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# A Comprehensive Comparison of Photogrammetric and RTK-GPS Methods for General Order Land Surveying

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**Abstract:** One of the main objectives of modern-day surveying is to maximize the efficiency and accuracy of mapping a landscape for natural features and elevations prior to the start of a construction project. This paper focuses on a comparison between terrestrial and aerial photogrammetry and real-time kinematic global positioning systems (RTK-GPSs) in terms of elevation accuracy, data expenditure, and time for each survey to be completed. Two sites in San Diego County were chosen to be studied with a combined area of about 1.14 acres, and a total station system was used to establish 572 control points between both areas. Two of the three methods investigated produced similar results in elevation and were well within the established standard, as the terrestrial photogrammetry averaged 0.0583 feet of error, the aerial photogrammetry averaged 0.345 feet of error, and the RTK-GPS averaged 0.0432 feet of error when compared to the total station ground truth. If data consumption is not a concern, the terrestrial photogrammetric method should be preferred to the aerial photogrammetric and RTK-GPS methods in topographic mapping and land monitoring due to the increase in time efficiency and in surface model detail while keeping within the Caltrans specified tolerance of error of 0.2 feet. For general order land surveys, the photogrammetric approach utilized with a Looq scanner would provide the most efficient and cost-effective survey while staying within the 0.2 foot tolerance of error. This method also allows for the utmost clarity of the resulting point cloud when analyzing terrain, break lines, or other features in the survey area.

**Keywords:** topographic surveying; photogrammetry; total station; RTK-GPS; terrestrial; aerial; point cloud; surface model

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## 1. Introduction

Topographic surveys map the elevations and display the features of a given plot of land with colors, contour lines, and symbols. Land surveying most often seeks to find the boundaries of properties, but topographic surveying encompasses volumetric analysis when utilized in earthwork operations in the construction industry. Topographic surveys are important for many different applications in a project lifecycle, including site layout, drainage, surface features, and earthwork [1,2]. Pre-construction and post-construction surveys report the as-built conditions of a site and act as legally stamped representations of the site. The most traditional methods for surveying a certain parcel of land typically include the use of a total station (TS) instrument or a global navigation satellite system (GNSS) with real-time kinematic (RTK) positioning [3]. A newer method of surveying that has been increasingly used in land mapping is the use of photogrammetry, which is what this research aims to compare with the RTK global positioning system (GPS) [4].

### 1.1. Study Motivation

Land surveying is a fundamental component of virtually all construction projects, transcending sector boundaries, project objectives, and geographical locations. By providing critical data on the terrain, boundaries, and environmental constraints, surveying ensures that construction plans are accurate and feasible, thereby mitigating financial risks associated with project modifications and delays. The US Bureau of Labor Statistics forecasts a 5% increase in surveyor employment from 2022 to 2032, a rate surpassing the average across all job sectors. This upward trend suggests a consistent demand for surveying services, fueled by the necessity for the accurate delineation of property lines, construction initiatives, and various land-related undertakings. It is projected that there will be approximately 3500 annual job vacancies for surveyors, primarily attributed to the replacement of professionals who shift to different careers or leave the workforce altogether [5]. Photogrammetric surveying has many benefits compared to traditional survey methods (RTK-GPS or total station), including being more labor and cost-efficient [6,7]. The purpose of this study was not only to evaluate the accuracy of the digital elevation models created using the RTK-GPS and photogrammetric methods but also to analyze the time, cost, and data size associated with each method. The photogrammetric method creates a model with many more data points than the traditional methods, which should theoretically increase accuracy. The density of the point clouds generated with photogrammetry can be very overwhelming, however, especially when engineering-level accuracy is not necessary for the survey. The technique of creating a topographic map or digital elevation model using a total station or RTK-GPS cannot include the additional benefit of comprehensive site capture, such as utilities, adjacent structures, and other unique ground surface features available in photogrammetry.

### *1.2. Total Station*

A total station (TS) is an instrument that is used for surveying that is equipped with an electronic theodolite and an electronic distance meter (EDM) to be able to measure horizontal angles, vertical angles, and distance. This is one of the most traditional instruments used in modern surveying. The values that are recorded with a TS include northing, easting, and elevation. TS's are best suited for measuring with tight accuracies or tolerances, such as buildings for bridges, but can be less accurate with distance [8]. Collecting data with a TS begins with setting up and leveling the total station over a point of known location and elevation. In companion to the total station is a receiver or prism, which is taken to numerous points of interest, leveled, and used to take direction and EDM's from the total station. Some devices, such as the robotic total station (RTS), can automatically sight and capture data on command from the data collector standing with the prism [9]. These measurements are then converted to northings, eastings, and changes in elevation, which are applied to the control point's known position and elevation. The total station is generally regarded to be very accurate, especially with decreased distance [8]. A few factors influence the accuracy of the readings on a total station, and those include temperature, pressure, and relative humidity [8]. These can all be corrected on modern day instruments by adjusting the readings. The general accuracy of total station systems is typically within 1.5 mm (vertical and horizontal) when measuring within 4900 feet.

### *1.3. RTK-GPS*

The GNSS is a radio-based positioning system that utilizes satellites to geolocate a signal [10]. The satellites send positional information, as well as a timestamp, to be able to calculate the position of the signal, but the use of three or more satellites is often used for increased accuracy. The GPS is a constellation of the GNSS owned by the United States, and controls certain satellites. Real-time kinematics (RTK) is a technology used in satellite positioning that uses a base station to connect to multiple satellites to pinpoint their location. The RTK-GPS may receive its information from a base station in one of two ways: a local base unit or service station. The former of the two is more frequently used on long-term job sites or earthwork monitoring. A rover is also used in conjunction with the base station to position itself in the field. The base station will send the rover corrections on the positioning data to bring the accuracy down within about an inch. The operator can command data from the base station with precise positioning and elevation. The baseline is the distance between the rover and the base station, and it is considered very accurate when the distance is less than 12.42 miles (20 km), as ionospheric and tropospheric signal refraction and orbit error can influence accuracy [11]. This system is not well-suited for urban areas where signals may be interrupted and may affect accuracy, and a TS used in conjunction with RTK is suggested for this situation [12]. Atmospheric conditions may also interfere with the accuracy of the GPS [13]. Both the TS and RTK-GPS methods are typically used to gather point data in a grid pattern, where a surface can be generated by interpolating the data. The general accuracy of RTK-GPSs is within 0.62 inches horizontally and 1.25 inches vertically.

