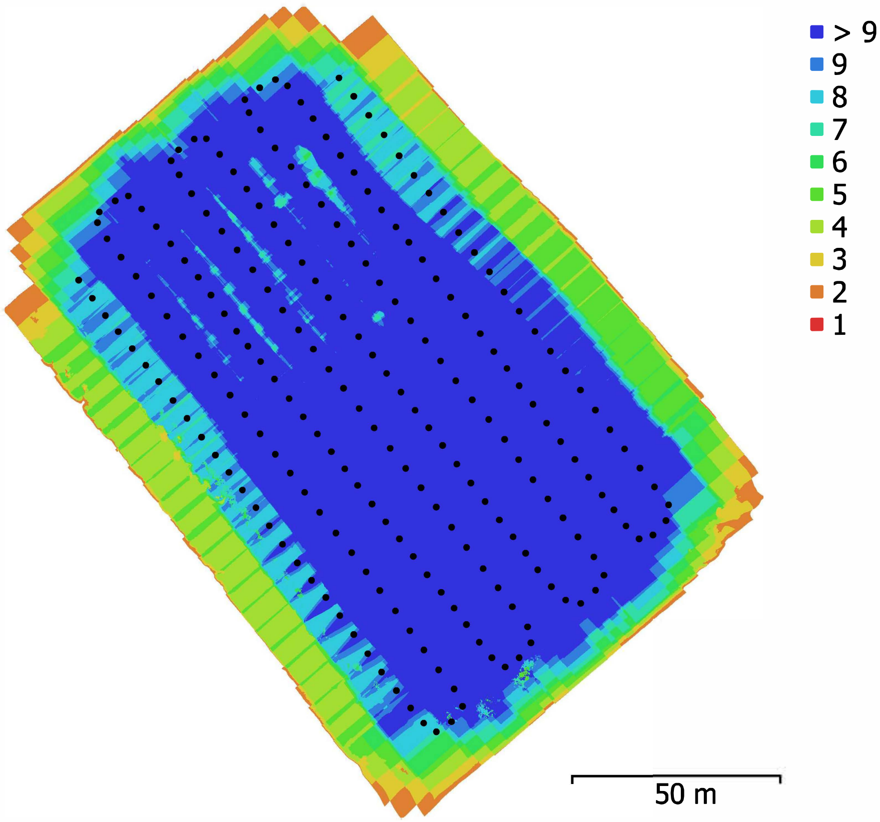


Fig. 1. Camera locations and image overlap.

Number of images:	223	Camera stations:	223
Flying altitude:	31.9 m	Tie points:	110,554
Ground resolution:	6.12 mm/pix	Projections:	721,403
Coverage area:	0.0196 km²	Reprojection error:	0.992 pix

Camera Model	Resolution	Focal Length	Pixel Size	Precalibrated
ILCE-6000 (19 mm)	6000 x 4000	19 mm	4.07 x 4.07 µm	No

Table 1. Cameras.

Camera Calibration

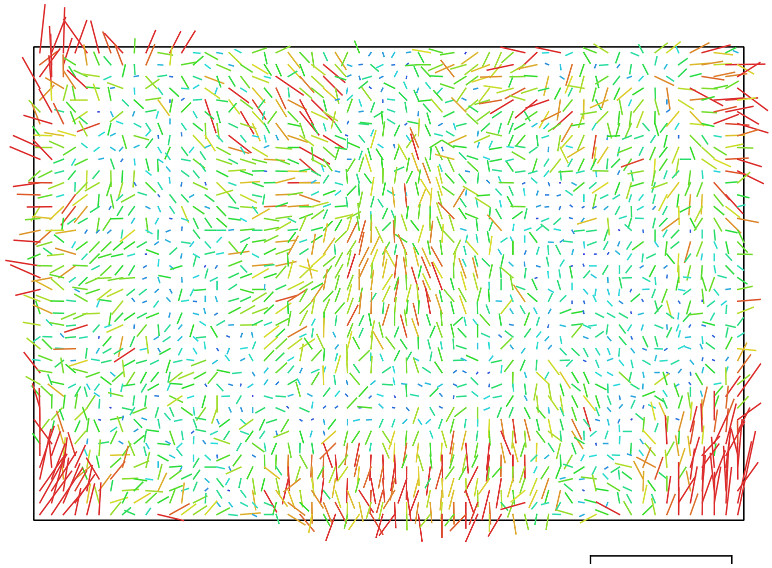


Fig. 2. Image residuals for ILCE-6000 (19 mm).

ILCE-6000 (19 mm)
223 images

Type	Resolution	Focal Length	Pixel Size
Frame	**6000 x 4000**	**19 mm**	**4.07 x 4.07 µm**

	Value	Error	F	Cx	Cy	B1	B2	K1	K2	K3	P1	P2
F	**4841.85**	0.94	1.00	0.00	0.00	-0.13	-0.02	-0.69	0.48	-0.25	0.01	-0.05
Cx	**1.8428**	0.15		1.00	0.07	0.02	-0.17	-0.01	0.01	-0.00	-0.15	0.02
Cy	**-25.8689**	0.17			1.00	0.17	0.04	-0.01	0.00	0.01	0.06	-0.25
B1	**2.46656**	0.067				1.00	-0.03	0.06	-0.05	0.03	-0.16	-0.30
B2	**0.550681**	0.065					1.00	0.01	-0.01	0.00	-0.05	0.18
K1	**-0.100766**	6e-05						1.00	-0.93	0.80	-0.01	0.06
K2	**0.129258**	0.0002							1.00	-0.95	0.02	-0.01
K3	**-0.0493062**	0.00022								1.00	-0.02	-0.01
P1	**0.000324949**	4.1e-06									1.00	-0.08
P2	**-0.000204845**	3.9e-06										1.00

Table 2. Calibration coefficients and correlation matrix.

Ground Control Points

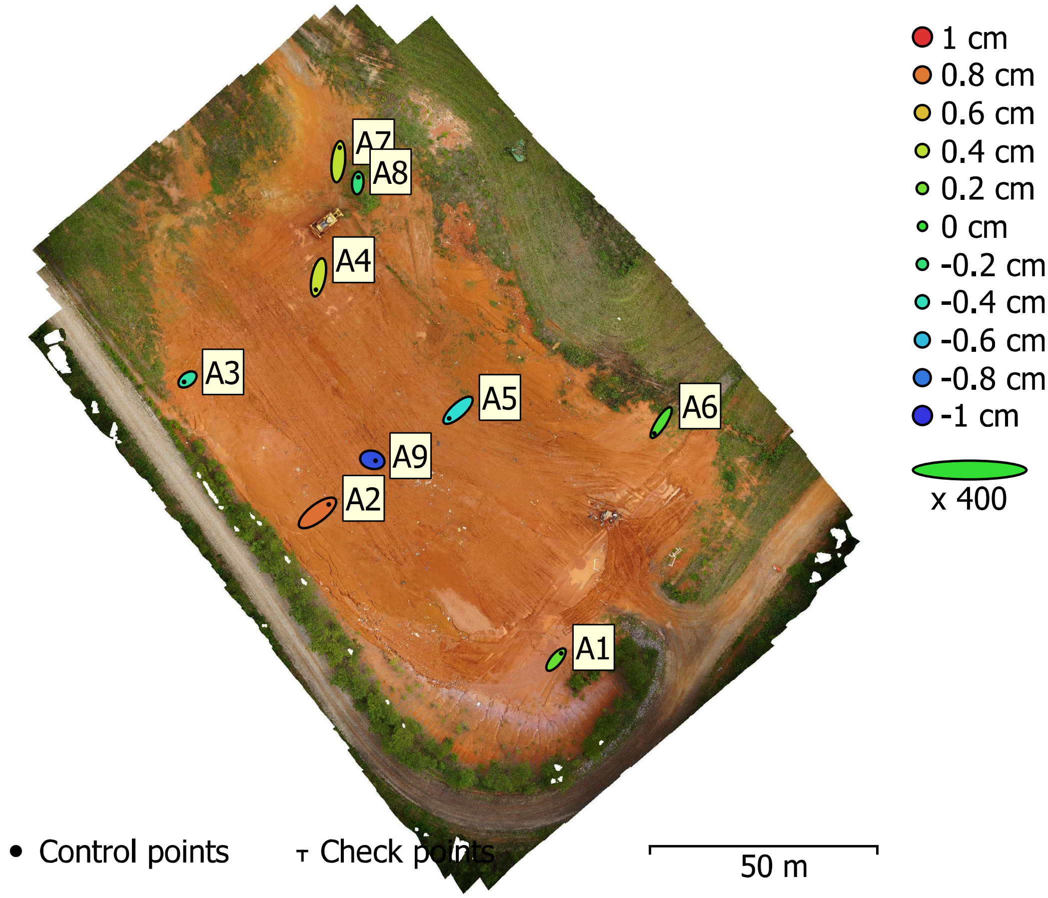


Fig. 3. GCP locations and error estimates.
Z error is represented by ellipse color. X,Y errors are represented by ellipse shape.
Estimated GCP locations are marked with a dot or crossing.

Count	**X error (cm)**	**Y error (cm)**	**Z error (cm)**	**XY error (cm)**	**Total (cm)**
9	0.639653	0.955158	0.502427	1.14956	1.25456

Table 3. Control points RMSE.
X - Easting, Y - Northing, Z - Altitude.

Label	X error (cm)	Y error (cm)	Z error (cm)	Total (cm)	Image (pix)
A1	0.577311	0.705693	0.158302	0.925392	0.191 (10)
A2	1.22132	0.930718	0.821767	1.7416	0.191 (9)
A3	-0.36206	-0.277514	-0.330067	0.563068	0.064 (6)
A4	-0.284244	-1.36036	0.433113	1.45566	0.174 (7)
A5	-0.960991	-0.876221	-0.463851	1.38073	0.117 (5)
A6	-0.756695	-1.1888	0.0913729	1.41215	0.100 (6)
A7	0.155752	1.53319	0.404154	1.59319	0.172 (11)
A8	0.050343	0.615765	-0.212081	0.653207	0.204 (8)
A9	0.350306	-0.0910523	-0.918249	0.987008	0.178 (6)
Total	**0.639653**	**0.955158**	**0.502427**	**1.25456**	**0.167**

Table 4. Control points.

X - Easting, Y - Northing, Z - Altitude.

Digital Elevation Model

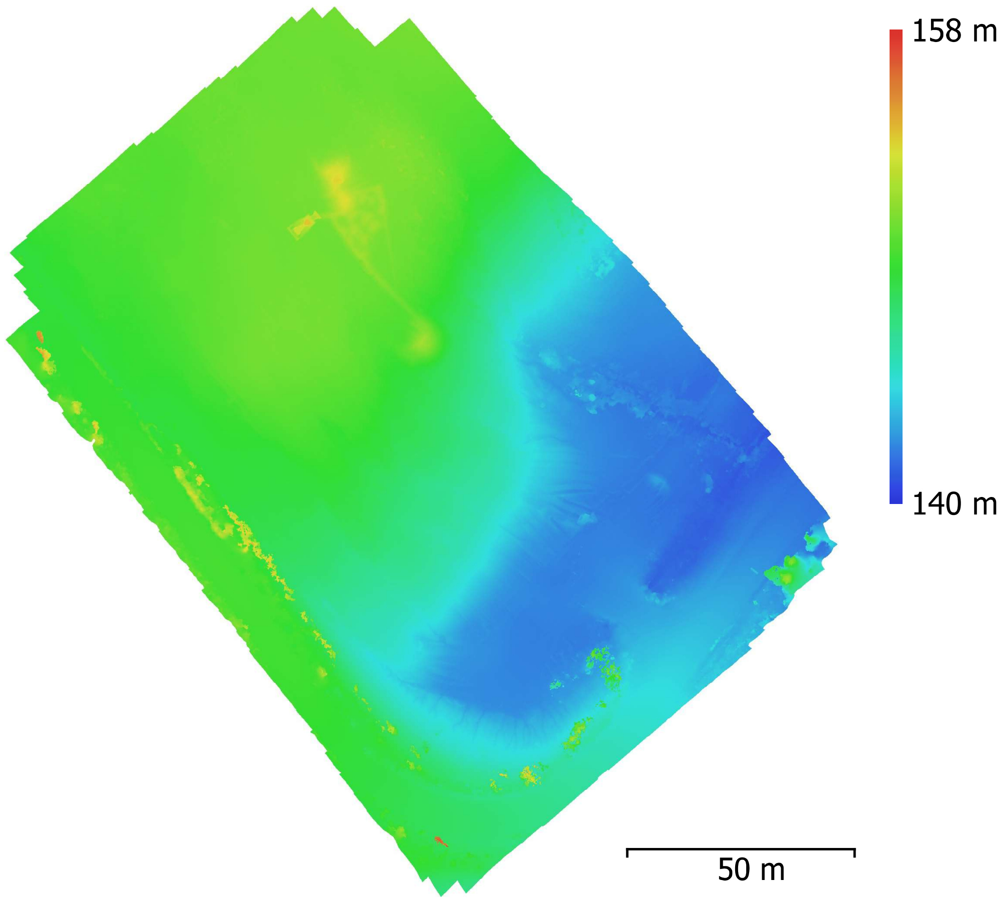


Fig. 4. Reconstructed digital elevation model.

Resolution:	2.45 cm/pix
Point density:	16.7 points/cm^2

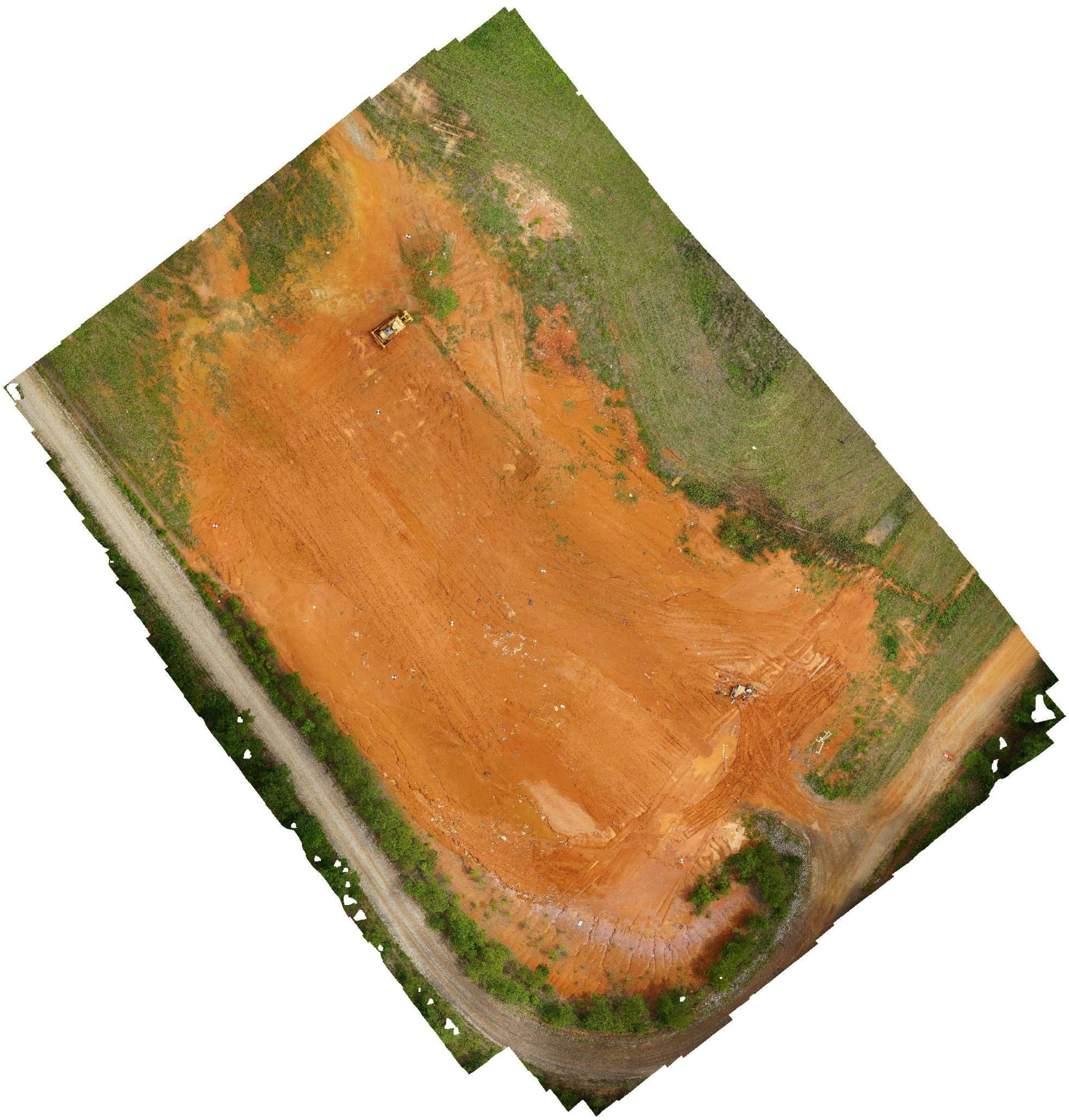
Processing Parameters

General	
Cameras	223
Aligned cameras	223
Markers	32
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Rotation angles	Yaw, Pitch, Roll
Point Cloud	
Points	110,554 of 129,314
RMS reprojection error	0.182768 (0.992438 pix)
Max reprojection error	1.29907 (31.3069 pix)
Mean key point size	5.28536 pix
Point colors	3 bands, uint8
Key points	No
Average tie point multiplicity	7.4365
Alignment parameters	
Accuracy	Medium
Generic preselection	No
Reference preselection	No
Key point limit	40,000
Tie point limit	4,000
Filter points by mask	No
Matching time	29 minutes 28 seconds
Alignment time	46 seconds
Optimization parameters	
Parameters	f, b1, b2, cx, cy, k1-k3, p1, p2
Optimization time	7 seconds
Dense Point Cloud	
Points	38,093,468
Point colors	3 bands, uint8
Reconstruction parameters	
Quality	Medium
Depth filtering	Aggressive
Depth maps generation time	3 minutes 57 seconds
Dense cloud generation time	5 minutes 25 seconds
DEM	
Size	11,592 x 12,443
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Reconstruction parameters	
Source data	Dense cloud
Interpolation	Enabled
Processing time	1 minutes 0 seconds
Orthomosaic	
Size	30,634 x 32,768
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Colors	3 bands, uint8
Reconstruction parameters	
Blending mode	Mosaic
Surface	DEM
Enable hole filling	Yes
Processing time	6 minutes 25 seconds
Software	
Version	1.4.2 build 6205
Platform	Windows 64

