LiDAR from drones employed for mapping archaeology – potential, benefits and challenges

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ABSTRACT

Although the use of both drones and LiDAR has become common in archaeology in recent years, LiDAR scanning from drones is still in its infancy. The technological development related to drones as well as laser scanner instruments has gradually reached the point where these can be integrated. In this paper we present the results from a test where the applicability of LiDAR used from a drone was studied. The study had two objectives – both based on comparative studies: i) Whether LiDAR from drones represents an improvement in terms of detection success; and ii) whether LiDAR from drones can increase the quality of the documentation of archaeological features and their physical properties based on remote sensing. A modest improvement of detection success was found, but was not as convincing as one would perhaps expect given the relatively large increase in terms of ground points. This has led us to the conclusion that very dense vegetation obstructs laser beams from reaching all the way to the bare earth. As regards accuracy in documenting archaeological features, the study showed more significant improvements. The last part of the paper is dedicated to a discussion of the pros and cons of using LiDAR from drones compared to conventional airborne laser scanning from aeroplanes or helicopters. The main advantages concern flexibility, low flight altitude and small laser footprint as well as the advantages of a far-reaching field of view. The disadvantages are related to price, battery capacity, size of area and especially the requirement of line of sight between the drone operator and the drone, a fact that restricts the efficiency in terms of mapping large areas. Nevertheless, the final conclusion is that LiDAR from drones has the potential to make a substantial improvement to archaeological remote sensing.

Keywords: LiDAR; drone; archaeological features; detection success; documentation

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Introduction

Aerial LiDAR was introduced to archaeology almost 20 years ago and has since become a widely used tool by those of the archaeological community preoccupied with remote sensing. When the first pioneers started making use of LiDAR data for archaeological purposes around the turn of the millennium, it immediately generated very convincing results, leading some to describe it as a quantum leap for archaeology (Bewley, Crutchley, & Shell, 2005). Nevertheless, some fields of improvement related to archaeological use were identified and, parallel with more general improvements in instrumentation and the technical aspects of airborne laser scanning, the archaeological community contributed to the development of visualization techniques in order to improve the ability to carry out archaeological interpretations of LiDAR-generated images (see e.g. Bennett, Welham, Hill, & Ford, 2012). Other areas of development related to LiDAR data where archaeologists have been engaged include the use of intensity data (Challis & Howard, 2013), and semi-automated detection of archaeological features (Bennett, Cowley, & De Laet, 2014).

Thus, LiDAR has increasingly entered the archaeological remote sensing toolbox, which until recently mainly contained aerial and satellite imagery. Over the last few years, the rapidly growing development of unmanned aerial vehicles (UAVs), or drones, has also attracted the attention of archaeologists, along with a range of other unmanned platforms such as kites, balloons, blimps etc. UAVs are powered aerial vehicles characterized by the fact that they are unmanned and remotely controlled by personnel on the ground (Campana, 2017). Normally, UAVs used for archaeological purposes are launched into the air carrying a camera for the documentation of excavation sites as well as for producing footage placing the excavation into a broader landscape context. Generating 3D models (digital surface models) and point clouds based on photogrammetric methods has become increasingly common, and relatively inexpensive photogrammetry software is now available; software that also has a comparatively low user-threshold. These factors are fundamental to the widespread use of drones and other UAVs in archaeology.

The drone branch of remote sensing is also characterized by a steady technological development that widens the area of utilization, also for the benefit of archaeologists. One of these developments is the possibility to mount LiDAR scanners on drones. So far, platforms used in airborne LiDAR have been either fixed-wing aeroplanes or helicopters, but these latest developments facilitate new possibilities for archaeologists. The wish to execute LiDAR scanning from drones is not completely new, it stretches back at least 10 years (Fantoni et al., 2004), but progress has been slow since it has been hampered by two important factors: weight and power (Charlton, Coveney, & McCarthy, 2009; Wallace, Lucieer, Watson, & Turner, 2012). Initially, LiDAR instruments were too heavy and therefore exceeded the payload of the UAVs. In addition, obtaining sufficient power to run the drone, the scanner and the positioning systems was an obstacle. In forestry research, experiments using UAV-borne LiDAR started around 2010 (Wallace et al., 2012), and in the ensuing years UAVs and LiDAR instruments were developed for use by various other industries and sectors. This now offers a potential use for archaeological purposes.