### *1.4. Photogrammetry*

Photogrammetry involves the use of multiple photographs from different perspectives to create a three-dimensional model of the region of interest [14]. The photographs share common points of interest, which are processed through an algorithm that results in the spatial position of these points. Prior to processing, additional control data may be added to the image stack, such as the positional data for known control points, to derive the initial estimates [15]. This allows for the estimation of error and a coordinate system to be embedded in the model for increased accuracy. The reprojection of these points into three-dimensional space is dependent on the lighting conditions in the photographs, as more uniform lighting results in lower reprojection error [16]. The product of the image processing is a dense point cloud that can be analyzed as a surface with "x, y, z" data across the entirety of the area. The photos used to create 3D spatial data can be taken from land (terrestrial photogrammetry) and air (aerial photogrammetry), and video cameras may be used as well. Both terrestrial and aerial methods are explored in this study and analyzed for their accuracy and efficiency.

### *1.5. Previous Studies*

The accuracy of the photogrammetric method has been tested against different survey techniques in recent studies. An RTS was compared to a close-range photogrammetric method for the volume calculation of an excavation, where the photogrammetry measured 30.012 $m^3$ when compared to the real volume of 32.054 $m^3$ (93.63% accurate) and yielded nearly the same accuracy as taking measurements with the RTS at 40 cm intervals [17]. One study demonstrated that an in-house developed UAV system used for stockpile volumetric surveys achieved positional accuracies and volume measurements comparable to conventional GNSS RTK surveys, with results showing a 0.7% agreement in stockpile volume and high repeatability and detail, sufficient for 1:200 scale mapping and 0.145 m contours [18]. Baseline Surveys Ltd. conducted a study to evaluate the precision of their drone-based photogrammetry. They compared the measurements from their unmanned aerial vehicle (UAV) to data from 45 checkpoints measured using an RTK-GPS. The results showed that the UAV photogrammetry was reliably accurate to within 41 mm horizontally and 68 mm vertically, with a ground sampling distance of 1 cm [19]. UAV photogrammetry has proved to offer a more labor and cost-efficient survey method when compared to RTK-GPS surveying due to the increase in data density and quality in a study performed in the Central Lydia archaeological survey in western Turkey [6]. In a comparison between analytical aerial photogrammetry, GPS, laser scanning, and total station surveys, it was found that the latter two represented the most efficient and precise methods for obtaining accurate digital terrain models [20]. A study involving the collection of 2950 control points via GNSS-RTK was compared to digital terrain models created using low-cost drone survey equipment with photogrammetry, where the root mean square errors (RMSEs) of the models were about 5 cm [21]. Another study focused on flow-regulated stormwater ponds compared UAV photogrammetry and airborne-LiDAR for surveying these ponds with respect to RTK-GNSS in situ observations, finding that UAV photogrammetry outperformed in wet ponds, provided acceptable results for dry ponds with corrections, and delivered high-resolution break-line features, suggesting multi-UAV collaborative photogrammetry as a cost-effective solution for large urban surveys [22].

Many previous studies have aimed at comparing terrestrial or aerial photogrammetry with LiDAR (light detection and ranging) systems in terms of accuracy and cost due to both of their abilities to output a DEM. A study conducted over a 4-hectare forest area in Germany found that UAV-based photogrammetric data closely matched airborne LiDAR data, with UAV data providing more detailed results, particularly in small tree detection, missing only 14 trees compared to 45 missed using LiDAR [23]. Another study demonstrated that both UAV-based airborne laser scanning (ALS) and structure from motion (SfM) photogrammetry could effectively measure and monitor forest structural properties, with ALS providing more accurate terrain and canopy data in dense forests, while SfM served as a cost-effective alternative, despite some limitations in dense canopy conditions [24]. A 2020 study evaluated the accuracy of digital surface models (DSMs) produced from four different unoccupied aerial systems (UASs) using photogrammetry, comparing them to a high-precision LiDAR-based DSM, finding that while UAS DSMs had RMSE values between $\pm 0.03$ and $\pm 0.06$ m, discrepancies in vegetated areas and outside ground control point coverage highlighted LiDAR's superiority in complex terrains [25]. Another accuracy comparison study compared elevations from mobile-terrestrial LiDAR, aerial LiDAR, and UAV photogrammetric data to conventional survey methods for roadway design, finding that aerial LiDAR provided the closest match, while mobile-terrestrial and UAV photogrammetric data were more accurate on road surfaces and level terrain, with a cost comparison highlighting the efficiency and cost-effectiveness of these remote-sensing methods [26].

Other research has aimed at using a UAV photogrammetric system in tandem with the RTK positioning of a UAV to analyze accuracy with varying parameters. A study performed in a forest area in western Turkey compared UAV-based RTK and PPK methods for accuracy in camera positioning and georeferencing, finding that RMS errors varied significantly by surface type, with the lowest errors on solid textures and emphasizing that the mean RMS error across surface types can be misleading [27]. A study in Taichung city assessed the accuracy of image data collected using a UAV system that utilized GNSS RTK and three-dimensional ground control points for urban land use mapping, finding that the use of ground control points significantly improved accuracy, with models without ground control points showing up to 40 cm error in two dimensions and 1 m in altitude, while models with ground control points achieved centimeter-level accuracy [28].

However, none of the studies reviewed above considered a comparison between terrestrial photogrammetry, UAV photogrammetry, and the RTK-GPS in terms of efficiency, accuracy, and disk capacity requirements. In other words, this research aimed to analyze three separate survey techniques for the same purpose of general order land surveying and identify which method is the most efficient and accurate for this size of survey. This study also features the use of the novel Looq scanner, which is absent from any previous studies.