Ft Gordon 150ft 35mm Report

Processing Report

03 July 2018



Survey Data

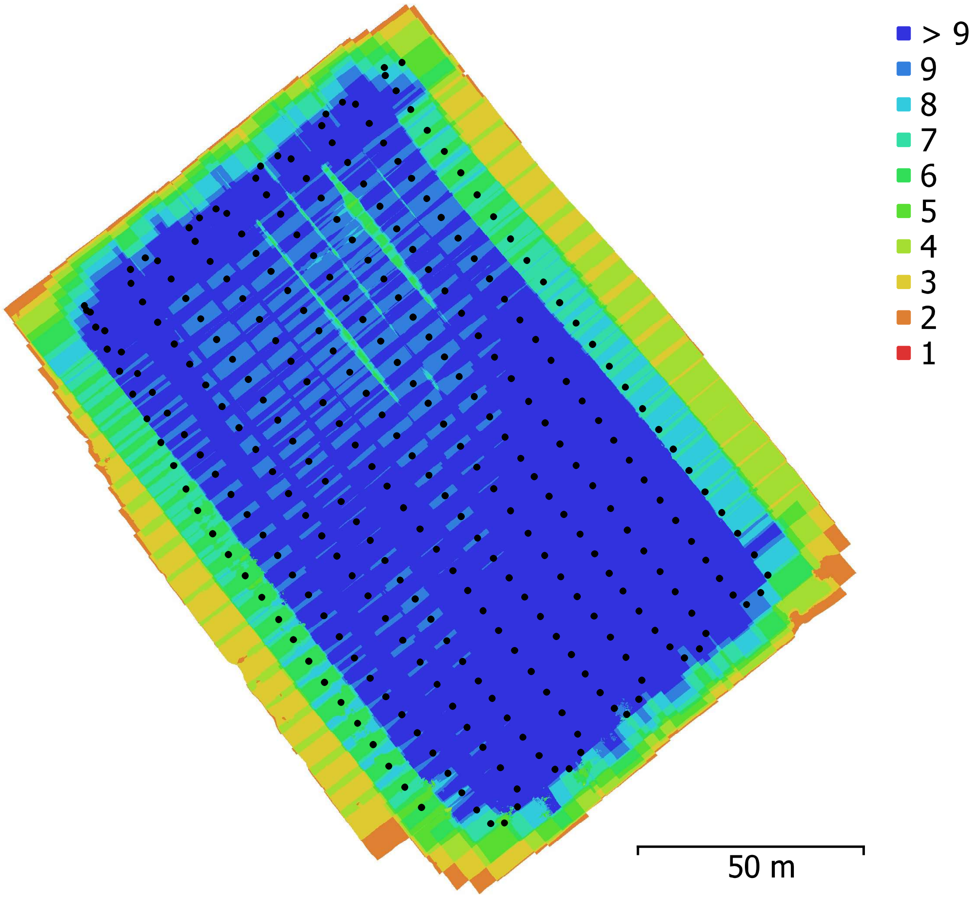


Fig. 1. Camera locations and image overlap.

Number of images:	303	Camera stations:	303
Flying altitude:	44.6 m	Tie points:	156,183
Ground resolution:	5.02 mm/pix	Projections:	1,032,545
Coverage area:	0.02 km²	Reprojection error:	0.957 pix

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

Table 1. Cameras.

Camera Calibration

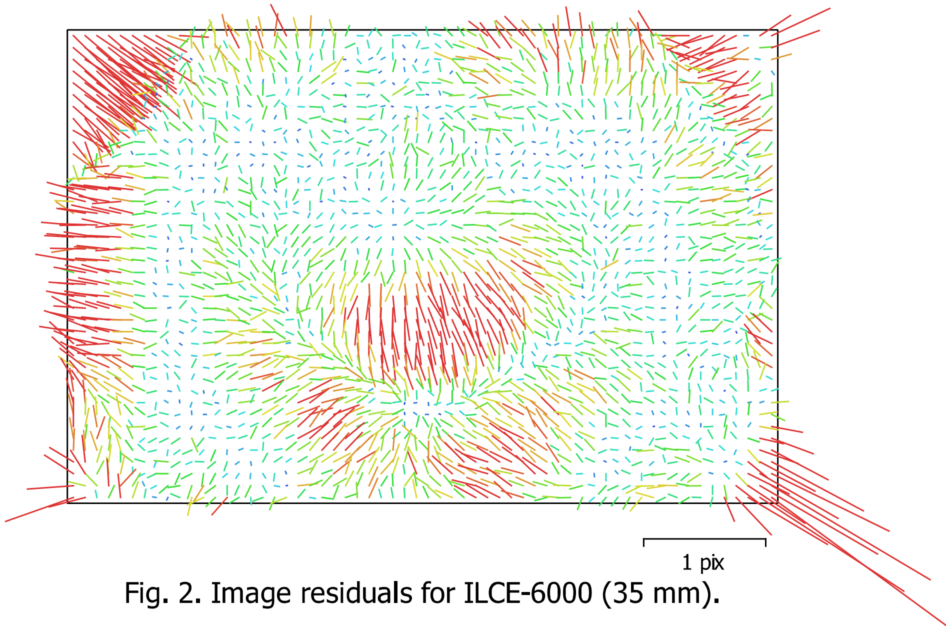


Fig. 2. Image residuals for ILCE-6000 (35 mm).

ILCE-6000 (35 mm)

303 images

Type	Resolution	Focal Length	Pixel Size
Frame	**6000 x 4000**	**35 mm**	**4.04 x 4.04 µm**

	Value	Error	Cx	Cy	B1	B2	K1	K2	K3	P1	P2
F	**8666.67**										
Cx	**-81.4298**	0.25	1.00	0.03	0.02	-0.15	-0.08	0.12	-0.16	-0.18	0.07
Cy	**9.62704**	0.29		1.00	0.10	0.06	0.03	-0.02	0.02	0.03	-0.11
B1	**2.50215**	0.11			1.00	-0.03	-0.00	-0.02	0.01	-0.20	-0.25
B2	**-7.83926**	0.11				1.00	0.01	-0.03	0.04	0.01	0.15
K1	**0.000973525**	0.00012					1.00	-0.96	0.90	0.00	0.01
K2	**-0.062784**	0.0016						1.00	-0.98	0.01	0.03
K3	**-1.29401**	0.0063							1.00	-0.01	-0.03
P1	**0.00264139**	5.9e-06								1.00	-0.07
P2	**0.000398531**	5.5e-06									1.00

Table 2. Calibration coefficients and correlation matrix.

Ground Control Points

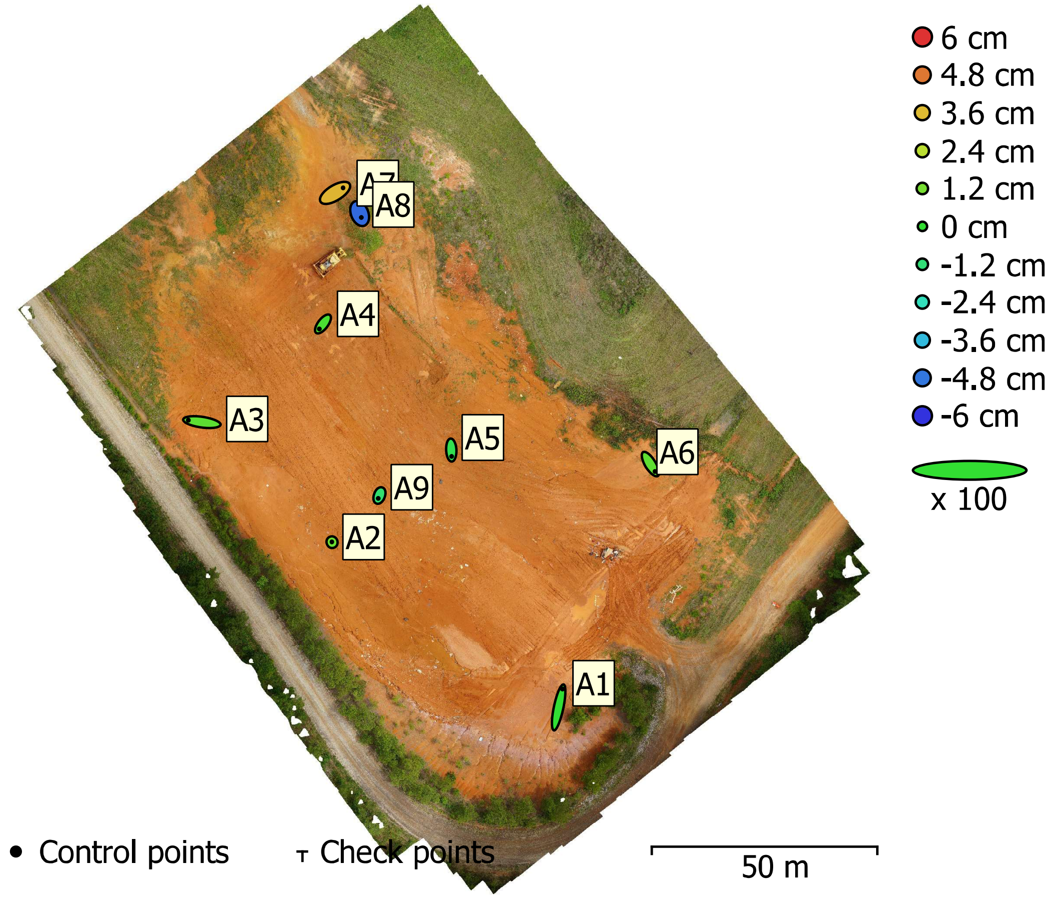


Fig. 3. GCP locations and error estimates.
Z error is represented by ellipse color. X,Y errors are represented by ellipse shape.
Estimated GCP locations are marked with a dot or crossing.

Count	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total (cm)
9	2.55355	3.34056	2.18176	4.20476	4.73709

Table 3. Control points RMSE.
X - Easting, Y - Northing, Z - Altitude.

Label	X error (cm)	Y error (cm)	Z error (cm)	Total (cm)	Image (pix)
A1	1.71358	8.15741	-0.0294802	8.33549	0.244 (10)
A2	-0.0637659	0.169413	1.00842	1.02454	0.184 (11)
A3	-5.94304	0.835236	0.726391	6.04525	0.191 (11)
A4	-1.6797	-2.18101	0.423358	2.78522	0.163 (7)
A5	0.144492	-2.83898	-0.530519	2.89173	0.259 (8)
A6	2.01851	-3.29162	0.777039	3.93864	0.173 (10)
A7	3.57063	2.18989	3.72179	5.60328	0.229 (9)
A8	0.72496	-1.74447	-5.0266	5.36986	0.173 (9)
A9	-0.483749	-1.29405	-1.05461	1.73804	0.132 (10)
Total	**2.55355**	**3.34056**	**2.18176**	**4.73709**	**0.197**

Table 4. Control points.

X - Easting, Y - Northing, Z - Altitude.

Digital Elevation Model

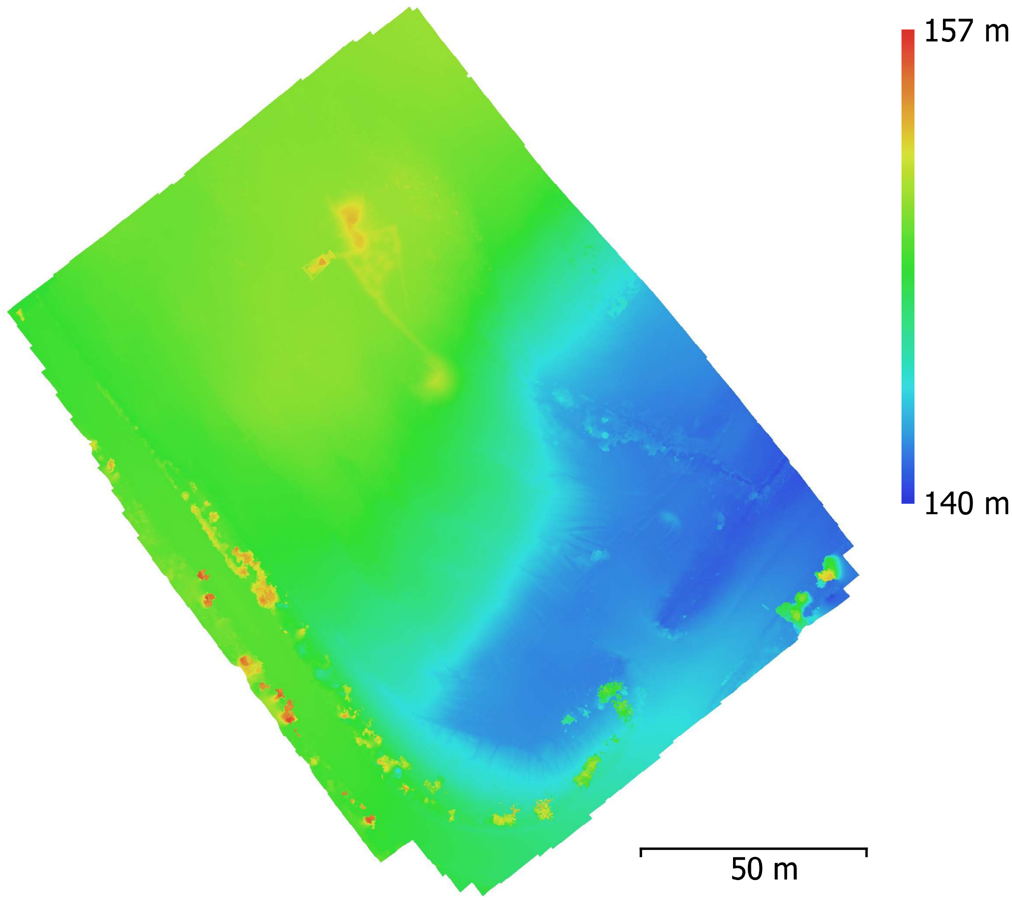


Fig. 4. Reconstructed digital elevation model.

Resolution:	2.01 cm/pix
Point density:	24.8 points/cm²

Processing Parameters

General	
Cameras	303
Aligned cameras	303
Markers	32
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Rotation angles	Yaw, Pitch, Roll
Point Cloud	
Points	156,183 of 179,173
RMS reprojection error	0.186338 (0.956927 pix)
Max reprojection error	1.11776 (39.7363 pix)
Mean key point size	5.03493 pix
Point colors	3 bands, uint8
Key points	No
Average tie point multiplicity	7.24165
Alignment parameters	
Accuracy	Medium
Generic preselection	No
Reference preselection	No
Key point limit	40,000
Tie point limit	4,000
Filter points by mask	No
Matching time	48 minutes 47 seconds
Alignment time	1 minutes 44 seconds
Optimization parameters	
Parameters	b1, b2, cx, cy, k1-k3, p1, p2
Optimization time	8 seconds
Dense Point Cloud	
Points	57,555,271
Point colors	3 bands, uint8
Reconstruction parameters	
Quality	Medium
Depth filtering	Aggressive
Depth maps generation time	5 minutes 5 seconds
Dense cloud generation time	6 minutes 38 seconds
DEM	
Size	14,417 x 15,390
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Reconstruction parameters	
Source data	Dense cloud
Interpolation	Enabled
Processing time	1 minutes 25 seconds
Orthomosaic	
Size	31,369 x 32,768
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Colors	3 bands, uint8
Reconstruction parameters	
Blending mode	Mosaic
Surface	DEM
Enable hole filling	Yes
Processing time	6 minutes 14 seconds
Software	
Version	1.4.2 build 6205
Platform	Windows 64

Ft Gordon 200ft 19mm Report

Processing Report

10 July 2018

Survey Data

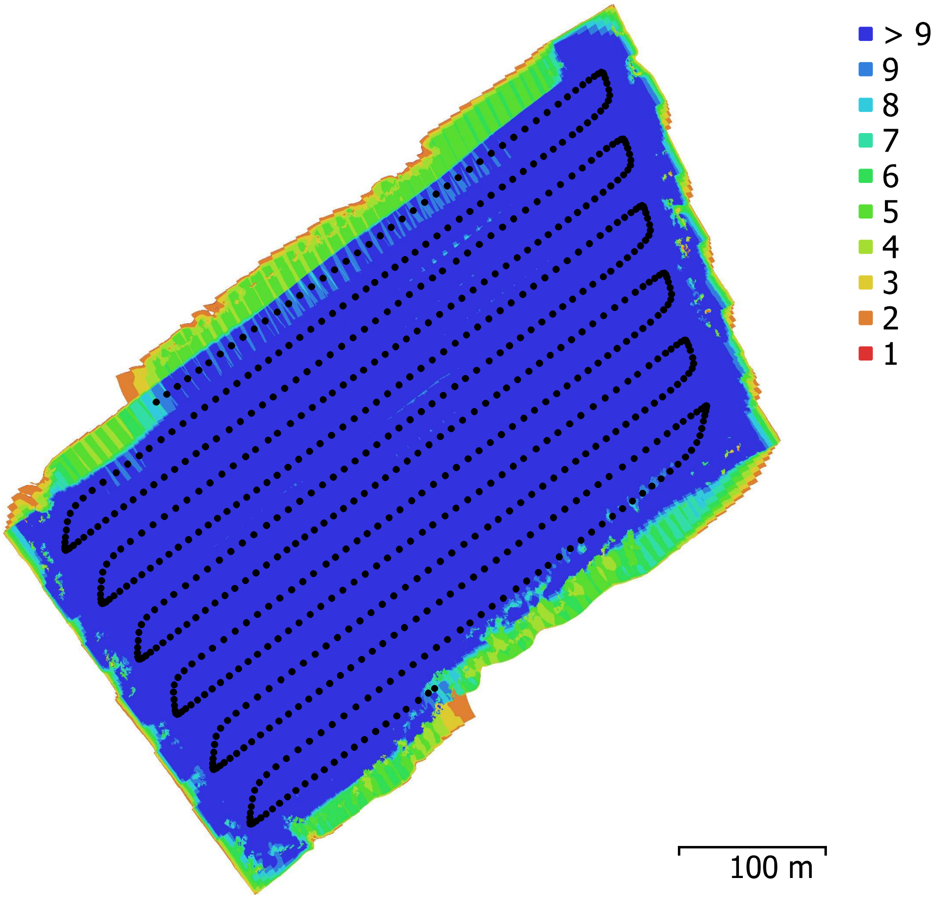


Fig. 1. Camera locations and image overlap.