Recently, a test was carried out in Norway where a wooded area with a range of different archaeological features were laser-scanned from a drone. This is a pioneering project, although not the only one where LiDAR from drone has been tested on archaeological objects (see Campana, 2017). A main reasoning behind our test is that flying at a low altitude with drones will ensure small footprints and therefore better vegetation penetration abilities and consequently improved detection success.

In order to study the outcome of drone-based scanning, previous studies and existing LiDAR data were included for comparison. This included an experimental detection success study from 2011, aimed at analysing the effects of pulse density and digital terrain model (DTM) smoothing. Here, four archaeologists with extensive LiDAR experience interpreted DTMs generated from LiDAR data with point densities of 1, 5 and 10 p/m^2, each with three different levels of DTM smoothing. The data were from a scanning conducted in 2007. Prior to the experimental study, the area was systematically surveyed for cultural remains by field walking and reconnaissance, resulting in the mapping of 334 archaeological features. The study revealed that there was a significant improvement in the detection success when the point density was increased from 1 to 5 p/m^2. It also showed an improvement when increasing the point density further from 5 to 10 p/m^2, but that this improvement was less pronounced. Regarding the DTM smoothing, the results showed that smoothing did not have any significant effect on the detection success (Bollandsås et al., 2012).

At the beginning of the 2000s, a resolution of 0.7 p/m^2 was set as the standard data quality in forestry before becoming the industry standard in much of the data acquisition in Norway in general. The aim of this standard was to increase map quality, especially regarding height-above-datum improvements. Thus 0.7 p/m^2 data have been collected from extensive areas in several municipalities over the years. In 2015, a national coverage campaign aiming for 2 p/m^2 was launched and is still ongoing, continuously producing new data from still larger areas. All data collected by the authorities are publicly available and free to download and use. This means that archaeologists working within the management sector in Norway, most of whom are affiliated with county municipalities, have these data at their disposal and use them on a regular basis in land-use planning. The access to these data also includes the academic world at universities, research institutes etc., which is naturally important in terms of carrying out further research and development.

The objectives addressed in this paper are: what is the added value of using UAVs as platforms compared to aeroplanes/helicopters when attempting to identify and map archaeological features? What are the advantages and disadvantages in terms of precision, resolution, detection success, price, practical issues and area size?

1 Methods and Results

In July 2016, a forested area measuring 1.9 km^2 and situated just north of Oslo Airport was laser-scanned using a Camflight X8HL drone carrying a Riegel VUX-1 LiDAR scanner (Figure 1 and Figure 2).[2] The weight of the scanner was 3.5 kg, and the total weight of the drone, scanner, camera, parachute and battery pack was 24.79 kg. The flight altitude was 120 m above ground and the moving speed 6 m/sec. The target pulse density was set to 260 p/m^2, which in reality resulted in 170 p/m^2 and a total of 421,139,544 laser points following post-survey processing. A classification of the data in off-ground and ground points, respectively, resulted in a ground point data set of 42,117,910 points and an average ground point distribution of 22 p/m^2. The accuracy of the DTM is approximately 2 cm in XYZ. The laser beam footprint was assessed to be 60 mm. Increased flying altitude will lead to larger footprints, and accordingly, the laser beam footprint will be 250 mm when flying the scanner 500 metres above ground level, and 500 mm if the altitude is increased to 1,000 metres (Riegl, 2017).