## 2. Materials and Methods

### *2.1. Study Sites*

Marathon Construction Corporation provided two sites in San Diego, California, to be surveyed for this study [29]. The first site was in the San Dieguito Wetlands in northern San Diego, just off the I-5 freeway, where a restoration project was underway. This site was chosen due to the control points being already established in the general area, as well as ease of access, little vegetation, ample line of sight, and firm ground above the water's edge. During the preliminary analysis, data points were planned to be collected over an area of about 0.72 acres ($450' \times 70'$). The second site that was provided for the study was a vacant lot in Lakeside, CA, approximated to be 0.42 acres ($220' \times 80'$). It was located adjacent to Riverford Road in Eastern San Diego; this area was sparsely populated with small vegetation and allowed ease of access and movement around the site. The control points for this site were recently established just adjacent to the northeast corner of the lot, so this site was also chosen due to the ease of visibility to the control location. Both study area locations are shown in Figure 1 and are seen in closer detail in Figure 2. The coordinate projection used in this study was California State Plane Zone 6. The North American Datum of 1983 (NAD83), used by North and Central America, was the horizontal datum used in this study for the positions of the measurements. The vertical datum for this study was performed as National Geodetic Vertical Datum 29 (NGVD29), measured in US feet. The NAD83 and NGVD29 data were used as reference frames for the projected coordinate system. The study areas did not necessitate the use of an Earth curvature correction factor, as they were both so small that the correction was be negligible.

**Figure 1.** Map of San Diego with the survey site locations.

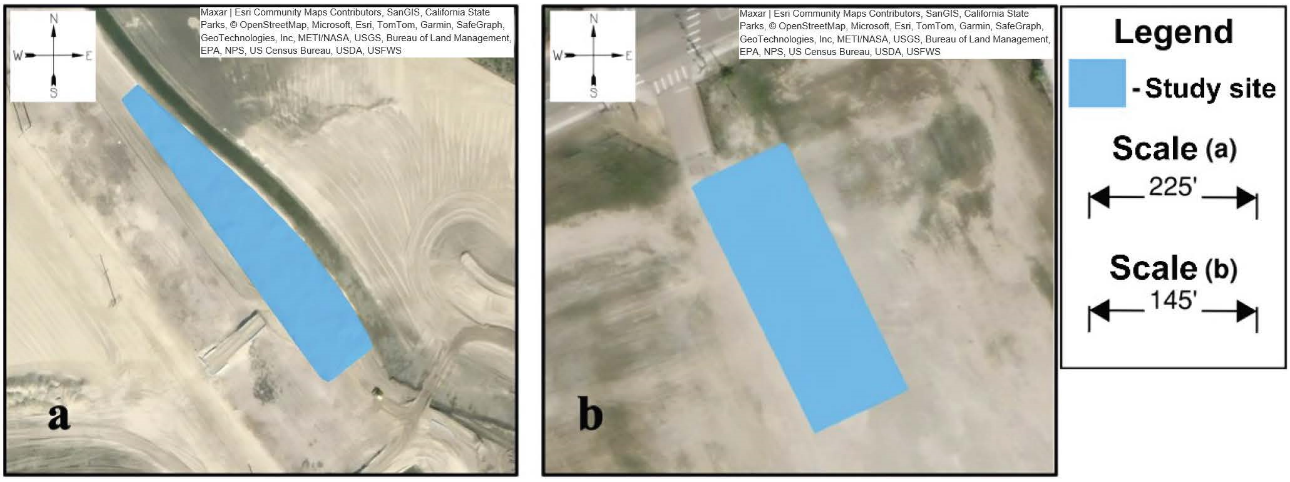

**Figure 2.** (**a**) San Dieguito survey site and (**b**) Lakeside survey site.

### 2.2. Study Equipment

The TOPCON DS-101AC total station and TOPCON FC-500 controller were used to capture the TS data at both sites, displayed in Figure 3a [30]. The DS-101AC unit had a telescope magnification of 30× and a prism EDM range of about 3.73 miles, well beyond the requirements for this study. This surveying system can be operated remotely via the operator of the FC-500 controller, as was performed in this study. The RTK-GPS was used to establish control for the TS collection at San Dieguito since the control points for this job site were very far and few [31]. The error in angular measurements using the electronic theodolite was stated to be within 1″ (second), and the EDM measurements were stated to have an accuracy of 1.5 mm via the product catalog [30]. For the data collection at the San Dieguito site, the TS used the control points established with the RTK-GPS, and Caltrans had established these points during the early stages of construction. In comparison, the data collection at the Lakeside site utilized a recent survey conducted on the property, where there was a control point established across the street on the northeast side of the property. For both sites, the methods of collecting the data were the same. The TS required two control points to automatically position itself in whichever datum the control points were referenced in through a process called "re-sectioning". Grids with dimensions of roughly $10' \times 10'$ were drawn out onto the field controller prior to data collection, which enabled the operator to roughly target a grid of equal pattern. After the measurements were recorded, the TS automatically produced a collection of recordings in the corresponding data of the control points. The Trimble Zephyr base antenna, SPS855 radio receiver, and SPS985 rover were used to collect the data for the RTK-GPS, displayed in Figure 3b [31]. The Zephyr 3 base antenna functions on all GNSSs. This system was already installed and configured at the job site, with the base station and radio installed at the laydown area about a ½ mile southwest of the data collection site. According to the SPS985 rover specifications, the error in horizontal and vertical accuracy was stated to be within 8 mm and 15 mm, respectively. The Trimble GPS can be set to whichever coordinate datum is being used. During the TS surveying, the northings and eastings of each point on the $10' \times 10'$ grid were saved onto the controller for reference using the RTK-GPS. The elevations at nearly the same locations of the TS data were recorded onto the controller in the coordinate datum that it was set to.