Number of images:	722	Camera stations:	722
Flying altitude:	60.6 m	Tie points:	609,279
Ground resolution:	1.14 cm/pix	Projections:	2,704,041
Coverage area:	0.164 km²	Reprojection error:	1.13 pix

Camera Model	Resolution	Focal Length	Pixel Size	Precalibrated
ILCE-6000 (19mm)	6000 x 4000	19 mm	4.07 x 4.07 μm	No

Table 1. Cameras.

Camera Calibration

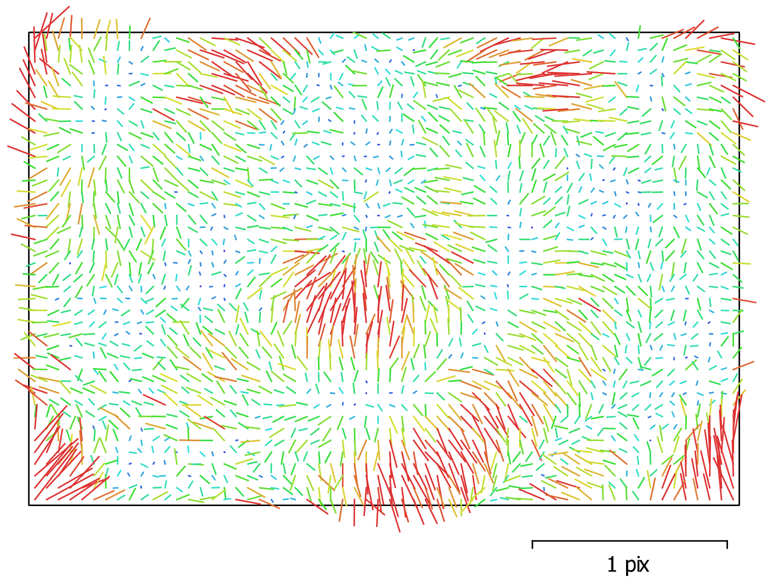


Fig. 2. Image residuals for ILCE-6000 (19mm).

ILCE-6000 (19mm)
722 images

Type	Resolution	Focal Length	Pixel Size
Frame	**6000 x 4000**	**19 mm**	**4.07 x 4.07 µm**

	Value	Error	F	Cx	Cy	B1	B2	K1	K2	K3	P1	P2
F	**4873.3**	0.57	1.00	-0.23	0.02	0.15	-0.03	-0.67	0.49	-0.24	0.18	-0.04
Cx	**4.37773**	0.095		1.00	-0.09	0.46	-0.10	0.12	-0.09	0.04	-0.17	0.04
Cy	**-20.0427**	0.1			1.00	0.02	0.58	-0.00	-0.01	0.02	0.02	-0.46
B1	**-0.787008**	0.018				1.00	-0.01	-0.13	0.08	-0.03	-0.20	-0.08
B2	**-2.9331**	0.019					1.00	0.03	-0.03	0.03	-0.03	-0.31
K1	**-0.101392**	3.7e-05						1.00	-0.95	0.82	-0.13	0.03
K2	**0.131011**	0.00013							1.00	-0.95	0.08	-0.01
K3	**-0.0488843**	0.00014								1.00	-0.04	-0.00
P1	**0.000250871**	1.8e-06									1.00	0.03
P2	**-0.000323563**	1.7e-06										1.00

Table 2. Calibration coefficients and correlation matrix.

Ground Control Points

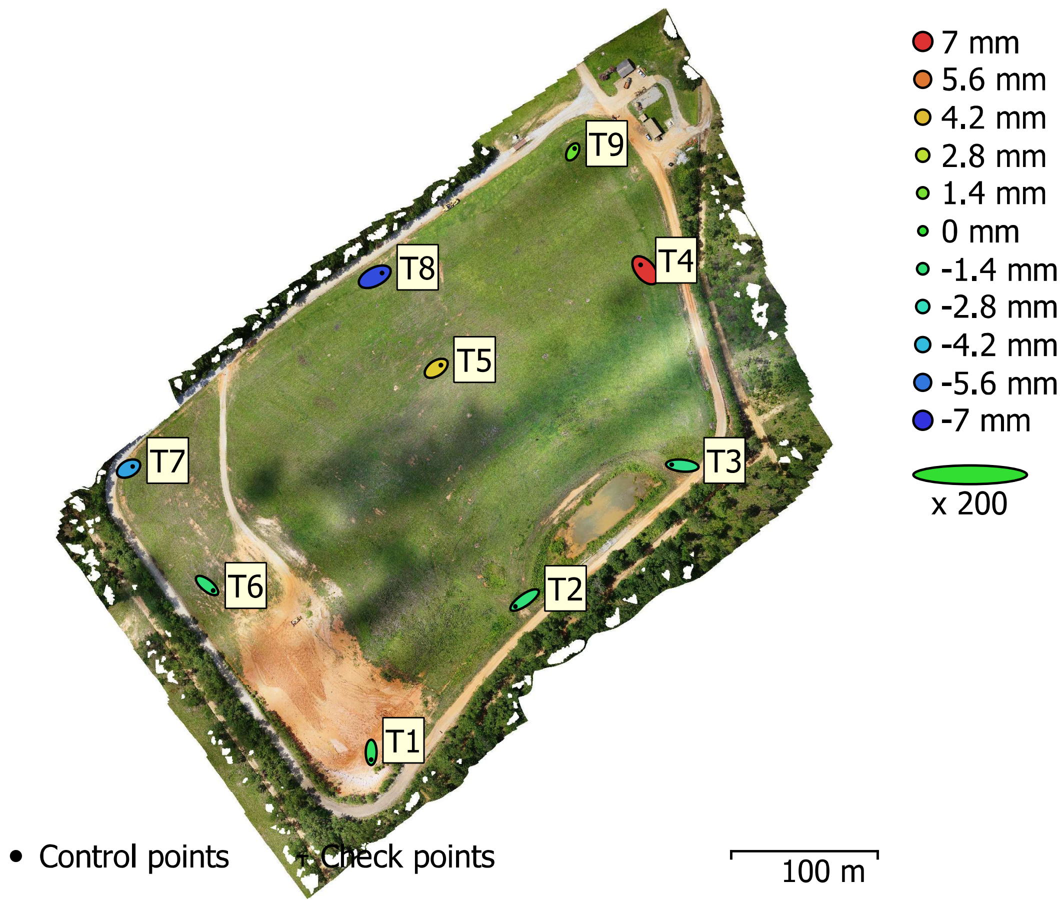


Fig. 3. GCP locations and error estimates.
Z error is represented by ellipse color. X,Y errors are represented by ellipse shape.
Estimated GCP locations are marked with a dot or crossing.

Count	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total (cm)
9	4.24667	3.13261	0.389183	5.27707	5.2914

Table 3. Control points RMSE.
X - Easting, Y - Northing, Z - Altitude.

Label	X error (cm)	Y error (cm)	Z error (cm)	Total (cm)	Image (pix)
T1	0.0220543	-4.94932	-0.0978523	4.95033	0.209 (13)
T2	-6.24394	-4.36283	-0.143428	7.6185	0.179 (9)
T3	-7.1614	0.653307	-0.177181	7.19332	0.229 (13)
T4	-3.08963	3.71758	0.692034	4.88315	0.131 (10)
T5	3.1942	2.21239	0.388358	3.90492	0.178 (9)
T6	4.21931	-3.4565	-0.14084	5.45617	0.126 (5)
T7	2.78317	1.45929	-0.469122	3.17737	0.150 (4)
T8	4.99894	2.53785	-0.646836	5.64344	0.081 (5)
T9	1.32221	2.26485	0.116565	2.62514	0.138 (8)
Total	**4.24667**	**3.13261**	**0.389183**	**5.2914**	**0.176**

Table 4. Control points.

X - Easting, Y - Northing, Z - Altitude.

Digital Elevation Model

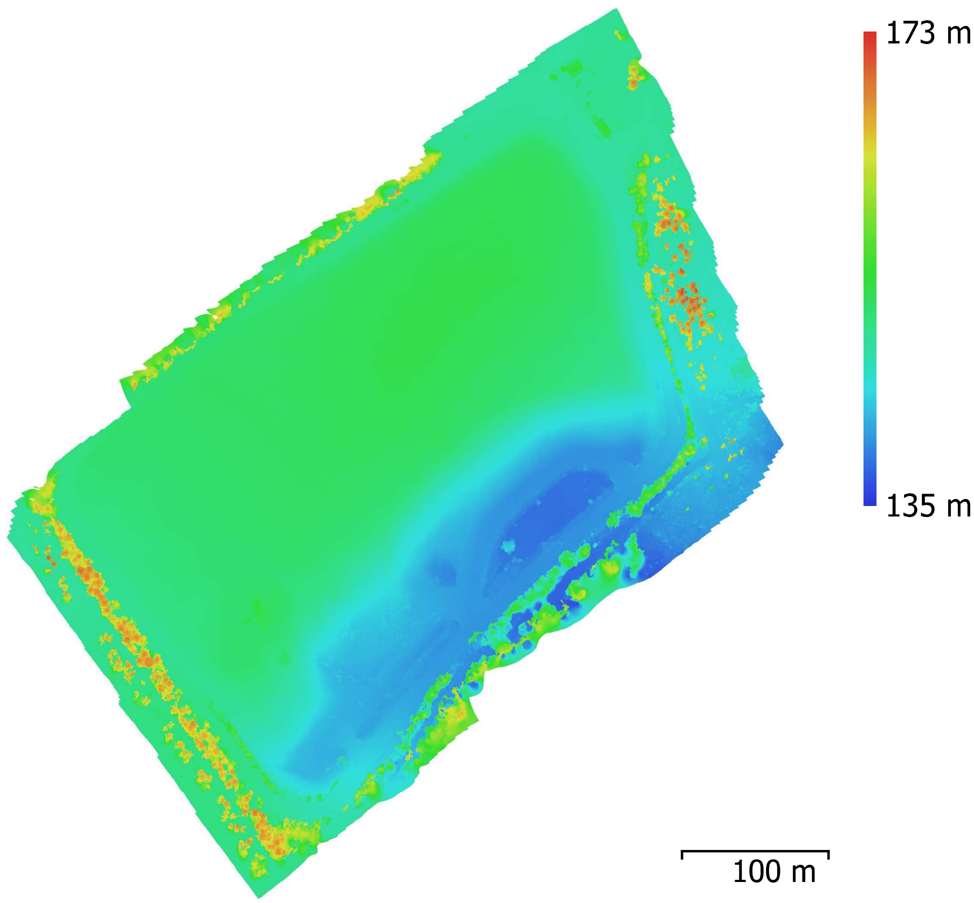


Fig. 4. Reconstructed digital elevation model.

Resolution:	4.56 cm/pix
Point density:	480 points/m²

Processing Parameters

General	
Cameras	722
Aligned cameras	722
Markers	32
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Rotation angles	Yaw, Pitch, Roll
Point Cloud	
Points	609,279 of 653,608
RMS reprojection error	0.162194 (1.13009 pix)
Max reprojection error	0.965167 (51.5525 pix)
Mean key point size	6.28787 pix
Point colors	3 bands, uint8
Key points	No
Average tie point multiplicity	4.77212
Alignment parameters	
Accuracy	Medium
Generic preselection	Yes
Key point limit	40,000
Tie point limit	4,000
Adaptive camera model fitting	Yes
Matching time	4 minutes 30 seconds
Alignment time	3 minutes 46 seconds
Optimization parameters	
Parameters	f, b1, b2, cx, cy, k1-k3, p1, p2
Adaptive camera model fitting	No
Optimization time	11 seconds
Dense Point Cloud	
Points	94,790,598
Point colors	3 bands, uint8
Reconstruction parameters	
Quality	Medium
Depth filtering	Aggressive
Depth maps generation time	12 minutes 35 seconds
Dense cloud generation time	23 minutes 1 seconds
DEM	
Size	17,149 x 17,156
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Reconstruction parameters	
Source data	Dense cloud
Interpolation	Enabled
Processing time	2 minutes 4 seconds
Orthomosaic	
Size	28,600 x 32,768
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Colors	3 bands, uint8
Reconstruction parameters	
Blending mode	Mosaic
Surface	DEM
Enable hole filling	Yes
Processing time	9 minutes 31 seconds
Software	
Version	1.4.2 build 6205
Platform	Windows 64

Ft Gordon 300ft 19mm Report

Processing Report

11 July 2018

Survey Data

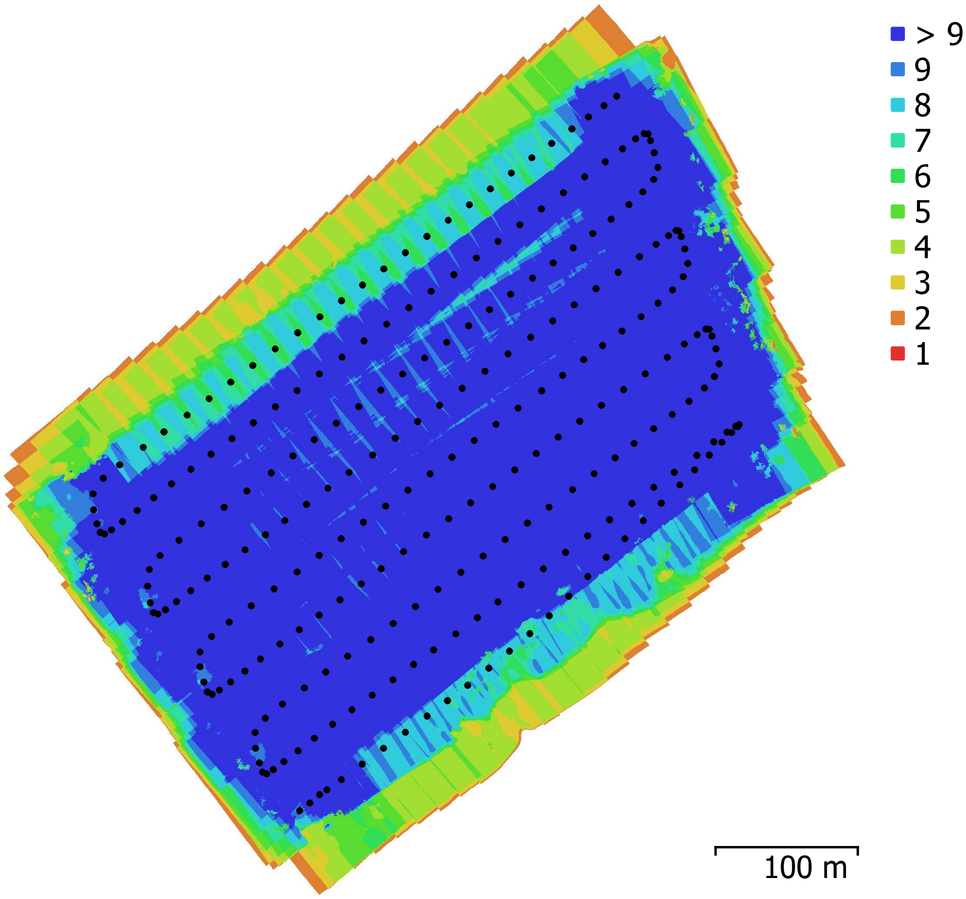


Fig. 1. Camera locations and image overlap.

Number of images:	264	Camera stations:	264
Flying altitude:	91.4 m	Tie points:	233,716
Ground resolution:	1.75 cm/pix	Projections:	1,004,866
Coverage area:	0.199 km²	Reprojection error:	1.09 pix

Camera Model	Resolution	Focal Length	Pixel Size	Precalibrated
ILCE-6000 (19mm)	6000 x 4000	19 mm	4.07 x 4.07 μm	No

Table 1. Cameras.

Camera Calibration

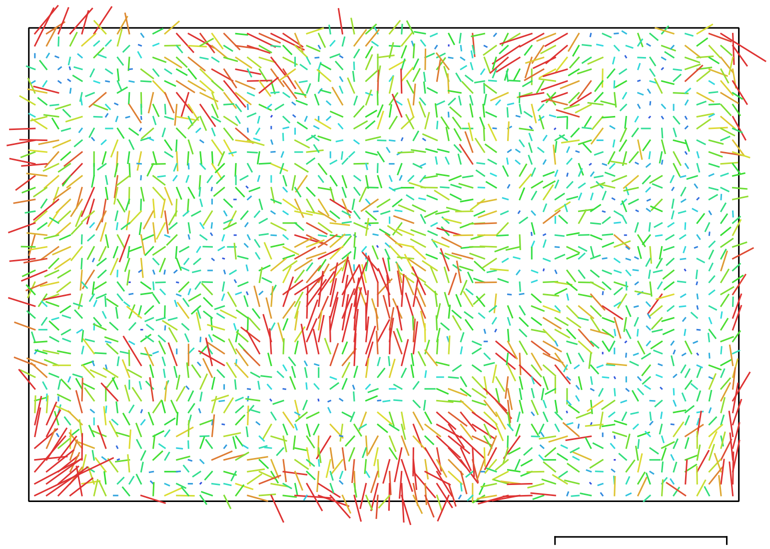


Fig. 2. Image residuals for ILCE-6000 (19mm).

ILCE-6000 (19mm)
264 images

Type	Resolution	Focal Length	Pixel Size
Frame	**6000 x 4000**	**19 mm**	**4.07 x 4.07 µm**

	Value	Error	F	Cx	Cy	B1	B2	K1	K2	K3	P1	P2
F	**4815.68**	0.91	1.00	-0.25	0.06	0.03	0.03	-0.70	0.50	-0.24	0.19	-0.09
Cx	**1.15095**	0.13		1.00	-0.05	0.39	-0.15	0.14	-0.09	0.03	-0.12	0.02
Cy	**-25.2187**	0.14			1.00	0.17	0.48	-0.04	0.02	0.00	0.03	-0.40
B1	**-0.424738**	0.019				1.00	0.07	-0.05	0.02	-0.01	-0.16	-0.24
B2	**-0.830257**	0.019					1.00	-0.02	0.00	0.01	0.04	-0.21
K1	**-0.098871**	5.7e-05						1.00	-0.95	0.80	-0.14	0.07
K2	**0.125481**	0.00019							1.00	-0.95	0.10	-0.04
K3	**-0.0462867**	0.0002								1.00	-0.05	0.02
P1	**0.000338614**	2.5e-06									1.00	0.01
P2	**-0.000260881**	2.3e-06										1.00

Table 2. Calibration coefficients and correlation matrix.