Figure 1. Map showing the drone-scanned area, which is partly situated in Eidsvoll municipality and partly in Nannestad municipality, approximately 50 km north of Oslo. The northern part of Oslo Airport Gardermoen is seen approximately 4 km south of the drone-scanned area.

Figure 2. The drone in action during the mapping of the study area. Photo: Geomatikk Survey.

The particular area for the test was chosen based on the fact that parts of the same area were used in the aforementioned 2011 study. As mentioned above, this previous test was related to various aspects of detection success when using LiDAR data for identifying cultural features in forested areas (Bollandsås et al., 2012, Risbøl et al., 2013), and the area was systematically field-surveyed in 2010 in order to establish a complete ground-truth reference data set.[3] This covers two parts of the drone-scanned area and was also utilized in the present study (Figure 3).

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[2] The basic metadata used here is taken from: Rapport om droneskanning for NIKU. Prosjekt Hurdal/Eidsvoll. Geomatikk Survey AS, juli 2016.

[3] Further information about the study area is found in Risbøl et al. 2013.

Figure 3. The area scanned from a drone in 2016 and the systematically field-surveyed areas from 2010. The archaeological features mapped during the field survey are indicated in green.

The approach used in the present study was twofold, where the results from the high-resolution drone scanning were partly a) compared with the results from the detection success study mentioned above, and b) compared with two data sets from previous general LiDAR campaigns: a 0.7 p/m^2 data set from 2007 and a 2 p/m^2 data set from the 2015 national LiDAR coverage project respectively (Table 1 and Figure 4).

1.1 Assessing the feature detection rate

For the present study, a part of the 2011 study area measuring 0.65 km^2 and comprising a total of 90 archaeological features was chosen. Thirteen of the features were not identified at all by any of the four test persons during the 2011 study, regardless of the resolution of the interpreted DTMs. In order to investigate whether a DTM generated from the drone scanning data would provide a better basis for identifying these difficult cognizable archaeological features a comparison was made. A DTM with an average of 22 p/m^2 was prepared and subsequently studied visually in Quick Terrain Modeler, a 3D point cloud and terrain visualization software package.[4] The same software was used in the 2011 study. Quick Terrain Modeler allows the interpreter to carry out real-time manipulation of LiDAR-generated 3D models. This includes navigating the model, shifting the light angle and direction, exaggerating the elevation, making digital cross-sections of potential anomalies etc. In none of the studies were the range of now available and commonly used visualization techniques used and the interpretations were solely based on plain hill-shaded images. This makes the present LiDAR from drones study comparable with the 2011 study.

The 13 features completely omitted in the 2011 study consisted of six house foundations, two charcoal pits and five charcoal kilns. When an interpretation was made of the UAV LiDAR-generated DTM it was possible to identify four of these features (Table 2). As the figures in the table also show, there is a considerable difference in terms of the number of ground points when comparing the 2011 data set with that of 2016. A multiplication factor was calculated for each of the 13 archaeological features by dividing the number of ground points from the 2016 scanning with those from the 2007/10 scanning. This was done in order to make the figures comparable. The number of ground points differs from feature to feature and varies totally from a multiplication factor from 1.2 as the lowest to 24.9 as the highest, and with an average of 12.9. However, the increase in the number of ground points does not seem to be the sole factor in explaining why four of the omitted features from the 2011 study are visible in the LiDAR-from-drone-generated DTM (Table 3). The four features have a multiplication factor ranging between 3.6 and 19.3, with a 10.6 average and thus below

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[4] www.appliedimagery.com

the total average. The multiplication factor of the nine features that are still not visible despite the increased DTM resolution is within a range from 1.2 to 24.9, with a 13.9 average multiplication factor.

Figure 4. a = 0.7 p/m², b = 2 p/m², c = 10 p/m², d = 22 p/m². Black circles = charcoal kilns, red circles = grave mounds, yellow circles = charcoal pits.

1.2 Assessing accuracy of feature description

The second objective in this study was a comparison between the LiDAR-from-drone-generated model with two widely available data sets: a 0.7 and a 2 p/m² data set.