**Figure 3.** (**a**) TS equipment and (**b**) RTK-GPS equipment.

The Looq AI scanner was used for the terrestrial photogrammetric data collection in this study and is featured in Figure 4a [32]. The scanner contained four cameras to capture the raw imagery and was connected to the cellular phone of the user to obtain a differential GNSS with streaming corrections. The user of the scanner collected the data in a snake-like fashion, walking in straight lines that spanned about 10 feet apart. The raw images and GNSS information were fed into a custom photogrammetric stack and a bundle adjustment, which is an optimization technique that clarifies the internal and external camera parameters and 3D coordinates estimations at the same time. Multi-station photogrammetry can be described as the measurement of an object in which most or all the regions of interest are pictured in three or more spatially separate photographs, and the bundle adjustment technique is particularly suited for this type of photogrammetry [33]. The product of this processing is a 3D geo-referenced model in ITRF2014, which is the newest realization of the international terrestrial reference system [34] and ellipsoidal heights. Looq performed horizontal and vertical data transformation and epoch shift on their models with automated processing tools to transform the results into NAD83, Epoch 1991.35, California State Plane Zone 6, and NGVD29. This transformation is necessary to be able to analyze and compare the positional data in the same geodetic datums as the RTK-GPS and TS measurements. An 'x,y,z' shift was performed after the transformation by aligning the PK nail seen in the point cloud with the established positional data for that point. The RTK-GPS and TS surveys were based on older benchmarks that were established in recent years, so some error can be expected when comparing them to the positional information recorded in the ITRF2014 geo-referenced model before being transformed. Black and white-coded targets for locating ground control were unavailable for this study, and PK nails with orange tape were used as a substitute. The scanner had a horizontal accuracy of about 2–3 cm with a vertical accuracy of 3–5 cm. When performing terrestrial photogrammetry, the weather conditions were overcast with moderate low-light conditions. This was a hindrance to the photogrammetric analysis as it presented more difficulty in locating the tie points between the images and could have resulted in dampened RGB values for the post-processed point cloud. The UAV photogrammetry utilized the DJI Air2S drone to capture aerial photos from a height of 98 feet. The DJI Air2S drone can be seen in Figure 4b. The overlap in images taken using the DJI Air2S was about 89.2%, corresponding to 39,162 square feet of overlap to triangulate the data points. Figure 5 displays the cross-hatched flight path that was programmed to fly the DJI Air2S drone at a speed of 17.7 feet per second, taking 1 picture per second. Using the Litchi for DJI Drones version 2.14.3 for iOS devices, the flight path was preprogrammed to fly in a cross hatched pattern over the survey site at the desired speed and altitude [35]. The DJI Air2S drone used a ground sampling distance of 0.13 inches. The weather conditions during the flight of the drone were clear and sunny, providing the most vivid point cloud possible. It is worth mentioning that the reason for the absence of varying parameters for UAV photogrammetry was to focus on the comparison of the methods generally rather than to find the most accurate and efficient parameters for solely UAV photogrammetry. The capture rate, altitude, and speed that were used in this study were pre-determined to be an accurate representation of the use of a UAV for this type and size of survey.

**Figure 4.** (**a**) Looq scanner and (**b**) DJI Air2S drone.

**Figure 5.** DJI Air2S flight pattern at the Lakeside site.

### *2.3. Data Analysis*

Part of the data analysis was performed in ArcGIS [36], a cloud-based mapping and analysis software used for many different functions, most importantly surface creation and viewing for the purposes of this study. The inverse distance-weighted (IDW) interpolation technique was used to create the elevation models for the RTK-GPS data. The fundamental principle of the IDW technique involves predicting unknown quantities, such as elevation, at a specific location by leveraging the values from surrounding known locations. This technique operates on the premise that the impact of these known points wanes as the distance increases. Consequently, points in closer proximity have a greater effect on the value being interpolated compared to those that are more distant. Due to the RTK-GPS coordinates being slightly deviated from the original TS coordinates, the created surface model allowed the extraction of the approximate elevations of the RTK-GPS data at the exact location of the TS coordinates. The other analysis tool used was the Looq web application, where the point clouds could be viewed and compared to the imported horizontal and vertical control data. This web application also contains shifting tools in which the point cloud can be relocated to a point of known position and elevation. UAV photogrammetry processing was performed in Agisoft Metashape version 2.1.1 stand-alone software, which created a 3D spatial data set from the images taken on the DJI Air2S drone [37].

The California Department of Transportation (Caltrans) states that for the purposes of general mapping, the LA standard of 0.2 feet (5 cm) is an acceptable tolerance for vertical measurements. When engineering accuracy is not necessary for surveying, this vertical tolerance is used. The TS instrument used in this study outputted the most accurate 6positional measurements compared to the other survey methods (especially when measuring in such a small area of land), and this study used the TS data as the ground truth for the analysis. The RTK-GPS and photogrammetric data were compared to the TS data, and this difference was measured against this Caltrans general order standard of 0.2 feet. In addition to the accuracy of the elevations, the size of the survey data and the length of time taken to perform the surveys were compared between the methods. The time began once the device was calibrated and ready for data collection, and the time ended once the last point was taken. No time was included for the transportation or setup.

## 3. Results

This section provides a detailed comparative account of the results. The associated discussions and interpretations are included in the next section. The TS control points and RTK-GPS topographic mapping of the San Dieguito and Lakeside sites were completed with 365 and 207 points, respectively. These points were imported into ArcGIS and were interpolated using the IDW technique to create a surface elevation model. The spatial analyst tool “Extract Values to Points” within ArcGIS used the desired TS coordinate positions and exported all of the associated elevations of the surface model to a table.

The terrestrial photogrammetry performed with the Looq scanner began at the first control point taken at the corner of the study area and continued in a snake-like pattern until scanning the far side of the study area. These data were processed using Looq's custom photogrammetric stack, transformed from ITRF2014 and ellipsoidal heights into NAD83 and NGVD29 data, and shifted using a control point of a known position and elevation. The shift was performed in the Looq web application by finding the monument located at the control point and shifting it to the known "x, y, z" values. The Lakeside terrestrial photogrammetric survey using the Looq scanner was performed over a much larger area than anticipated due to the original site control monuments being positioned about 90 feet east of the nearest TS recording. This resulted in a much larger data requirement for the processed point cloud file as it expanded the survey area by about two times the original size, as it required us to include the monuments to be able to perform the "x, y, z" shift. This shift was necessary to reduce the positional error between the Looq scan and the TS data, as we were solely focused on the error in elevation for this analysis. The control monument was easily identifiable on the point cloud, and the entire data set was shifted to match the known position of the monument. UAV photogrammetry could only be performed at the Lakeside location, as the use of a drone at the San Dieguito location was unavailable due to ongoing construction.