Ground Control Points

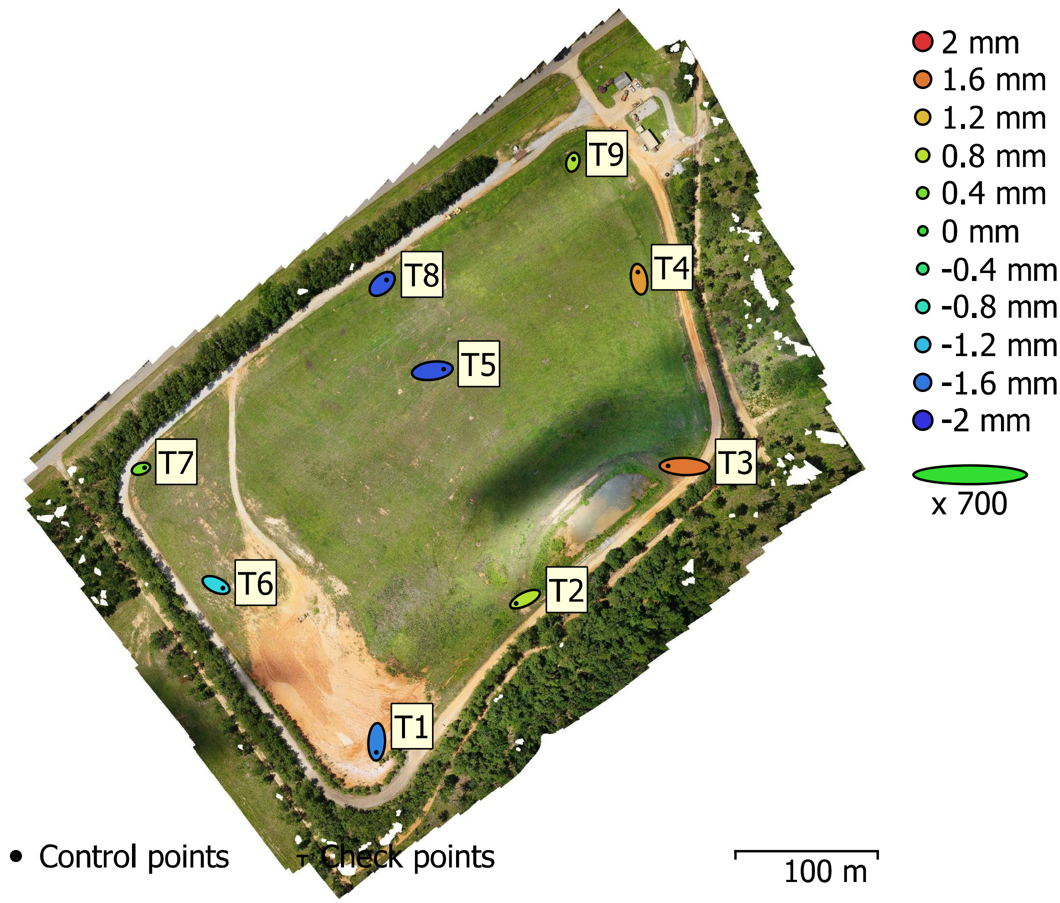


Fig. 3. GCP locations and error estimates.

Z error is represented by ellipse color. X,Y errors are represented by ellipse shape.

Estimated GCP locations are marked with a dot or crossing.

Count	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total (cm)
9	1.57658	0.992865	0.131594	1.86317	1.86781

Table 3. Control points RMSE.

X - Easting, Y - Northing, Z - Altitude.

Label	**X error (cm)**	**Y error (cm)**	**Z error (cm)**	**Total (cm)**	**Image (pix)**
T1	-0.0897398	-2.09325	-0.151759	2.10066	0.123 (9)
T2	-1.75819	-0.873312	0.0749999	1.96457	0.104 (7)
T3	-3.2892	0.117832	0.160733	3.29524	0.099 (9)
T4	-0.265259	1.467	0.139939	1.49734	0.107 (9)
T5	2.29607	0.316912	-0.179784	2.3248	0.103 (7)
T6	1.32947	-0.60459	-0.105181	1.46427	0.128 (8)
T7	0.725628	0.227474	0.0412972	0.761568	0.122 (5)
T8	0.886173	0.803331	-0.17826	1.20931	0.155 (6)
T9	0.175136	0.631375	0.0700872	0.658953	0.132 (7)
Total	**1.57658**	**0.992865**	**0.131594**	**1.86781**	**0.119**

Table 4. Control points.

X - Easting, Y - Northing, Z - Altitude.

Digital Elevation Model

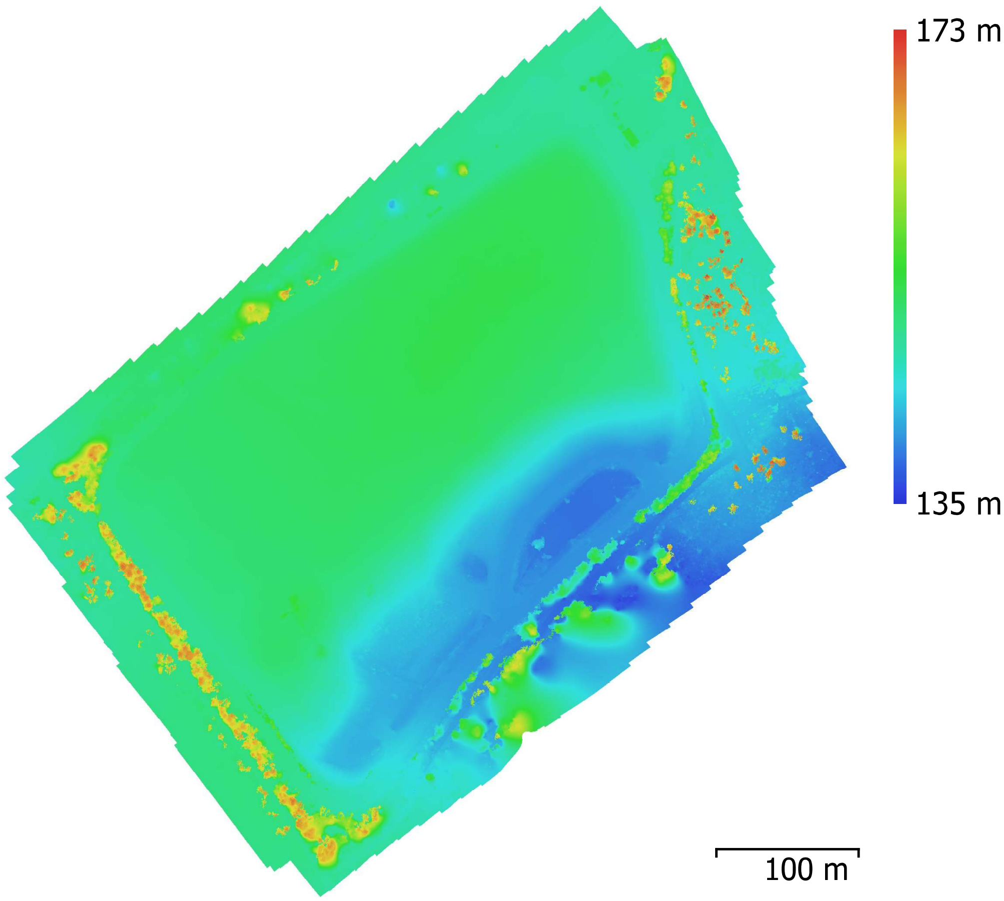


Fig. 4. Reconstructed digital elevation model.

Resolution:	3.51 cm/pix
Point density:	814 points/m²

Processing Parameters

General	
Cameras	264
Aligned cameras	264
Markers	32
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Rotation angles	Yaw, Pitch, Roll
Point Cloud	
Points	233,716 of 250,391
RMS reprojection error	0.155528 (1.08775 pix)
Max reprojection error	0.636615 (30.3888 pix)
Mean key point size	6.454 pix
Point colors	3 bands, uint8
Key points	No
Average tie point multiplicity	4.49949
Alignment parameters	
Accuracy	Medium
Generic preselection	Yes
Key point limit	40,000
Tie point limit	4,000
Adaptive camera model fitting	Yes
Matching time	1 minutes 22 seconds
Alignment time	54 seconds
Optimization parameters	
Parameters	f, b1, b2, cx, cy, k1-k3, p1, p2
Adaptive camera model fitting	No
Optimization time	3 seconds
Dense Point Cloud	
Points	173,146,331
Point colors	3 bands, uint8
Reconstruction parameters	
Quality	High
Depth filtering	Aggressive
Depth maps generation time	15 minutes 16 seconds
Dense cloud generation time	31 minutes 42 seconds
DEM	
Size	23,801 x 23,468
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Reconstruction parameters	
Source data	Dense cloud
Interpolation	Enabled
Processing time	3 minutes 0 seconds
Orthomosaic	
Size	31,002 x 32,768
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Colors	3 bands, uint8
Reconstruction parameters	
Blending mode	Mosaic
Surface	DEM
Enable hole filling	Yes
Processing time	8 minutes 30 seconds
Software	
Version	1.4.2 build 6205
Platform	Windows 64

Ft Gordon 300ft 35mm Report

Processing Report

05 July 2018

Survey Data

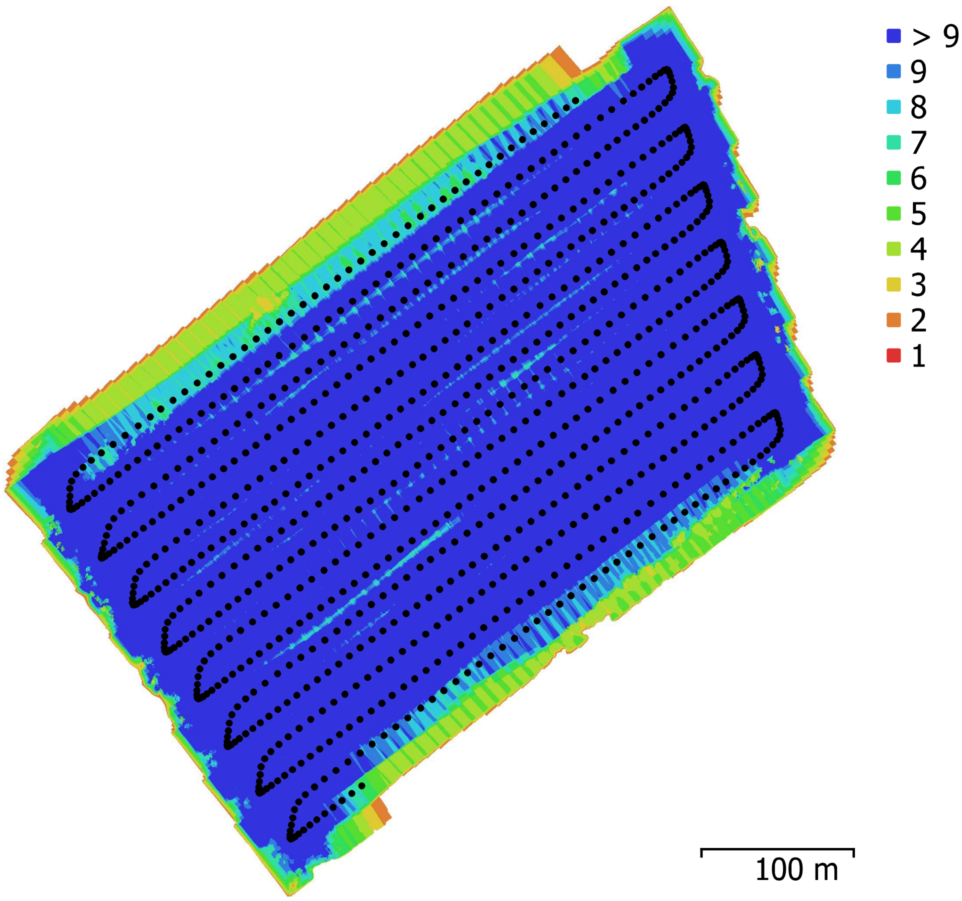


Fig. 1. Camera locations and image overlap.

Number of images:	893	Camera stations:	893
Flying altitude:	88.8 m	Tie points:	583,005
Ground resolution:	9.51 mm/pix	Projections:	3,486,653
Coverage area:	0.165 km²	Reprojection error:	1.1 pix

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

Table 1. Cameras.

Camera Calibration

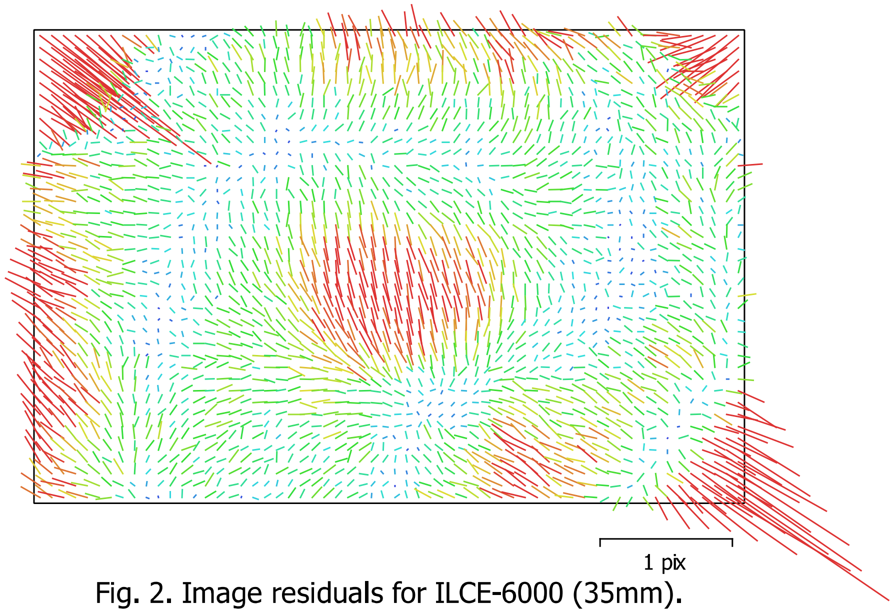


Fig. 2. Image residuals for ILCE-6000 (35mm).

ILCE-6000 (35mm)

893 images

Type	Resolution	Focal Length	Pixel Size
Frame	**6000 x 4000**	**35 mm**	**4.04 x 4.04 µm**

	Value	Error	F	Cx	Cy	B1	B2	K1	K2	K3	K4	P1	P2
F	**9034.49**	0.83	1.00	-0.20	0.07	-0.09	-0.05	0.02	-0.08	0.10	-0.16	0.21	0.02
Cx	**-85.2305**	0.14		1.00	-0.07	0.45	-0.11	0.08	-0.10	0.12	-0.13	-0.30	-0.06
Cy	**36.0806**	0.16			1.00	0.05	0.49	-0.01	0.01	-0.02	0.02	0.03	-0.26
B1	**-8.78121**	0.03				1.00	0.02	0.04	-0.05	0.06	-0.06	-0.37	-0.13
B2	**-14.7213**	0.03					1.00	-0.02	0.03	-0.03	0.04	0.02	-0.15
K1	**0.0473849**	0.00018						1.00	-0.97	0.93	-0.87	-0.00	-0.00
K2	**-1.30062**	0.0043							1.00	-0.99	0.96	-0.01	0.00
K3	**9.7779**	0.04								1.00	-0.99	0.01	-0.00
K4	**-35.884**	0.13									1.00	-0.02	0.00
P1	**0.00248292**	2.7e-06										1.00	0.05
P2	**0.000840828**	2.1e-06											1.00

Table 2. Calibration coefficients and correlation matrix.

Ground Control Points

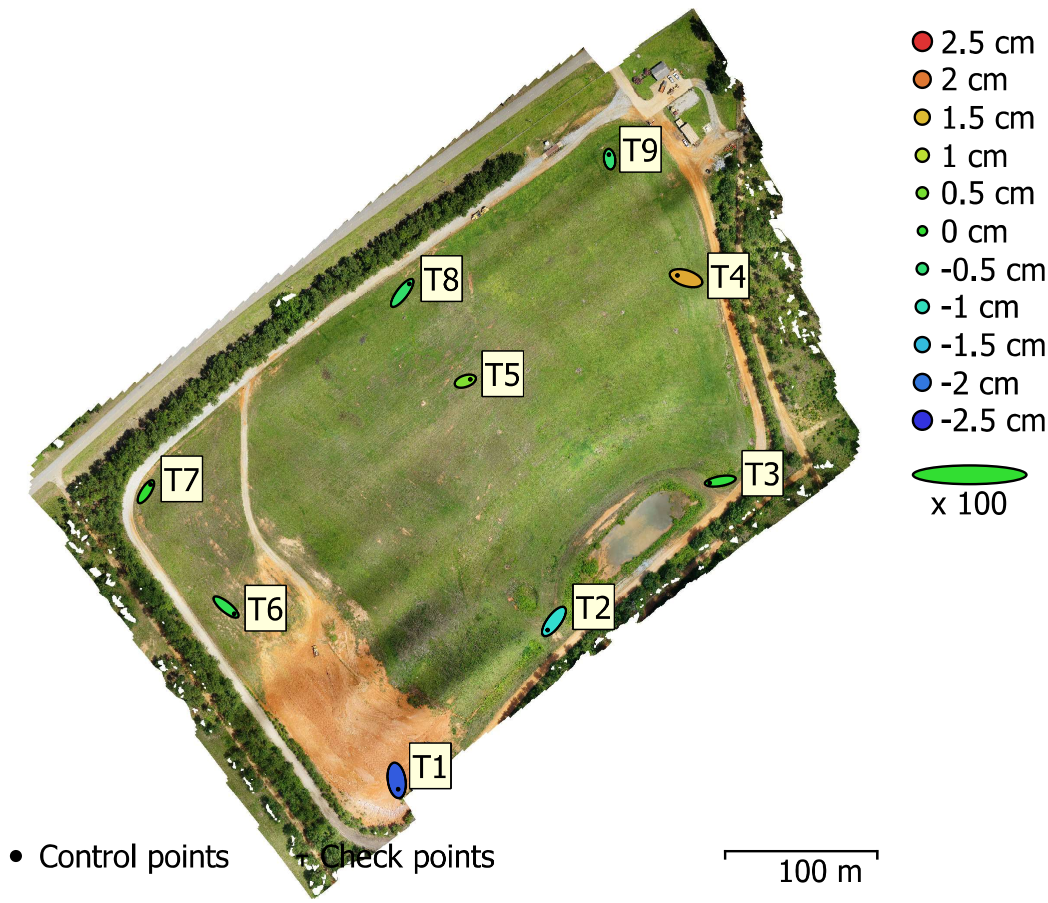


Fig. 3. GCP locations and error estimates.
Z error is represented by ellipse color. X,Y errors are represented by ellipse shape.
Estimated GCP locations are marked with a dot or crossing.