The comparison we have pursued in part two of the study is related to the quality obtainable in terms of documentation of cultural features identified by remote sensing. Unlike the identification of features, documentation is about recording and describing the specific features and their main physical properties. What is the accuracy of this compared with measurements taken on location? In other words, this part of the study highlights the effect of increased point density on the ability to retrieve more detailed information about the identified and mapped archaeological features. This was done by comparing field surveys carried out in 2010 with indoor computer-based digital measurements using the 0.7, 2 and 22 p/m² data sets, respectively.

The archaeological features used in this part of the study were eight grave mounds and 13 charcoal pits; thereby representing both convex- and concave-shaped features. Analyses were made based on the diameter and height of the grave mounds plus the diameter and depth of the charcoal pits (Table 4). The fieldwork measurements were set as the template with which the digital desk-based measurements were compared. When the computer-based digital measurements were carried out, each archaeological feature was measured in the same compass direction from the one resolution to the other in order to make the figures comparable.

The comparison study shows that the measurements vary considerably (Figure 5a, b, c, d). It is quite clear that accuracy increases with increased point density. Basically, this trend is clear, although some deviations exist, but these are few and the overall picture is clear. This is further illustrated in Figure 6, which shows the average accuracy variation.

Figure 5a, b, c, d. These graphs illustrate the variations between the measurements of the archaeological features. The straight horizontal line is the field measurements and the other lines indicate the deviations from these.

Figure 6. The average variation of accuracy. What is shown is the deviation from the field measurements. 1 = diameter grave mounds; 2 = height grave mounds; 3 = diameter charcoal pits; 4 = depth charcoal pits.

As shown in Table 5, the ability to estimate dimensions of both grave mounds and charcoal pits is high when considering the drone data, where the average measurements are distributed around 90% accuracy compared with the field measurements. Except for the diameter of the grave mounds, the accuracy concerning 2 p/m^2 data falls to just below 80%. This decrease is maintained and reinforced regarding the lowest resolution although in unequal degree, as the numbers are better for mounds than for pits.

2 Discussion

The results observed through this study need to be explained and discussed. The expectations that a significant increase of point density combined with narrow footprints would generate high resolution DTMs of such a quality that the detection success would improve substantially was only partially fulfilled. The study has proven a slight, but by no means decisive increase in terms of detection success. It seems that the trend shown in the 2011 study (Bollandsås et al., 2012) is confirmed. That study showed that the effect of increasing point density is most pronounced from 1 to 5 p/m^2 but that it diminishes from 5 to 10 p/m^2. The present study shows a similar gentle increase to 22 p/m^2. It seems the positive effect of flying at low altitude with drones and thus collecting ground points with narrow footprints as compared to the use of fixed-wing aeroplanes or helicopter platforms, does not occur to any great extent. One likely explanation for this might be that certain types of low shrub vegetation are very dense and thus impenetrable regardless of target pulse density and size of footprints. The data were collected in August/September and July, respectively which makes them comparable in terms of season. The intersection between resolution and types of vegetation when generating DTMs for archaeological purposes are well-known issues, and often mentioned when archaeologists report their results. This is mainly discussed in relation to LiDAR projects in forested areas (Doneus, Briese, Fera, & Janner, 2008). Crow, Benham, Devereux, and Amable (2007) published an elaborate study, showing how woodland canopy and understorey vegetation affect the ability to interpret DTMs for archaeology. When laser-scanning woodlands, large parts of the laser pulses are reflected from the canopy or lower parts of the trees, while some parts reach all the way to the ground. When LiDAR is used for archaeological purposes, we obviously want as many ground points as possible in order to generate high-resolution DTMs. The quality of the terrain model depends on the number of points that actually hit the bare ground. LiDAR data are usually classified in off-ground and ground points, but this part of the data processing is more complex than it might look at first sight. Algorithms are used, which successfully filter data with a high degree of reliability when the difference between the first and last pulse is high. If the difference is low, for instance between the top of shrub vegetation and the ground surface, the reliability of the filtering drops. So, although one of the most important advantages of LiDAR compared to other remote sensing techniques is its vegetation-penetrating abilities, vegetation can in many cases be a significant hindrance. As reported by Crow et al. (2007), vegetation porosity is poorest in areas with dense conifer vegetation in terms of tree types, and in areas with tall understorey vegetation like bramble and bracken fronds. These two types are incidentally mutually exclusive, as very dense canopies will prevent any understorey vegetation from establishing in the shade on the ground below.