To process the elevations at every single TS coordinate, Looq was used to process the point clouds to create miniature 3 × 3 DEMs about each TS coordinate based on the input grid size, which was made to be 1 foot. This algorithm then found the average point elevation under the influence of the surrounding points within the input grid size. The elevation information that was extracted using the RTK-GPS and Looq scanner method was compared to the TS control information, and the RMSEs were calculated in Table 1. The time cost and data expenditure are tabulated for both survey methods and locations in Tables 2–4. In these tables, PC disk space represents the amount of memory required by each point cloud file, while DEM disk space is the post-processed digital elevation model file size.

**Table 1.** Survey method accuracy.

| | **Elevation RMSE (ft)** | | |
|---|---|---|---|
| **Site** | **RTK-GPS** | **Looq Scanner** | **DJI Air2S** |
| San Dieguito | 0.0357 | 0.0576 | N/A |
| Lakeside | 0.0565 | 0.0594 | 0.345 |
| Weighted Average * | 0.0432 | 0.0583 | 0.345 |

* Note: the averages are weighted by the number of control points at each location. The elevation RMSEs for the RTK-GPS and Looq scanner are with respect to the TS control as the ground truth.

**Table 2.** RTK-GPS time and data expenditure.

| **Site** | **Data Points** | **DEM Disk Space (MB)** | **Survey Time (min)** |
|---|---|---|---|
| San Dieguito | 365 | 0.647 | 68.8 |
| Lakeside | 207 | 0.342 | 41.5 |

**Table 3.** Looq scanner time and data expenditure.

| **Site** | **Data Points** | **PC Disk Space (GB)** | **DEM Disk Space (MB)** | **Survey Time (min)** |
|---|---|---|---|---|
| San Dieguito | 63,081,981 | 1.60 | 55.71 | 22.4 |
| Lakeside | 245,270,125 | 6.23 | 107.19 | 38.2 |

**Table 4.** DJI Air2S time and data expenditure.

| Site | Data Points | PC Disk Space (GB) | DEM Disk Space (MB) | Survey Time (min) |
|---|---|---|---|---|
| Lakeside | 56,868,837 | 1.66 | 53.85 | 5.3 |

Note: The DJI Air2S drone was added to compare to the other methods in this study after initially only focusing on the RTK-GPS and terrestrial photogrammetry. By this time, the owner of the San Dieguito property had graded the survey area, nullifying any additional analysis of the site.

The DEMs for the RTK-GPS and Looq scanner and the point clouds generated at the San Dieguito and Lakeside sites are displayed in Figures 6 and 7, respectively. The vertical error with respect to the TS ground truth is shown for the San Dieguito and Lakeside sites in Figures 8 and 9. The surface generated using the error in inches between the Looq scanner elevation data and the TS ground truth at the Lakeside site seemed to have a skewed plane, as the error slowly increased from −1.61 inches to 1.20 inches.