Count	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total (cm)
9	8.64931	8.38227	1.03581	12.0446	12.0891

Table 3. Control points RMSE.
X - Easting, Y - Northing, Z - Altitude.

Label	X error (cm)	Y error (cm)	Z error (cm)	Total (cm)	Image (pix)
T1	1.82706	-11.5989	-2.20285	11.9468	0.246 (3)
T2	-8.42716	-11.2905	-1.14651	14.1353	0.115 (5)
T3	-13.7891	-2.36328	-0.0920294	13.9905	0.161 (7)
T4	-11.3015	3.58299	1.64228	11.9691	0.303 (8)
T5	6.54871	2.22412	0.56501	6.93913	0.272 (6)
T6	10.6582	-8.66082	-0.235463	13.7354	0.271 (9)
T7	6.05676	9.39213	-0.00728591	11.1757	0.246 (11)
T8	9.34208	12.1584	-0.405558	15.3384	0.194 (6)
T9	-0.797235	5.99432	-0.494268	6.06727	0.175 (8)
Total	**8.64931**	**8.38227**	**1.03581**	**12.0891**	**0.232**

Table 4. Control points.

X - Easting, Y - Northing, Z - Altitude.

Digital Elevation Model

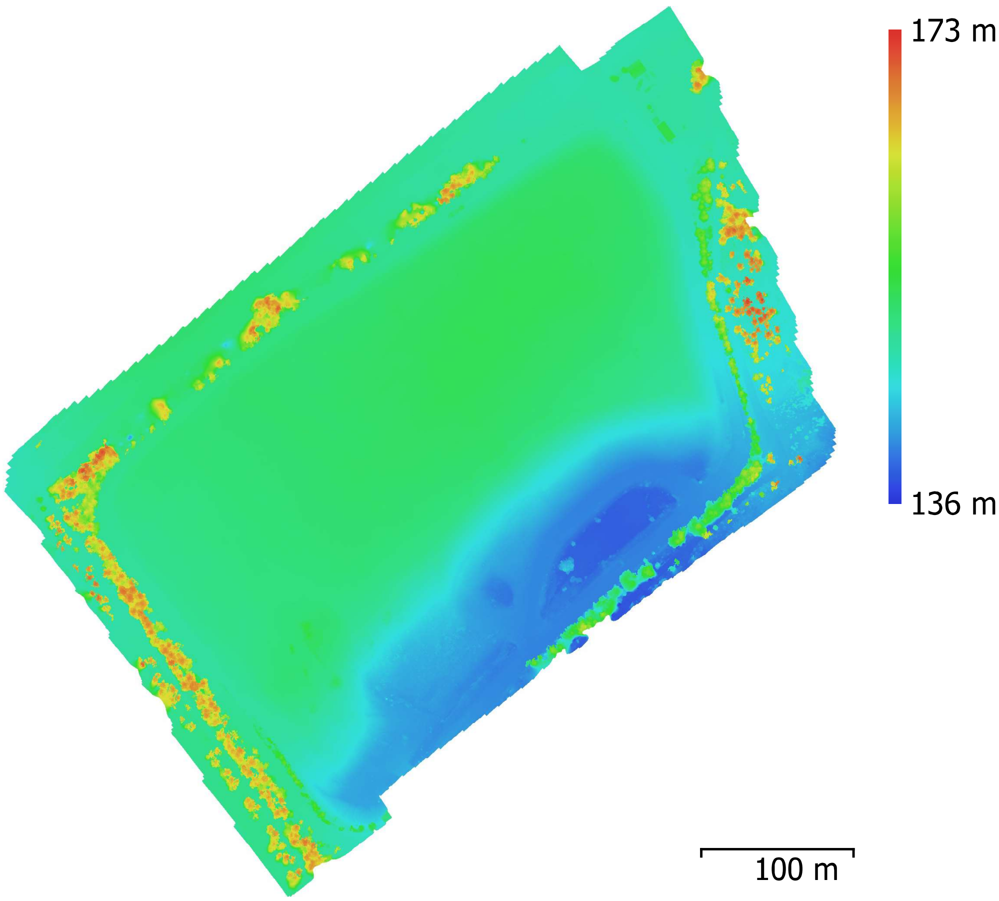


Fig. 4. Reconstructed digital elevation model.

Resolution:	3.8 cm/pix
Point density:	691 points/m²

Processing Parameters

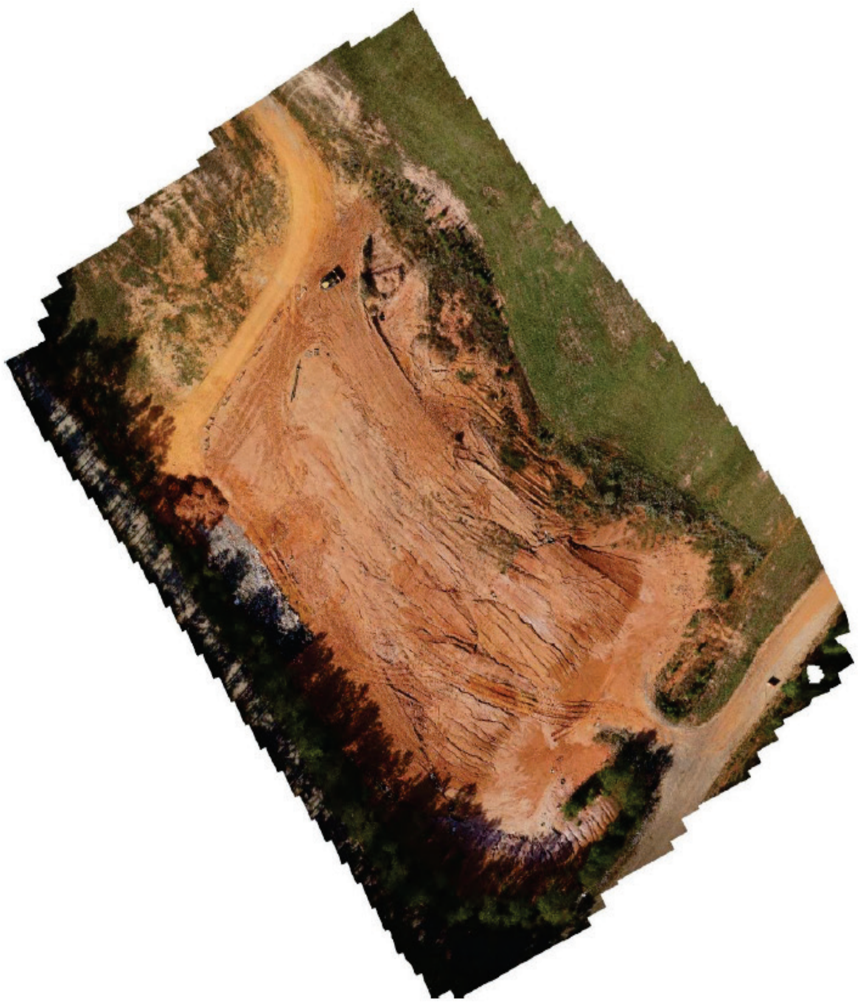
General	
Cameras	893
Aligned cameras	893
Markers	32
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Rotation angles	Yaw, Pitch, Roll
Point Cloud	
Points	583,005 of 626,810
RMS reprojection error	0.190225 (1.09931 pix)
Max reprojection error	1.2636 (57.5755 pix)
Mean key point size	5.64228 pix
Point colors	3 bands, uint8
Key points	No
Average tie point multiplicity	6.16042
Alignment parameters	
Accuracy	Medium
Generic preselection	Yes
Key point limit	40,000
Tie point limit	4,000
Adaptive camera model fitting	Yes
Matching time	6 minutes 29 seconds
Alignment time	5 minutes 42 seconds
Optimization parameters	
Parameters	f, b1, b2, cx, cy, k1-k4, p1, p2
Adaptive camera model fitting	No
Optimization time	24 seconds
Dense Point Cloud	
Points	135,190,056
Point colors	3 bands, uint8
Reconstruction parameters	
Quality	Medium
Depth filtering	Aggressive
Depth maps generation time	18 minutes 23 seconds
Dense cloud generation time	28 minutes 57 seconds
DEM	
Size	23,018 x 22,268
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Reconstruction parameters	
Source data	Dense cloud
Interpolation	Enabled
Processing time	2 minutes 40 seconds
Orthomosaic	
Size	57,463 x 61,475
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Colors	3 bands, uint8
Reconstruction parameters	
Blending mode	Mosaic
Surface	DEM
Enable hole filling	Yes
Processing time	22 minutes 20 seconds
Software	
Version	1.4.2 build 6205
Platform	Windows 64

Appendix B: December 2018 Reports

Ft Gordon Active 100ft 19mm_M_Report

Processing Report

27 December 2018



Survey Data

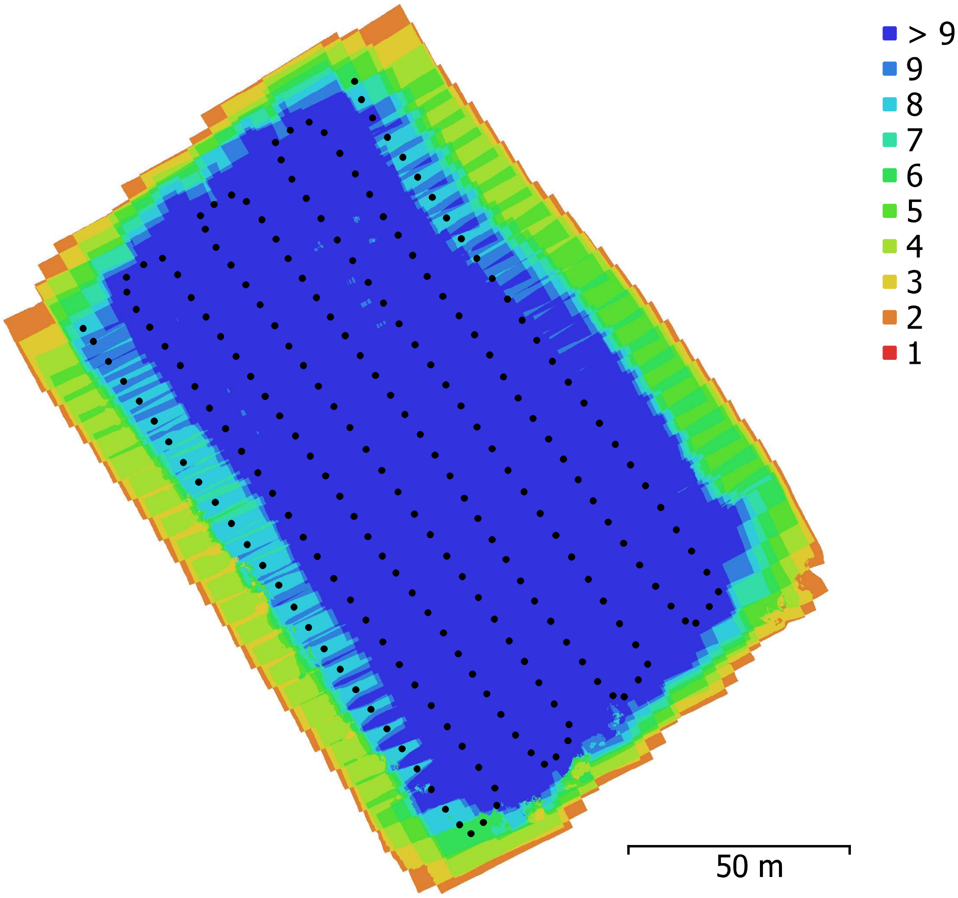


Fig. 1. Camera locations and image overlap.

Number of images:	222	Camera stations:	222
Flying altitude:	31.4 m	Tie points:	126,534
Ground resolution:	6.24 mm/pix	Projections:	856,237
Coverage area:	0.0202 km²	Reprojection error:	1.15 pix

Camera Model	Resolution	Focal Length	Pixel Size	Precalibrated
ILCE-6000 (19mm)	6000 x 4000	19 mm	4.07 x 4.07 μm	No

Table 1. Cameras.

Camera Calibration

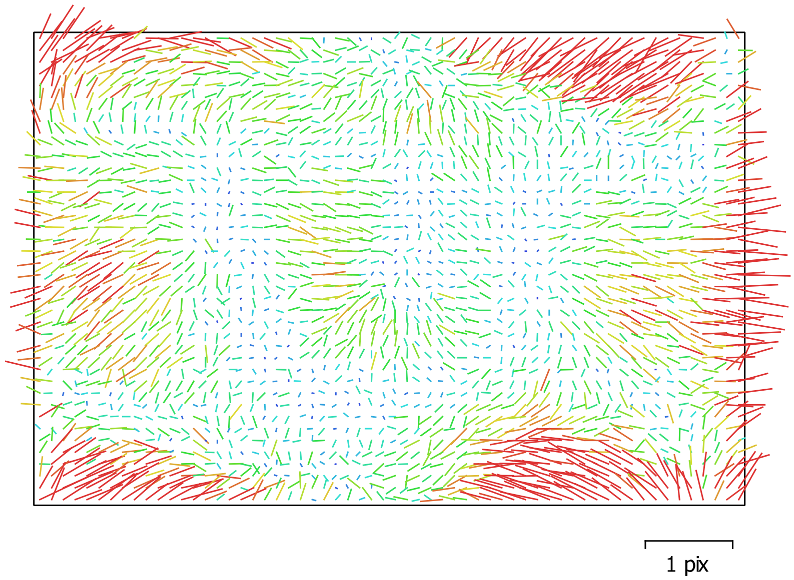


Fig. 2. Image residuals for ILCE-6000 (19mm).

ILCE-6000 (19mm)

222 images

Type	Resolution	Focal Length	Pixel Size
Frame	**6000 x 4000**	**19 mm**	**4.07 x 4.07 µm**

	Value	Error	Cx	Cy	B1	B2	K1	K2	K3	P1	P2
F	4666.67										
Cx	3.85239	0.2	1.00	-0.09	-0.19	0.13	-0.03	0.01	-0.01	-0.17	0.10
Cy	-7.20748	0.24		1.00	-0.02	-0.22	0.01	0.01	-0.01	0.09	-0.13
B1	-4.83691	0.084			1.00	0.02	-0.00	-0.00	0.02	0.14	0.10
B2	4.88797	0.084				1.00	-0.01	-0.01	0.01	0.09	0.12
K1	-0.0859591	5.8e-05					1.00	-0.94	0.89	0.03	-0.01
K2	0.101528	0.00022						1.00	-0.99	0.01	0.01
K3	-0.0275526	0.00025							1.00	-0.01	-0.00
P1	0.000634962	7.4e-06								1.00	-0.12
P2	-0.00125413	6.2e-06									1.00

Table 2. Calibration coefficients and correlation matrix.

Ground Control Points

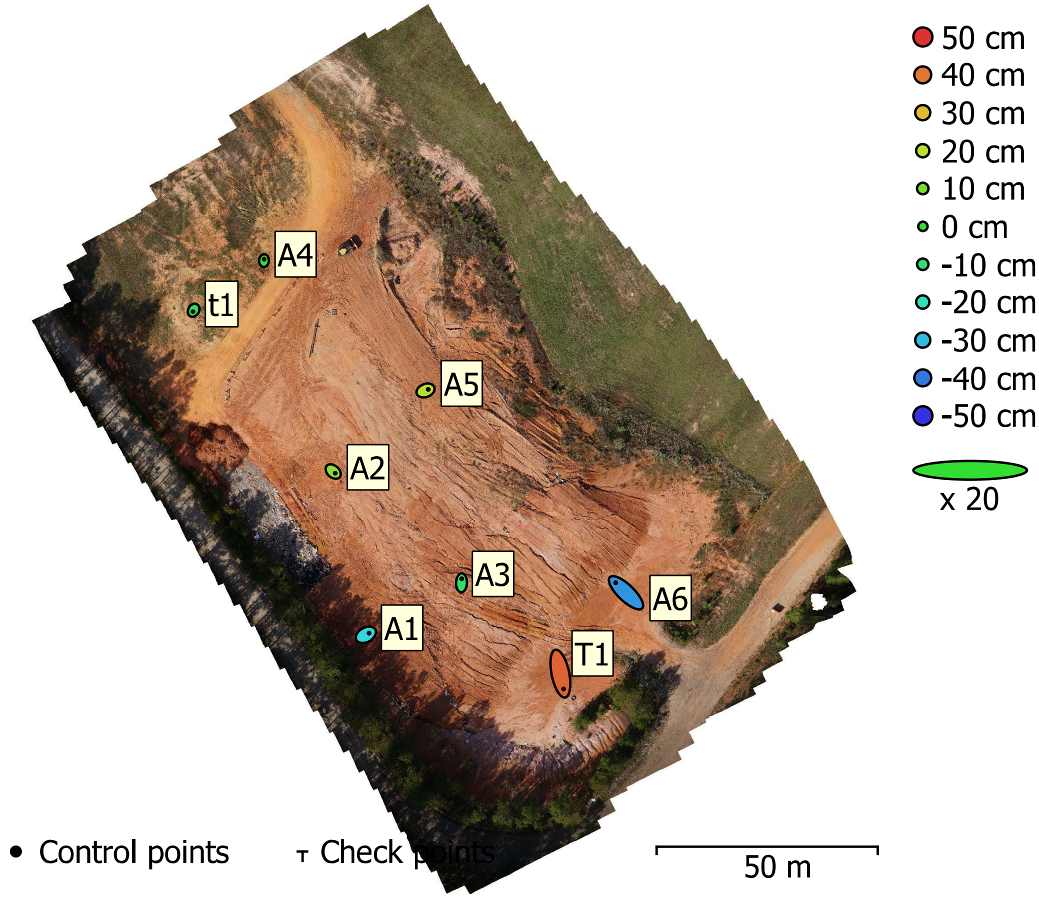


Fig. 3. GCP locations and error estimates.
Z error is represented by ellipse color. X,Y errors are represented by ellipse shape.
Estimated GCP locations are marked with a dot or crossing.