The vegetation in our study area varies considerably, especially in terms of density, but must overall be characterized as relatively open, mixed woodland (spruce, pine and birch) with some coppice, and with an understorey dominated by bilberry shrub. The latter can in some areas be quite dense and with a height of up to 30 cm. Generally, the area is well suited to laser scanning, but the understorey is in some areas so dense and tall that it represents a problem for determining the actual bare ground when the LiDAR data is processed. This most likely explains the relatively poor effect of scanning with high density and small footprints. Irrespective of platform, better results might have been obtained by conducting the laser scanning in the leaf-off season (as with deciduous trees and shrubs), a time where the undergrowth is also sparse. In Norway this limits the survey season to late autumn or early spring in order to avoid snow in the winter season. The drone scanning was carried out in July, and the 2007 data, which is used for comparison under similar seasonal conditions, in August/September. However, it cannot be ruled out that the variations in detection success might be explained by changes in the vegetation cover from one mapping campaign to the next as a consequence of time, since detailed studies of vegetation were not carried out as part of the study. This is a potential flaw, but based on simple visual studies of aerial photos we can state that no marked vegetation change occurred throughout the period in force.

The drone data was processed and classified by the data provider, using their standard processing software Terrasolid TerraScan. This was also done deliberately in order to treat the new data in the same way as the comparison data, since just comparison is the focus of the present study. Detection success might increase if a more thorough processing is carried out by experts with competence in both the use of LiDAR and the mapping of archaeological features in forested areas, with a dedicated view on the purpose of the scanning: to detect as many archaeological features as possible. Also, there is reason to believe that the use of various visualization techniques such as Local Relief Model, Sky View Factor etc. (see Kokalj & Hesse, 2017) would result in the identification of more features. As neither of these was used in the previous studies, such an approach falls outside the scope of this paper. Yet, a next step in future studies utilizing this LiDAR-from-drone data set could be new and improved processing and classification, including the use of different visualization techniques. This would provide a fairer assessment of the potential of LiDAR from drones, based on its own premises.

To sum up this section, the effect of using drones as platform must be characterized as modest in terms of detection success, although some improvement has been shown. These improvements seem to be purely based on what one would expect from increasing the ground point density from 10 to 22 p/m^2, while any immediate effect of smaller footprints is difficult to verify. Collecting high-density data sets is not restricted to drone-based laser scanning but is also obtainable with scanning from fixed-wing aeroplanes or helicopters, as has been demonstrated, for instance, in an Irish example with 64 p/m^2 (Shaw & Corns, 2011) and a Danish example where 45 p/m^2 were collected (Olesen & Mauritsen, 2012).

In addition to vegetation penetration abilities, one of the greatest advantages of LiDAR is its usefulness for mapping human impact in the form of identifying cultural features on a landscape scale. LiDAR provides a method for mapping large and inaccessible areas in a very effective manner. This enables a better understanding of past landscape use and also creates unique possibilities for conducting studies where quantitative calculations are important, for instance in terms of charcoal production, iron production, mining industry etc. In that respect, metric accuracy is important in order to generate a solid basis for one's calculations. This study shows that working with a high-resolution data set provides good conditions for this.