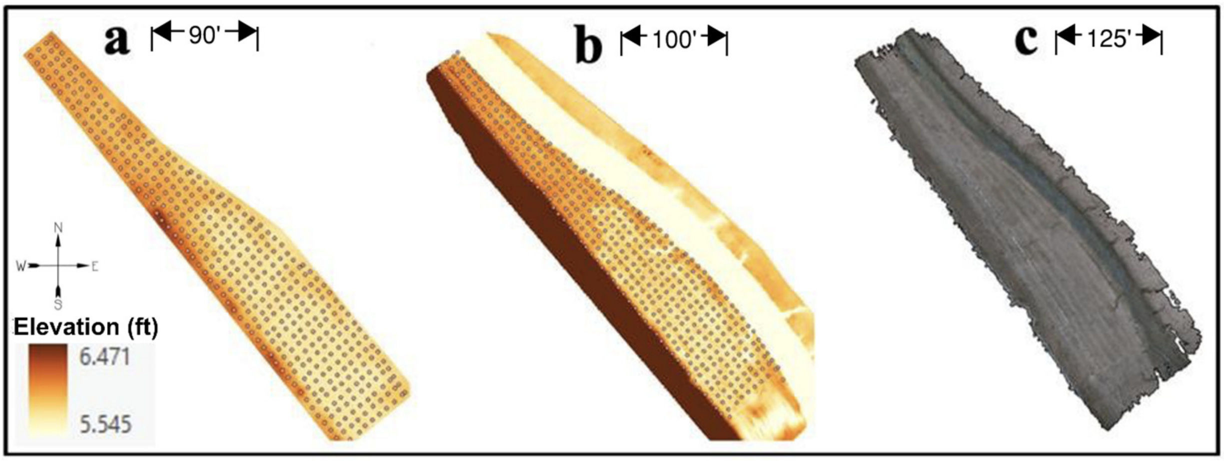

**Figure 6.** San Dieguito (**a**) RTK-GPS DEM, (**b**) Looq scanner DEM, and (**c**) Looq point cloud.

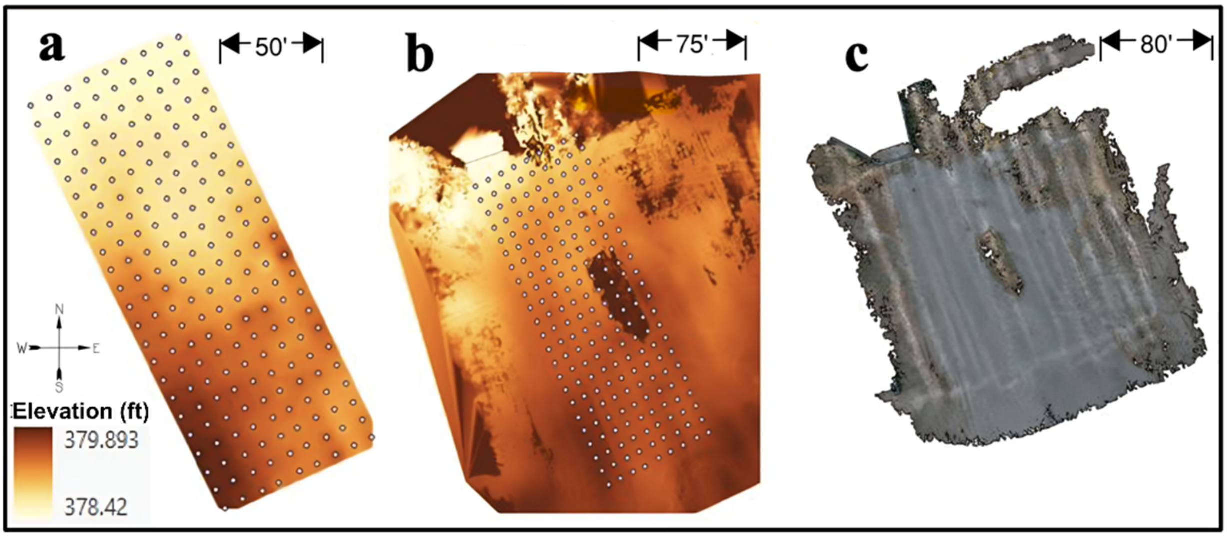

**Figure 7.** Lakeside (**a**) RTK-GPS DEM, (**b**) Looq scanner DEM, and (**c**) Looq point cloud.

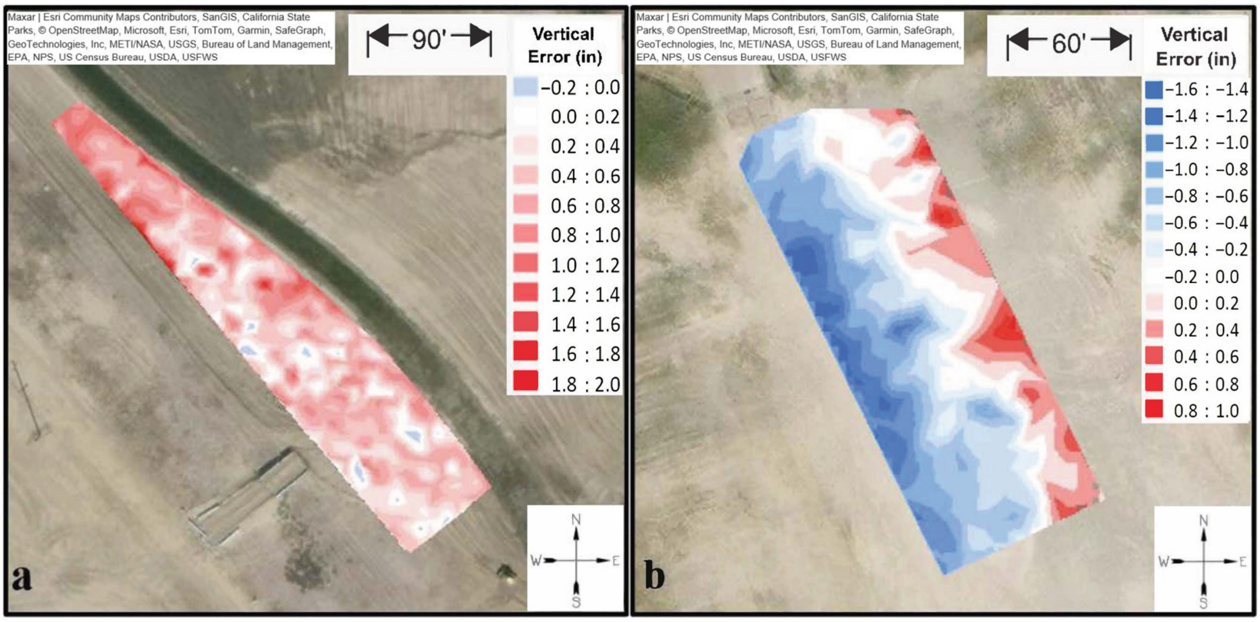

**Figure 8.** (**a**) San Dieguito and (**b**) Lakeside vertical error using the Looq scanner.

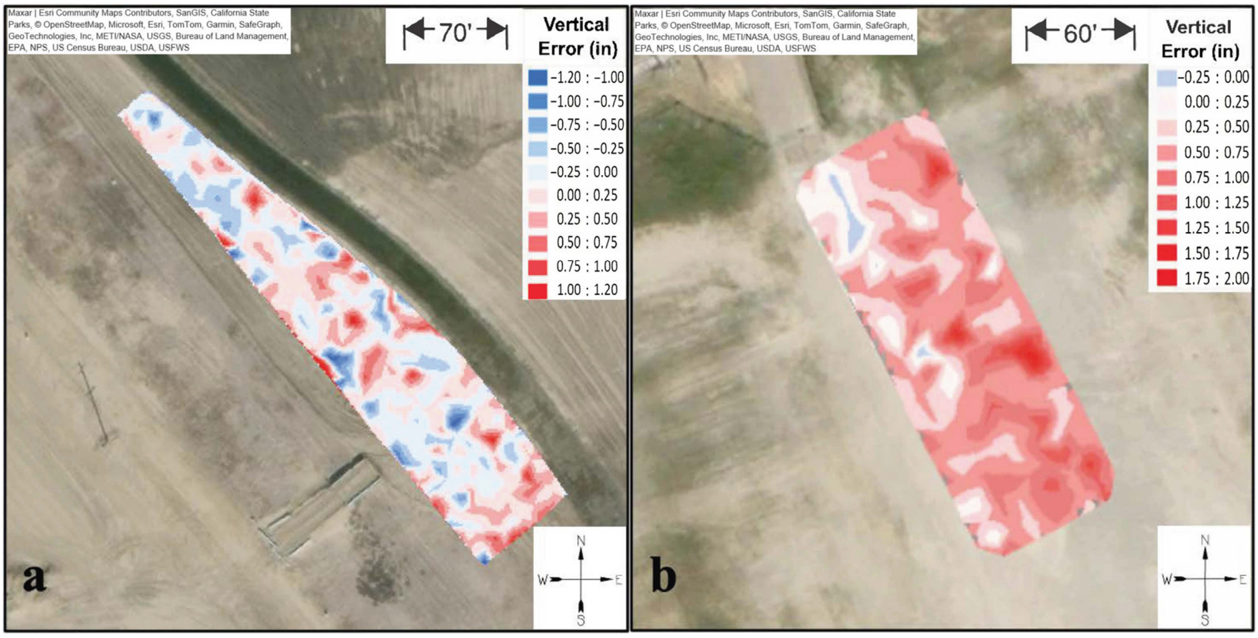

**Figure 9.** (**a**) San Dieguito and (**b**) Lakeside vertical error using the RTK-GPS.

## 4. Discussion

In terms of the analysis of the terrestrial and UAV photogrammetric methods, there are a few key findings in the post-processed point clouds. The cameras on the Looq device were able to capture the surrounding vertical features with much more clarity than the UAV method. For example, the north gate at the Lakeside site was captured in detail using the Looq scanner but was almost not taken into consideration at all using the DJI Air2S drone, as seen in Figure 10. This is a significant advantage when taking vertical, adjacent structures into consideration during a survey, as the Looq scanner can easily and accurately identify objects that are in the immediate area of the site (e.g., utilities, power lines, or fencing).

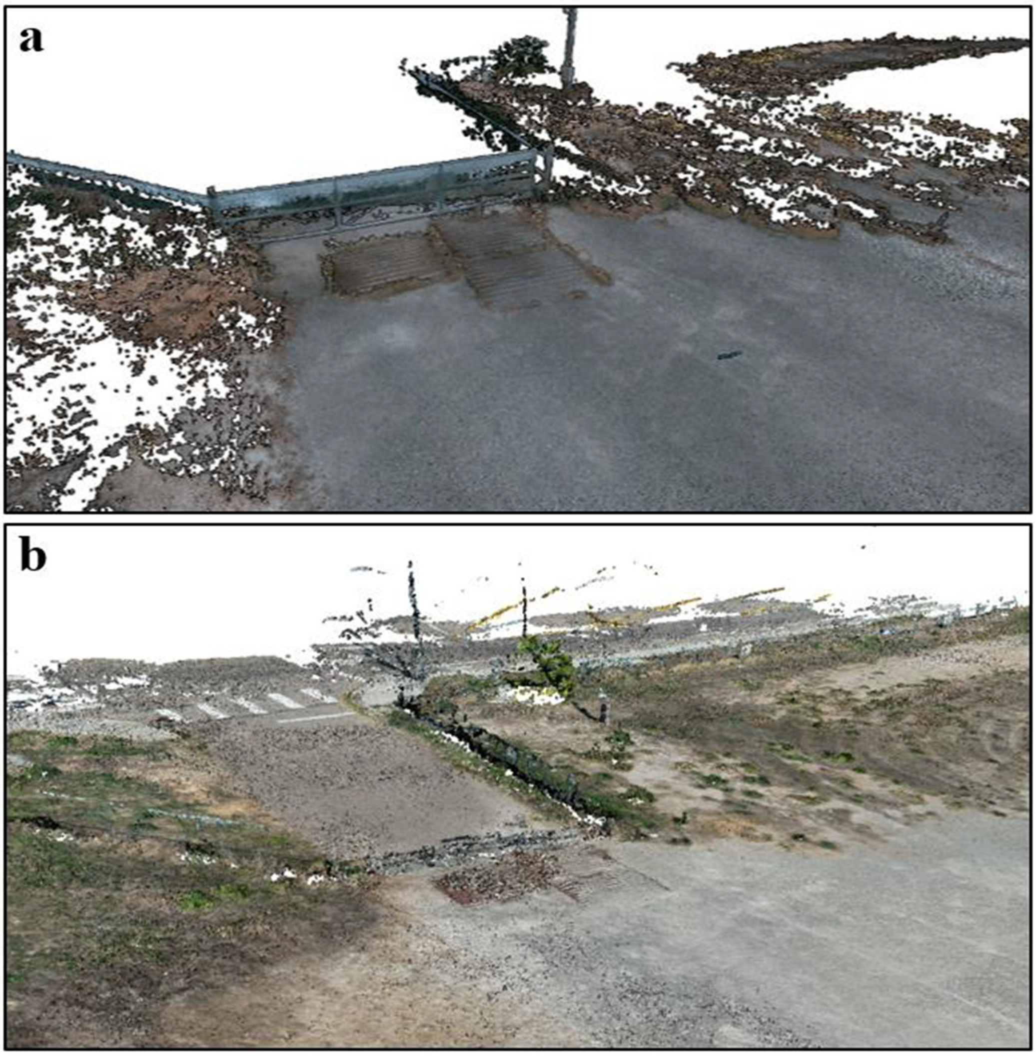

**Figure 10.** Lakeside north gate with the (**a**) Looq scanner and (**b**) DJI Air2S drone.

As the Looq scanner took pictures from four different angles at once from about 4 feet above the ground surface, the product of this method was an extremely dense point cloud that was able to capture much finer detailing of the ground surface. The pictures taken with the Looq scanner were processed and contained many more tie points to create a much more detailed point cloud of the ground surface conditions. These detailed conditions can be seen in Figure 11, focusing on the steel grating at the north gate entrance. The Looq scanner was able to clearly define the rise and fall of each step in the grating, in addition to providing such a dense point cloud that it appeared to be a surface. The DJI Air2S drone captured a much sparser array of points, unable to distinguish the ground surface from the steel grating. The RGB values of the point cloud in the Looq scan allowed the viewer to easily distinguish between the gravel and the steel grating. The differing weather conditions between the terrestrial and aerial photogrammetry can be seen in Figure 8, as the RGB values captured using the DJI Air2S drone on a sunny day produced a much brighter and more vivid point cloud for aesthetic analysis compared to the Looq scanner, which produced a darker range of colors due to the low-light conditions.