Count	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total (cm)
8	9.37694	15.1633	23.572	17.8284	29.5549

Table 3. Control points RMSE.
X - Easting, Y - Northing, Z - Altitude.

Label	X error (cm)	Y error (cm)	Z error (cm)	Total (cm)	Image (pix)
T1	7.15146	-34.522	43.0076	55.6108	0.308 (11)
t1	-1.71559	-2.93592	-6.67489	7.49113	0.171 (10)
A4	0.236631	3.44225	1.12355	3.6287	0.199 (8)
A5	5.9691	2.319	19.0124	20.0619	0.349 (8)
A2	4.40345	-3.86841	13.1125	14.3629	0.346 (7)
A6	-23.3118	22.6025	-35.7787	48.3159	0.383 (14)
A1	7.12228	3.90726	-25.9887	27.2287	0.301 (5)
A3	0.295768	8.98274	-7.79119	11.8945	0.342 (12)
Total	**9.37694**	**15.1633**	**23.572**	**29.5549**	**0.314**

Table 4. Control points.

X - Easting, Y - Northing, Z - Altitude.

Digital Elevation Model

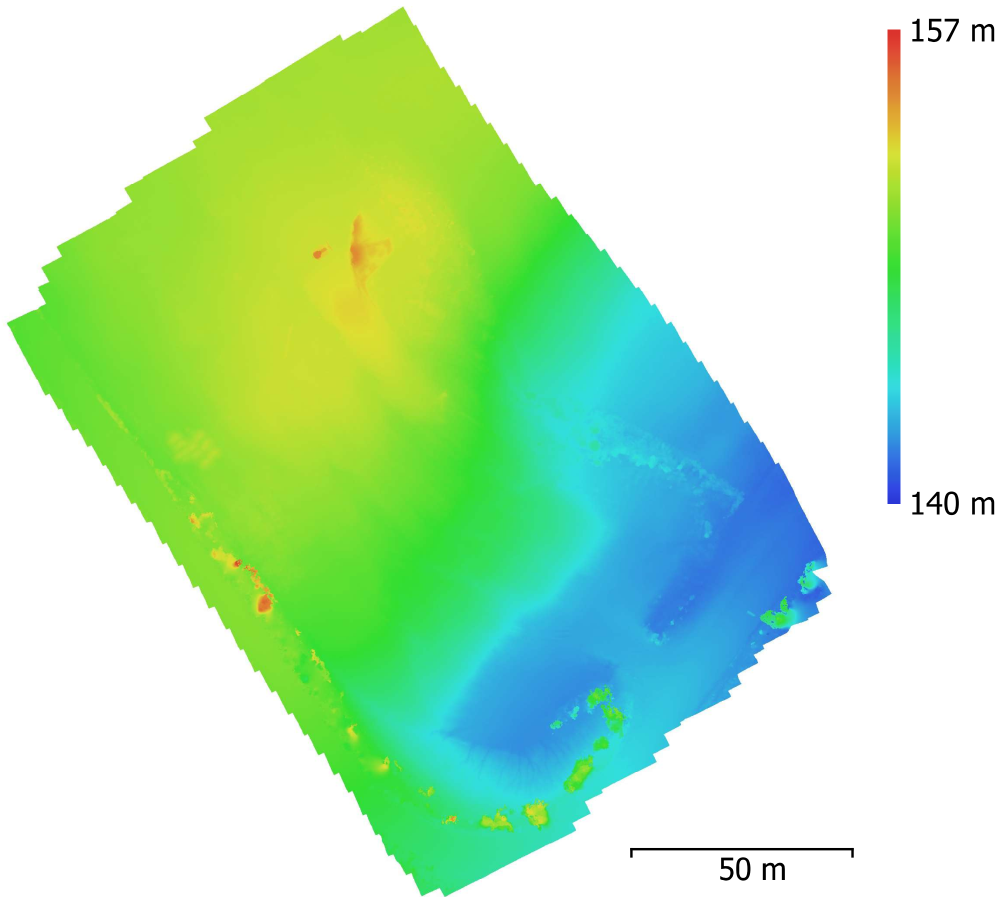


Fig. 4. Reconstructed digital elevation model.

Resolution:	2.5 cm/pix
Point density:	16.1 points/cm²

Processing Parameters

General	
Cameras	222
Aligned cameras	222
Markers	31
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Rotation angles	Yaw, Pitch, Roll
Point Cloud	
Points	126,534 of 135,985
RMS reprojection error	0.220426 (1.1477 pix)
Max reprojection error	1.6029 (28.1116 pix)
Mean key point size	5.25332 pix
Point colors	3 bands, uint8
Key points	No
Average tie point multiplicity	7.04745
Alignment parameters	
Accuracy	Medium
Generic preselection	Yes
Key point limit	40,000
Tie point limit	4,000
Adaptive camera model fitting	Yes
Matching time	1 minutes 31 seconds
Alignment time	45 seconds
Optimization parameters	
Parameters	b1, b2, cx, cy, k1-k3, p1, p2
Adaptive camera model fitting	No
Optimization time	3 seconds
Dense Point Cloud	
Points	36,922,299
Point colors	3 bands, uint8
Reconstruction parameters	
Quality	Medium
Depth filtering	Aggressive
Depth maps generation time	4 minutes 8 seconds
Dense cloud generation time	5 minutes 23 seconds
DEM	
Size	10,937 x 12,029
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Reconstruction parameters	
Source data	Dense cloud
Interpolation	Enabled
Processing time	57 seconds
Orthomosaic	
Size	7,589 x 8,192
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Colors	3 bands, uint8
Reconstruction parameters	
Blending mode	Mosaic
Surface	DEM
Enable hole filling	Yes
Processing time	53 seconds
Software	
Version	1.4.2 build 6205
Platform	Windows 64

Ft_Gordon_All_200ft_19mm_M_Report

Processing Report

27 December 2018

Survey Data

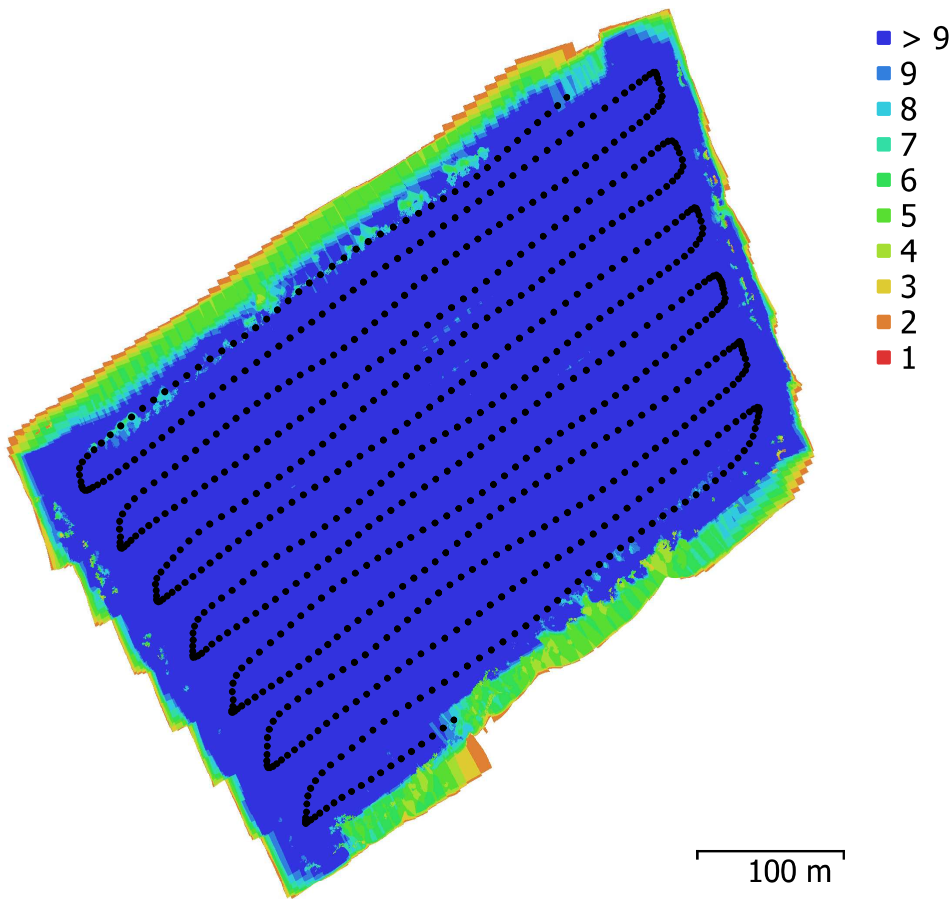


Fig. 1. Camera locations and image overlap.

Number of images:	781	Camera stations:	781
Flying altitude:	63.8 m	Tie points:	367,316
Ground resolution:	1.18 cm/pix	Projections:	3,040,445
Coverage area:	0.181 km²	Reprojection error:	1.36 pix

Camera Model	Resolution	Focal Length	Pixel Size	Precalibrated
ILCE-6000 (19mm)	6000 x 4000	19 mm	4.07 x 4.07 μm	No

Table 1. Cameras.

Camera Calibration

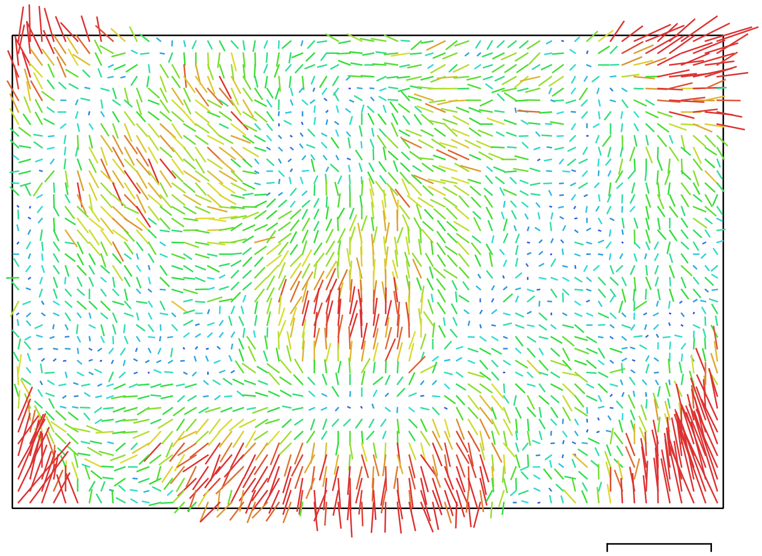


Fig. 2. Image residuals for ILCE-6000 (19mm).

ILCE-6000 (19mm)

781 images

Type	Resolution	Focal Length	Pixel Size
Frame	**6000 x 4000**	**19 mm**	**4.07 x 4.07 µm**

	Value	Error	F	Cx	Cy	B1	B2	K1	K2	K3	P1	P2
F	**4979.18**	0.57	1.00	-0.18	-0.24	0.11	0.17	-0.63	0.44	-0.21	0.14	0.20
Cx	**15.9416**	0.09		1.00	0.01	0.36	0.14	0.10	-0.06	0.01	-0.19	-0.03
Cy	**17.308**	0.1			1.00	-0.28	0.41	0.14	-0.09	0.03	-0.04	-0.41
B1	**1.39315**	0.022				1.00	0.01	-0.08	0.04	-0.01	-0.24	0.17
B2	**1.23168**	0.022					1.00	-0.11	0.08	-0.05	-0.12	-0.09
K1	**-0.105762**	4.1e-05						1.00	-0.95	0.83	-0.09	-0.13
K2	**0.145191**	0.00015							1.00	-0.96	0.05	0.08
K3	**-0.0588299**	0.00018								1.00	-0.01	-0.03
P1	**0.00043611**	1.9e-06									1.00	0.05
P2	**-0.000333857**	1.6e-06										1.00

Table 2. Calibration coefficients and correlation matrix.

Ground Control Points

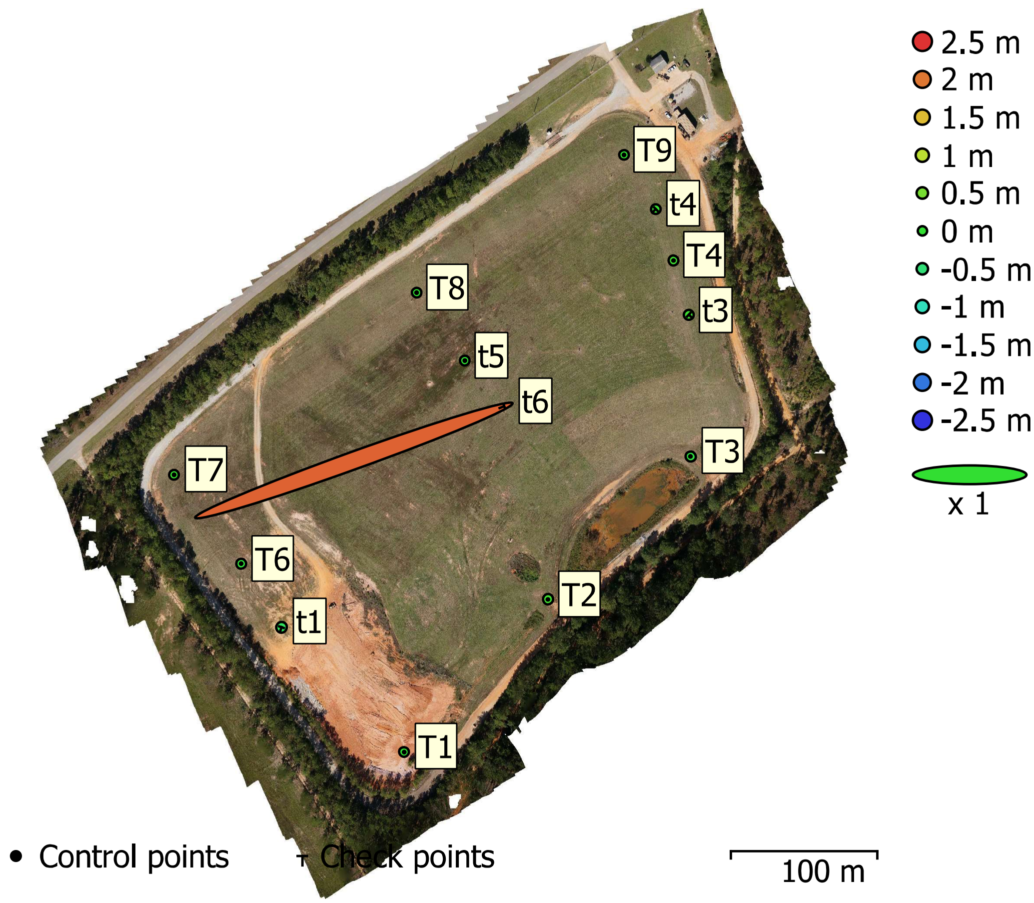


Fig. 3. GCP locations and error estimates.
Z error is represented by ellipse color. X,Y errors are represented by ellipse shape.
Estimated GCP locations are marked with a dot or crossing.

Count	X error (m)	Y error (m)	Z error (m)	XY error (m)	Total (m)
9	0.10579	0.139726	0.0632756	0.175257	0.18633

Table 3. Control points RMSE.
X - Easting, Y - Northing, Z - Altitude.

Count	X error (m)	Y error (m)	Z error (m)	XY error (m)	Total (m)
4	102.715	36.9782	1.08982	109.169	109.174

Table 4. Check points RMSE.
X - Easting, Y - Northing, Z - Altitude.

Label	X error (m)	Y error (m)	Z error (m)	Total (m)	Image (pix)
T1	0.125005	-0.0931427	-0.0199415	0.157161	0.455 (9)
T2	-0.0657414	-0.345265	0.104417	0.366651	0.346 (11)
T3	-0.260875	0.100642	-0.108259	0.299841	0.237 (12)
T4	-0.00498646	0.0506224	0.0813449	0.09594	0.348 (14)
T9	0.0575996	0.0163817	-0.0173849	0.0623563	0.465 (12)
T8	0.0173055	0.0552876	-0.00255785	0.0579891	0.342 (13)
t5	0.0138496	0.0863127	-0.0122267	0.0882677	0.419 (8)
T7	0.0281577	-0.0258526	0.0387846	0.0544561	0.291 (12)
T6	0.089959	0.153926	-0.0665882	0.190315	0.371 (9)
Total	**0.10579**	**0.139726**	**0.0632756**	**0.18633**	**0.365**

Table 5. Control points.
X - Easting, Y - Northing, Z - Altitude.

Label	X error (m)	Y error (m)	Z error (m)	Total (m)	Image (pix)
t3	-0.0595936	0.050804	0.0841196	0.114929	0.318 (14)
t4	0.0367747	0.0383387	0.0443818	0.0692241	0.412 (10)
t6	205.43	73.9559	2.15626	218.348	0.386 (11)
t1	0.0943756	0.289353	-0.303912	0.430109	0.429 (8)
Total	**102.715**	**36.9782**	**1.08982**	**109.174**	**0.381**

Table 6. Check points.
X - Easting, Y - Northing, Z - Altitude.

Digital Elevation Model

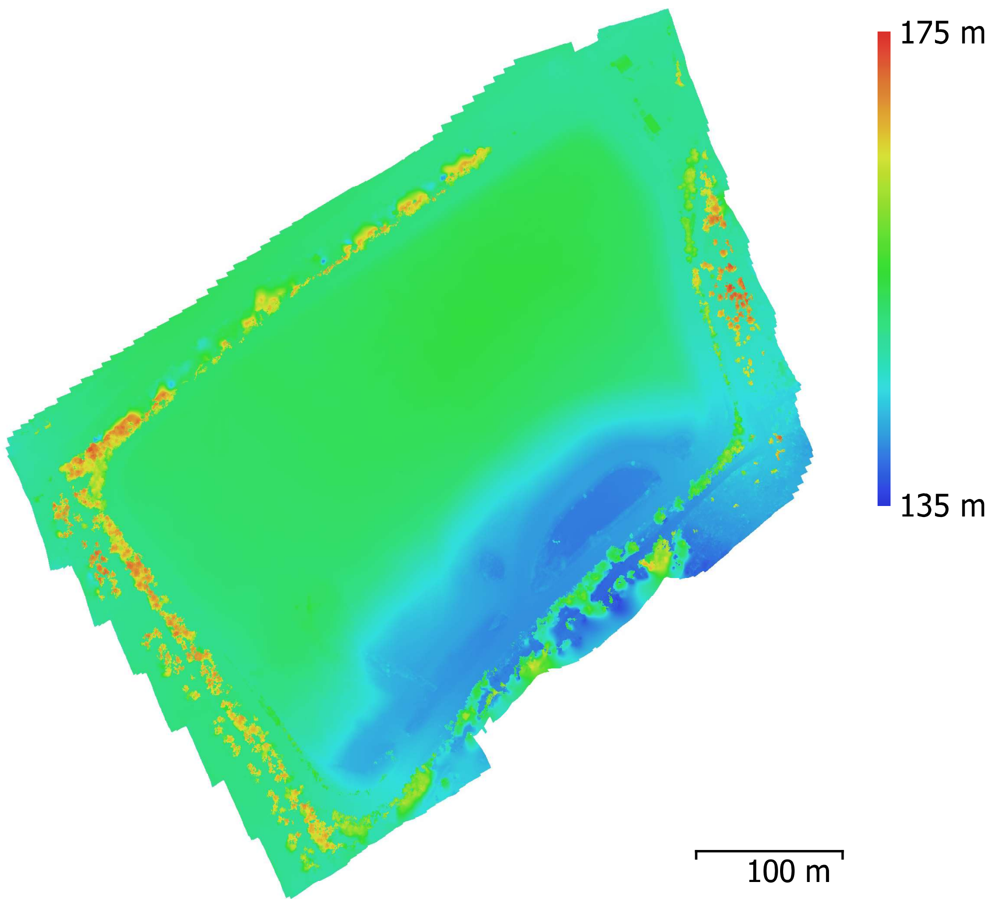


Fig. 4. Reconstructed digital elevation model.

Resolution:	4.71 cm/pix
Point density:	451 points/m²

Processing Parameters

General	
Cameras	781
Aligned cameras	781
Markers	31
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Rotation angles	Yaw, Pitch, Roll
Point Cloud	
Points	367,316 of 403,401
RMS reprojection error	0.254308 (1.35526 pix)
Max reprojection error	1.38528 (49.2445 pix)
Mean key point size	5.40195 pix
Point colors	3 bands, uint8
Key points	No
Average tie point multiplicity	8.67252
Alignment parameters	
Accuracy	Medium
Generic preselection	Yes
Key point limit	40,000
Tie point limit	4,000
Adaptive camera model fitting	Yes
Matching time	6 minutes 23 seconds
Alignment time	3 minutes 52 seconds
Optimization parameters	
Parameters	f, b1, b2, cx, cy, k1-k3, p1, p2
Adaptive camera model fitting	No
Optimization time	15 seconds
Dense Point Cloud	
Points	93,156,768
Point colors	3 bands, uint8
Reconstruction parameters	
Quality	Medium
Depth filtering	Aggressive
Depth maps generation time	20 minutes 45 seconds
Dense cloud generation time	33 minutes 24 seconds
DEM	
Size	19,565 x 19,072
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Reconstruction parameters	
Source data	Dense cloud
Interpolation	Enabled
Processing time	2 minutes 12 seconds
Orthomosaic	
Size	7,435 x 8,192
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Colors	3 bands, uint8
Reconstruction parameters	
Blending mode	Mosaic
Surface	DEM
Enable hole filling	Yes
Processing time	3 minutes 29 seconds
Software	
Version	1.4.2 build 6205
Platform	Windows 64

Ft_Gordon_All_250ft_RX1R_FF_Report

Processing Report

27 December 2018

Survey Data

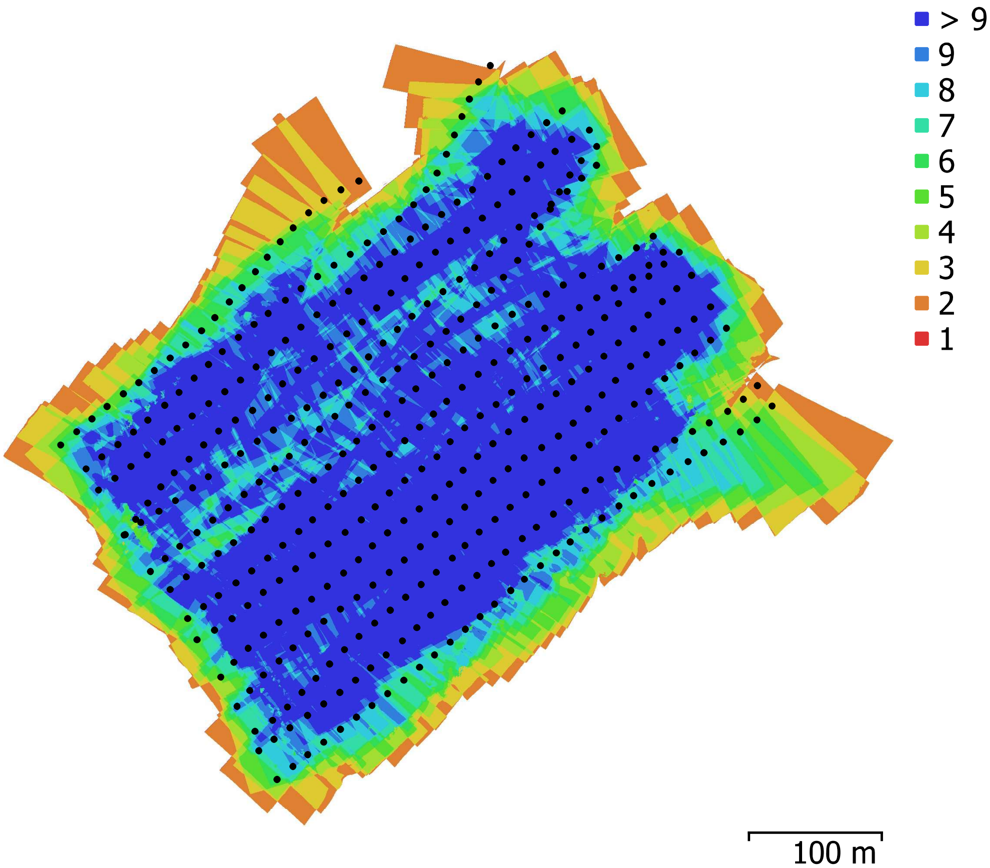


Fig. 1. Camera locations and image overlap.

Number of images:	433	Camera stations:	431
Flying altitude:	74.8 m	Tie points:	303,870
Ground resolution:	9.43 mm/pix	Projections:	1,619,361
Coverage area:	0.199 km²	Reprojection error:	0.957 pix

Camera Model	Resolution	Focal Length	Pixel Size	Precalibrated
DSC-RX1RM2 (35mm)	7952 x 5304	35 mm	4.53 x 4.53 μm	No

Table 1. Cameras.

Camera Calibration

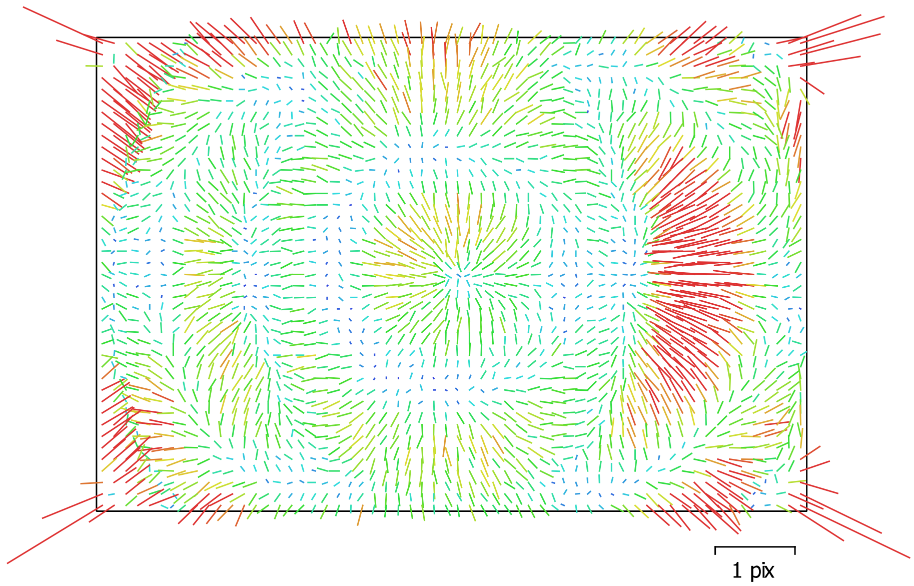


Fig. 2. Image residuals for DSC-RX1RM2 (35mm).

DSC-RX1RM2 (35mm)

433 images

Type	Resolution	Focal Length	Pixel Size
Frame	**7952 x 5304**	**35 mm**	**4.53 x 4.53 µm**

	Value	Error	F	Cx	Cy	B1	B2	K1	K2	K3	K4	P1	P2
F	**7545.75**	0.3	1.00	-0.10	-0.38	0.09	0.10	-0.18	0.17	-0.26	0.35	0.10	0.25
Cx	**6.29874**	0.072		1.00	0.04	0.06	0.25	0.03	-0.03	0.05	-0.06	-0.00	-0.02
Cy	**10.4675**	0.079			1.00	-0.31	0.00	0.03	-0.04	0.08	-0.12	-0.06	-0.18
B1	**4.43861**	0.019				1.00	0.02	0.01	-0.02	0.00	0.02	-0.03	0.16
B2	**1.90162**	0.021					1.00	-0.00	-0.00	-0.01	0.02	-0.09	-0.03
K1	**-0.111193**	9.4e-05						1.00	-0.98	0.93	-0.87	-0.01	-0.02
K2	**0.505365**	0.00088							1.00	-0.98	0.94	0.01	0.01
K3	**-2.54771**	0.0033								1.00	-0.99	-0.02	-0.04
K4	**3.78047**	0.0041									1.00	0.03	0.07
P1	**0.00017065**	1.8e-06										1.00	0.02
P2	**0.000649134**	1.6e-06											1.00

Table 2. Calibration coefficients and correlation matrix.

Ground Control Points

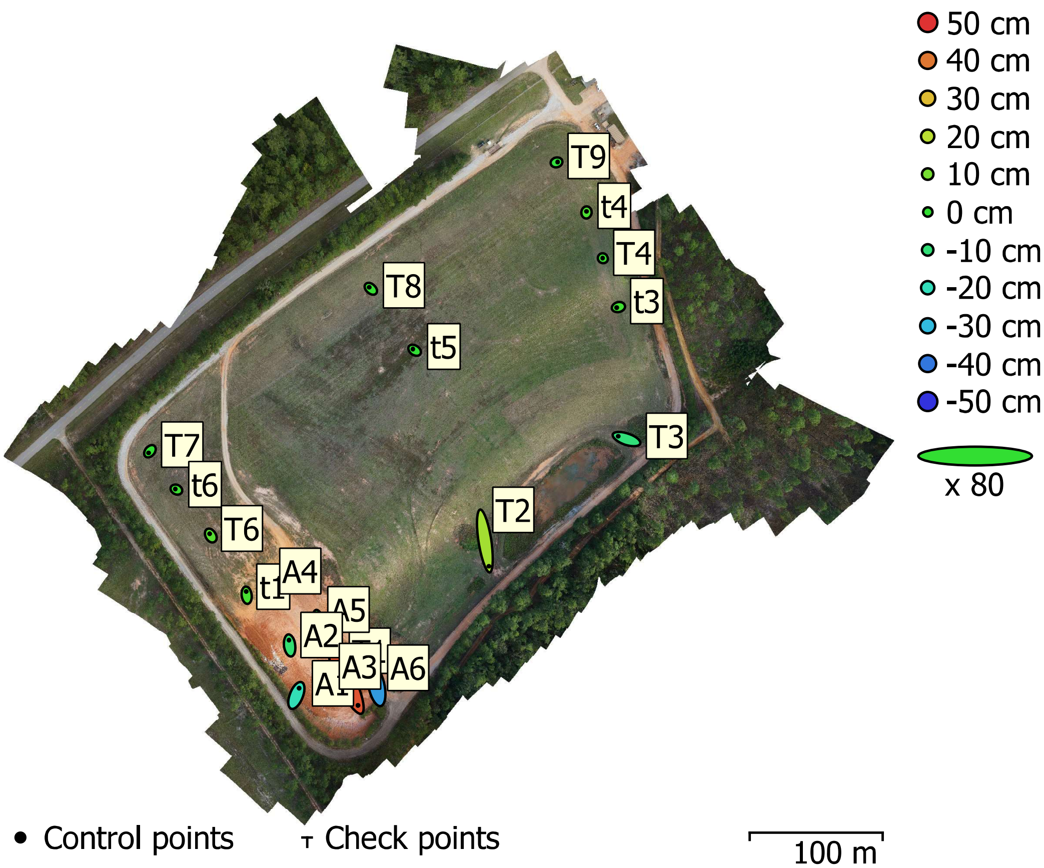


Fig. 3. GCP locations and error estimates.
Z error is represented by ellipse color. X,Y errors are represented by ellipse shape.
Estimated GCP locations are marked with a dot or crossing.

Count	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total (cm)
19	6.87968	17.4162	15.8674	18.7258	24.5444

Table 3. Control points RMSE.
X - Easting, Y - Northing, Z - Altitude.

Label	X error (cm)	Y error (cm)	Z error (cm)	Total (cm)	Image (pix)
T1	21.8513	-46.5472	45.1474	68.4282	0.930 (3)
T2	7.28566	-47.4159	16.4911	50.7278	0.551 (5)
T3	-15.5529	5.21465	-10.3404	19.391	0.155 (5)
T4	-0.441118	0.347703	0.955827	1.10864	0.057 (3)
t3	-3.38978	-0.854988	2.06174	4.05861	0.065 (4)
t4	0.199946	2.00514	3.77676	4.28071	0.008 (2)
T9	2.10799	0.591358	-1.49478	2.65098	0.063 (4)
T8	-3.24773	2.92372	0.465125	4.39457	0.104 (5)
t5	-3.29521	2.25134	-0.355157	4.00663	0.005 (2)
T7	-2.61908	-3.17669	-0.0538446	4.11751	0.157 (4)
t6	-2.05114	1.07588	1.28632	2.6494	0.146 (3)
T6	-2.12895	3.50648	5.38241	6.76743	0.050 (3)
t1	-0.755164	6.98498	3.21737	7.72733	0.127 (4)
A4	-2.74323	6.14878	6.67675	9.48218	0.150 (6)
A5	-2.49673	12.7037	-3.51588	13.4156	0.158 (3)
A2	-1.3268	10.1729	-9.18302	13.7687	0.243 (5)
A6	-5.11699	23.4117	-34.8793	42.3185	0.699 (3)
A1	5.35733	13.5349	-19.2276	24.1163	0.378 (2)
A3	-1.63243	13.9965	-24.0007	27.8316	0.578 (2)
Total	**6.87968**	**17.4162**	**15.8674**	**24.5444**	**0.332**

Table 4. Control points.

X - Easting, Y - Northing, Z - Altitude.

Digital Elevation Model

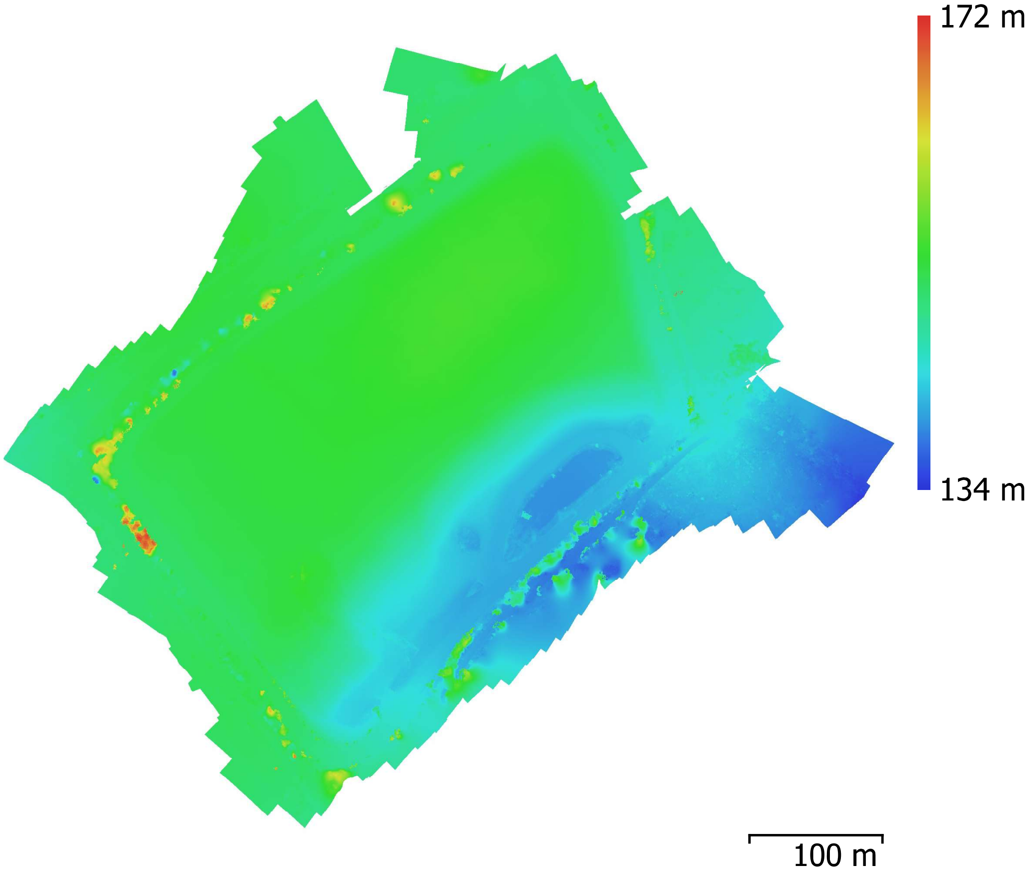


Fig. 4. Reconstructed digital elevation model.