One of the most noticeable advantages of using a photogrammetric technique is the clarity in both the point clouds and output DEM of the survey site. The density of the point cloud enables the ArcGIS Pro version 3.1.1 software tools to create an extremely detailed surface model that is suitable for capturing the elevation of any point of interest in the domain of the scan. When compared to the RTK-GPS point-and-shoot technique, the resulting DEM will only increase in detail with an increase in the number of data points collected. One of the disadvantages of the photogrammetric method is the inaccurate portrayal of the ground surface elevation in the presence of objects that are lying on the surface, such as vegetation, whereas the ability of the receivers for the RTK-GPS and TS system to rest on the actual ground surface when recording data eliminates this inaccurate portrayal. This is very evident in the Lakeside scan, where a patch of vegetation significantly increased the error between the photogrammetry and TS results. However, the ability of the Looq scanner to capture this vegetation may be helpful in a study that involves the actual ground conditions of a site rather than the elevation. An unexpected result from the photogrammetry was the widened scanning area around the perimeter of the study area, as the outward-facing cameras on the device could reach distances as far as the Looq photogrammetric stack and bundle adjustment could allow for, which depended on the features surrounding the study area. For example, the Looq scanner captured approximately an additional 10 feet on the west perimeter of the designated survey area at the Lakeside site, with the ground staying primarily flat with no distinct features in elevation, whereas the San Dieguito scan captured approximately an additional 50 feet on the eastern side of the survey due to the elevation change and easily distinguishable ground surface features in the riverbed.

**Figure 11.** Lakeside north gate grating captured with the (**a**) Looq scanner and (**b**) DJI Air2S drone.

Another remarkable capability of both terrestrial and UAV photogrammetric scans is the ability to incorporate RGB values for every single point of captured data. This allows the viewer to be able to see the actual ground conditions in extreme detail as they appear at the time the survey is taken, including the identification of certain types of ground materials. The RTK-GPS method can only obtain positional characteristics for each collected data point.

As shown in Table 1, the RMSEs calculated for both the RTK-GPS and Looq scanner are well within the Caltrans general order survey accuracy of 0.2 feet (about 2.4 inches). The accuracy of the Looq scanner was extremely accurate, as it averaged about 0.70 inches of error when compared to the TS control. This error could have been a result of the data transformation. The NAD83 horizontal datum and NGVD29 vertical datum contained fixed coordinates, meaning that they did not reflect the changes in position due to Earth's tectonic plate shifting. Another potential source of error is the presence of vegetation on the ground surface, inaccurately representing the actual ground elevation for a certain point. In terms of the RTK-GPS inaccuracy of about 0.52 inches compared to the TS control, the potential error sources could be attributed to atmospheric effects and environmental factors since the operating range for both sites between the rover and base stations was very close and within the limits. The DJI Air2S drone averaged about 0.345 ft of error, which did not fall within the 0.2ft Caltrans general order standard. This may be attributed to the lack of numerous ground control points, as well as the absence of any corrected GNSS positions. The incorporation of a real-time or post-processed correction solution to the drone would allow for increased accuracy and would be more comparable to the other methods in this study.

The data collection process using the Looq scanner was much more efficient at capturing data when compared to the RTK-GPS, as the photogrammetric method recorded an average of 5,088,318 points per minute compared to the 5.19 points per minute recorded with the RTK-GPS. The DJI Air2S drone was able to record 10,729,969 points per minute, about twice as efficient as the Looq scanner due to the speed at which the drone was programmed at 17.7 feet per second. One of the causes of this increased efficiency is the ability of photogrammetric processing to obtain position data on thousands of tie points to create a dense point cloud. This increase in efficiency for photogrammetry has the effect of increasing the data expenditure tremendously, averaging about 2.104 GB per acre for the point cloud disk space before being compressed into a digital elevation model using the Looq scanner. The RTK-GPS averaged about 0.867 MB per acre, significantly reducing the digital memory requirement to about 0.04% of the required amount to process the photos in a photogrammetric stack. If the photogrammetric method is sought after with disk space in consideration, the DJI Air2S aerial photogrammetric method should be utilized, as it recorded data at a rate of 0.41 GB per acre, requiring about 80.5% less space than the Looq scanner. However, one would be sacrificing much of the clarity of the point cloud using the aerial method compared to the Looq Scanner.

## 5. Conclusions

Topographic and general order land surveys are distinct in the way that engineering level accuracy is not necessary, although they are extremely important for planning land development, managing irrigation, observing volume changes, and many more functions. The ability to be as accurate and efficient as possible has been the main objective of modern-day surveying. If disk capacity is not a concern for the surveying and mapping of an area of interest, the photogrammetric method utilized in this study should be seen as the superior survey method as it resulted in nearly the same accuracy in a much more efficient manner. The presented paper contributes to the body of knowledge and practice in the field of general order land surveying by collecting and processing real-world data. It provides a detailed comparison of three separate survey techniques (i.e., terrestrial photogrammetry, UAV photogrammetry, and RTK-GPS) in terms of efficiency, accuracy, and disk capacity requirements and identifies the most efficient and accurate approach. Another major contribution of this study is the use of the Looq scanner, which is a very recently developed tool in the market that uses a novel approach to surveying. The results indicate that the photogrammetric approach utilized with a Looq scanner would provide the most efficient and cost-effective survey while staying within the 0.2 foot tolerance of error. This method also allows for the utmost clarity of the resulting point cloud when analyzing the terrain, break lines, or other features in a survey area. In terms of the study limitations, coordinate conversions had to take place to be able to compare the surveys, contributing to the positional error of the data. The use of global coordinates for all survey methods should be preferred in studies building off this work. Further investigations should consider analyzing the difference between arbitrary points on the DEMs created using the survey methods, which should consider the accuracy of the DEM created rather than the accuracy of the specified points collected using the TS or RTK-GPS methods. The use of LiDAR (light detection and ranging) in comparison to these other methods in the creation of DEMs and the accuracy of survey methods should be considered as well. The less dense point cloud resulting from UAV photogrammetry can be further explored by decreasing the elevation and matching that of a terrestrial photogrammetric device to compare the two methods by the quality and detail of the resulting point cloud, as well as the efficiency in terms of the time required to take the surveys. Lastly, the Looq scanner and its ability to identify objects with extreme clarity should be utilized in conjunction with artificial intelligence in future studies to automatically identify break lines, utilities, and other structures that are present in a site scan.

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