Resolution:	3.77 cm/pix
Point density:	703 points/m²

Processing Parameters

General	
Cameras	433
Aligned cameras	431
Markers	31
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Rotation angles	Yaw, Pitch, Roll
Point Cloud	
Points	303,870 of 328,500
RMS reprojection error	0.17687 (0.95725 pix)
Max reprojection error	2.10861 (43.2373 pix)
Mean key point size	5.60602 pix
Point colors	3 bands, uint8
Key points	No
Average tie point multiplicity	5.49782
Alignment parameters	
Accuracy	Medium
Generic preselection	Yes
Key point limit	40,000
Tie point limit	4,000
Adaptive camera model fitting	Yes
Matching time	3 minutes 34 seconds
Alignment time	1 minutes 29 seconds
Optimization parameters	
Parameters	f, b1, b2, cx, cy, k1-k4, p1, p2
Adaptive camera model fitting	No
Optimization time	5 seconds
Dense Point Cloud	
Points	128,782,564
Point colors	3 bands, uint8
Reconstruction parameters	
Quality	Medium
Depth filtering	Aggressive
Depth maps generation time	11 minutes 21 seconds
Dense cloud generation time	17 minutes 29 seconds
DEM	
Size	23,933 x 23,392
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Reconstruction parameters	
Source data	Dense cloud
Interpolation	Enabled
Processing time	2 minutes 43 seconds
Orthomosaic	
Size	8,192 x 7,181
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Colors	3 bands, uint8
Reconstruction parameters	
Blending mode	Mosaic
Surface	DEM
Enable hole filling	Yes
Processing time	1 minutes 45 seconds
Software	
Version	1.4.2 build 6205
Platform	Windows 64

Ft_Gordon_Carter_200ft_19mm_M_Report

Processing Report

27 December 2018

Survey Data

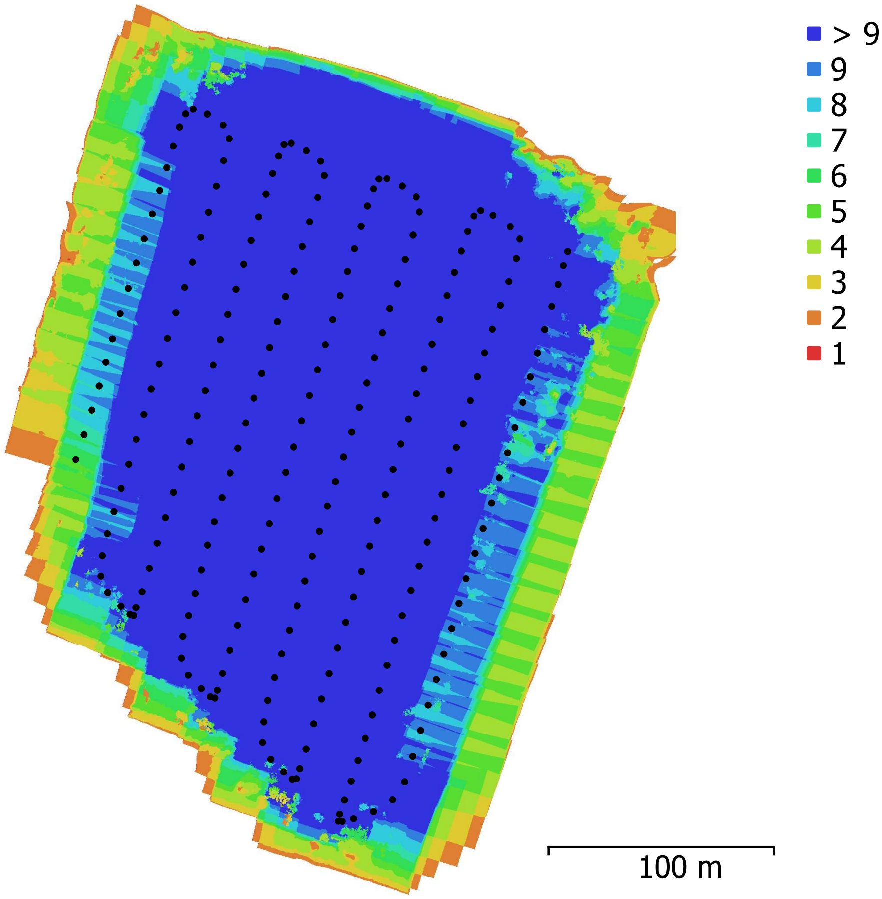


Fig. 1. Camera locations and image overlap.

Number of images:	225	Camera stations:	225
Flying altitude:	68.8 m	Tie points:	130,311
Ground resolution:	1.29 cm/pix	Projections:	859,747
Coverage area:	0.0773 km²	Reprojection error:	1.1 pix

Camera Model	Resolution	Focal Length	Pixel Size	Precalibrated
ILCE-6000 (19mm)	6000 x 4000	19 mm	4.07 x 4.07 µm	No

Table 1. Cameras.

Camera Calibration

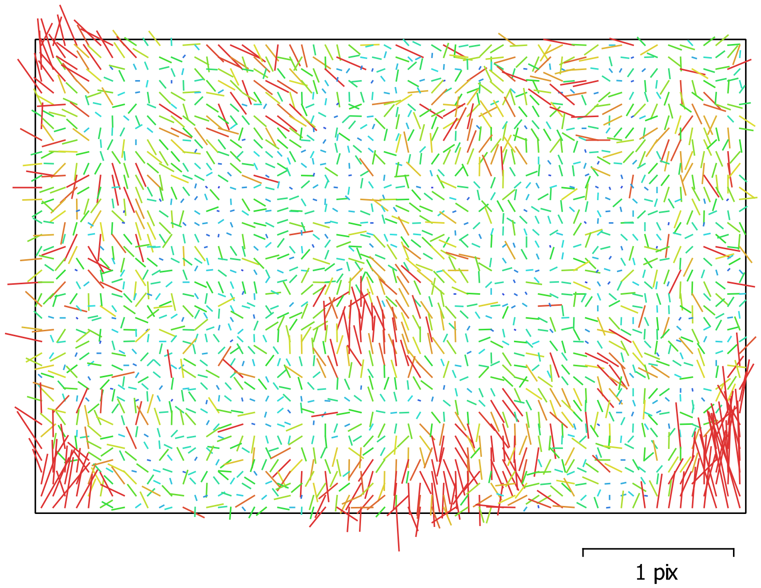


Fig. 2. Image residuals for ILCE-6000 (19mm).

ILCE-6000 (19mm)

225 images

Type	Resolution	Focal Length	Pixel Size
Frame	**6000 x 4000**	**19 mm**	**4.07 x 4.07 µm**

	Value	Error	F	Cx	Cy	B1	B2	K1	K2	K3	P1	P2
F	**4930.84**	0.9	1.00	0.18	-0.33	0.08	-0.10	-0.66	0.51	-0.28	-0.08	0.24
Cx	**13.3144**	0.14		1.00	-0.13	-0.24	0.29	-0.13	0.10	-0.06	-0.17	0.07
Cy	**-0.927566**	0.17			1.00	-0.32	-0.29	0.22	-0.16	0.08	0.04	-0.38
B1	**1.6237**	0.036				1.00	0.04	-0.06	0.04	-0.01	0.11	0.25
B2	**0.94748**	0.036					1.00	0.05	-0.05	0.03	-0.07	0.21
K1	**-0.103714**	5.8e-05						1.00	-0.95	0.84	0.07	-0.18
K2	**0.137899**	0.00021							1.00	-0.96	-0.04	0.10
K3	**-0.0532853**	0.00024								1.00	0.02	-0.03
P1	**0.000381603**	3.2e-06									1.00	-0.00
P2	**-0.000120415**	3.1e-06										1.00

Table 2. Calibration coefficients and correlation matrix.

Ground Control Points

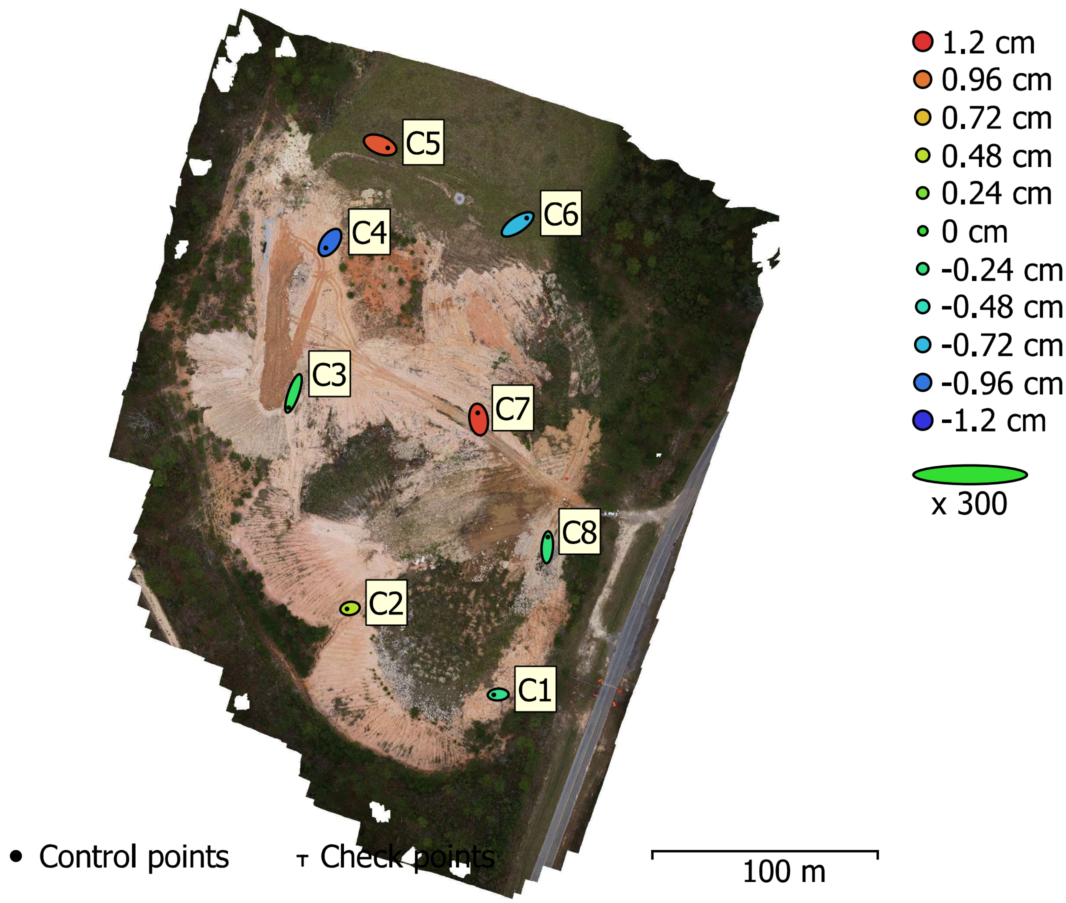


Fig. 3. GCP locations and error estimates.
Z error is represented by ellipse color. X,Y errors are represented by ellipse shape.
Estimated GCP locations are marked with a dot or crossing.

Count	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total (cm)
8	1.51345	2.16492	0.740026	2.64148	2.74318

Table 3. Control points RMSE.
X - Easting, Y - Northing, Z - Altitude.

Label	X error (cm)	Y error (cm)	Z error (cm)	Total (cm)	Image (pix)
C1	-1.30195	-0.0707814	-0.311375	1.34054	0.234 (5)
C2	-0.917243	-0.152865	0.457821	1.03649	0.215 (6)
C3	-1.40868	-4.17954	-0.161462	4.4135	0.317 (7)
C4	-1.1837	-1.64379	-0.994391	2.25655	0.281 (9)
C5	2.23326	-0.859827	1.07483	2.62335	0.276 (9)
C8	0.183288	3.04824	-0.242103	3.06333	0.367 (11)
C7	-0.291238	1.97133	1.1428	2.29716	0.266 (5)
C6	2.70121	1.83812	-0.73472	3.34889	0.253 (10)
Total	**1.51345**	**2.16492**	**0.740026**	**2.74318**	**0.287**

Table 4. Control points.

X - Easting, Y - Northing, Z - Altitude.

Digital Elevation Model

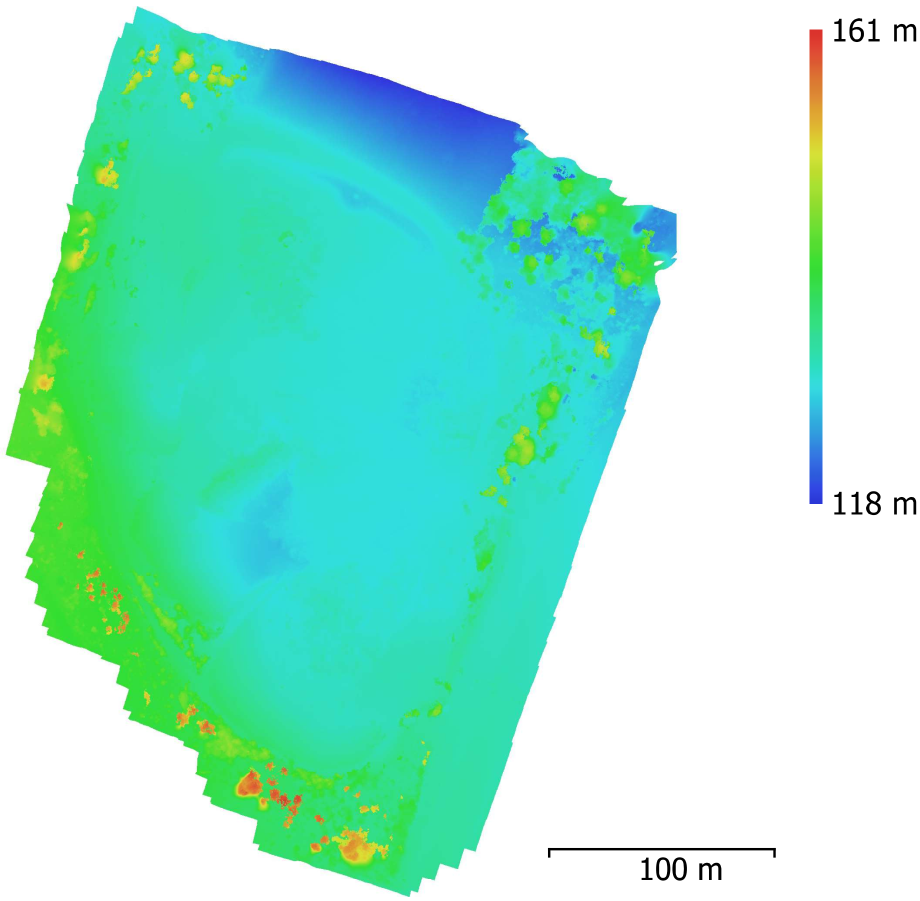


Fig. 4. Reconstructed digital elevation model.

Resolution:	5.16 cm/pix
Point density:	375 points/m²

Processing Parameters

General	
Cameras	225
Aligned cameras	225
Markers	8
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Rotation angles	Yaw, Pitch, Roll
Point Cloud	
Points	130,311 of 141,176
RMS reprojection error	0.184845 (1.0984 pix)
Max reprojection error	0.972964 (39.7656 pix)
Mean key point size	5.93969 pix
Point colors	3 bands, uint8
Key points	No
Average tie point multiplicity	6.9431
Alignment parameters	
Accuracy	Medium
Generic preselection	Yes
Key point limit	40,000
Tie point limit	4,000
Adaptive camera model fitting	Yes
Matching time	1 minutes 44 seconds
Alignment time	46 seconds
Optimization parameters	
Parameters	f, b1, b2, cx, cy, k1-k3, p1, p2
Adaptive camera model fitting	No
Optimization time	4 seconds
Dense Point Cloud	
Points	36,429,910
Point colors	3 bands, uint8
Reconstruction parameters	
Quality	Medium
Depth filtering	Aggressive
Depth maps generation time	4 minutes 13 seconds
Dense cloud generation time	6 minutes 59 seconds
DEM	
Size	6,357 x 9,295
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Reconstruction parameters	
Source data	Dense cloud
Interpolation	Enabled
Processing time	44 seconds
Orthomosaic	
Size	6,175 x 8,192
Coordinate system	NAD83 / UTM zone 17N (EPSG::26917)
Colors	3 bands, uint8
Reconstruction parameters	
Blending mode	Mosaic
Surface	DEM
Enable hole filling	Yes
Processing time	1 minutes 3 seconds
Software	
Version	1.4.2 build 6205
Platform	Windows 64

Abbreviations

ASIP	Army Stationing and Installation Plan
C&D	Construction and demolition
CERL	Construction Engineering Research Laboratory
COTS	Commercial off-the-shelf
DEM	Digital elevation models
DSLR	Digital single-lens reflex
ERDC	Engineer Research and Development Center
FAA	Federal Aviation Administration
GCP	Ground control points
GSL	Geotechnical and Structures Laboratory
ISWMP	Integrated solid waste management plans
NDVI	Normalized Difference Vegetation Index
PIC	Pilot in command
SSPP	Strategic Sustainability Performance Plan
sUAS	Small unmanned aircraft systems
SWAR	Solid Waste Annual Reporting
UFGS	Unified Facilities Guide Specifications
USACE	US Army Corps of Engineers
VLOS	Visual line of sight
VO	Visual observer

REPORT DOCUMENTATION PAGE

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Angela B. Urban, Ryan C. Strange, Andrew B. Ward, Giselle Rodriguez, and Heidi R. Howard

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"Comprehensive Waste Management & Landfill Facility Assessment," MIPR 11106470

14. ABSTRACT

Finite and decreasing landfill space on Army installations is a significant concern. Efficient waste management is essential for achieving resiliency and extending the lifespan of remaining landfills. The purpose of this demonstration was to conduct independent performance tests of small unmanned aircraft systems (sUAS) and their utility for providing landfill assessments in remote areas where physical presence is either dangerous or inefficient.

An active, near capacity construction and demolition (C&D) landfill at Fort Gordon, Georgia was identified for the demonstration. The flights, data requirements, and outputs generated by the sUAS flyovers were analyzed for efficacy in detecting cell capacity and subsidence. Each flight took 1–2 hours for mobilization, ground marker placement, flight, and postflight analysis. Volumetric and topographic surveys were analyzed in less time than is typical for traditional surveying methods.

After initial setup of ground markers and rectification, sUAS flights save a significant amount of time. However, skilled individuals are required for flights and for processing and maintaining data. The technology is widely relevant to the Army, is commercially available, and offers an average of 30% cost savings in terms of manpower, repeatability, and equipment. The use of sUAS technology is recommended for monitoring and surveying Army landfills

15. SUBJECT TERMS
Drone aircraft; Military bases; Refuse and refuse disposal; Remote sensing; Sanitary landfills–Monitoring

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