The improvements related to the accuracy of documenting the physical properties of the archaeological features are clearer compared to the detection success. The green line in Figure 5 a–d is generally closer to the horizontal orange line, which shows the field measurements. The average figures presented in Figure 6 speak for themselves. Still, there are some variations and it seems that the positive effect related to measurement accuracy is more pronounced regarding the concave features than the convex ones. Challenges in documenting the depths of archaeological features using LiDAR have been reported earlier and are explained by technical restraints (Risbøl, 2010). A combination of scanner angle, depth of pits and the steepness of their sides might result in an absence of ground points in narrow pits. Flying at a low altitude using a drone might be the explanation behind the most pronounced increase in accuracy; that of measuring the depth of pits as shown in Table 5. The improved measurements can most likely be ascribed to an effect of smaller footprints and consequently an averaging of the echo signal over a smaller area.

Differently to the indoor computer-based measurements, which were done systematically in terms of compass direction, information concerning cardinal points is missing from the field measurements. This might be a flaw, but given the fact that most of the archaeological features are circular we consider that the effect of this is restricted. Thus, we assess that the measurements from the fieldwork constitute a reasonable basis of comparison despite the lack of directional information.

In this part of the study the drone data were compared to data from what are considered to be more favourable parts of the season in terms of vegetation cover. This strengthens the results related to the improvements of measurements accuracy, given the fact that the drone scanning was conducted mid-summer with full vegetation blossom.

The last part of this discussion is about the advantages and disadvantages of using drones as a platform for laser scanning as opposed to the use of fixed-wing aeroplanes or helicopters. Let us start with the advantages. A drone is portable. It is easily transported in a small van and it therefore represents a high degree of flexibility (Figure 7). Our first attempt to conduct the drone survey over our study area was cancelled at the last minute due to a sudden shift in weather conditions. The flying was postponed to the following day, when it was carried out without any problems. This flexibility also makes drones an obvious choice if the area to be scanned is small. In our case the study area was almost 2 km^2 and the flying time needed for full coverage was 57 minutes (29 minutes + 28 minutes, with a landing between the two flights in order to change the battery pack). For such a small operation it seems much more obvious to use a small and much more easy-to-handle platform. Low flight altitude is undoubtedly an advantage compared to aeroplane or helicopter. Even though high point density is obtainable with aeroplanes or helicopters as mentioned earlier, drone scanning offers the possibility of mapping with extremely high resolution. In one case, a point density of 1 500 p/m^2 was acquired for forestry applications using LiDAR from a drone (Mandlburger et al., 2015). Flying at a low altitude should also guarantee a small laser footprint, which was one of the reasons we initiated this test. Although the effect of this was limited in this study, at least in terms of detection success, there is still reason to believe that narrow footprints will allow for more real ground hits and thus provide high resolution DTMs devoid of a larger percentage of shrub than is possible with conventional platforms with higher flight altitudes (Figure 8). If flying low is required but prevented by altitude restrictions, using a drone is an obvious choice with its possibilities for flying much closer to the ground than aeroplanes or helicopters. The scanning of vertical and sloping surfaces has long been considered a challenge in airborne LiDAR. The angle of the laser beam makes it inapplicable for documenting vertical faces of features such as buildings, stone walls, menhirs etc. Drones, with their lower flying altitude, combined with their flexible manoeuvrability, overcome this challenge. The scanning angle used in the present study was 90º (45º to each side from vertical position) but the scanner used makes it possible to scan with a field of view of 330º (Riegl, 2017).

Figure 7. The drone in a small van. Photo: Ole Risbøl.

Figure 8. This segment of the LiDAR-from-drone scanned area illustrates the high resolution of the generated DTM containing a lot of information about human impact on the landscape.

All these aspects show that drones have considerable advantage compared to platforms usually used for airborne laser scanning, but there are also some disadvantages that need to be addressed. The most obvious is the fact that LiDAR from drones is much costlier than scanning from conventional platforms, especially compared with fixed-wing aeroplanes. Many factors influence the cost of a laser scanning mission, such as the size of the area, geographical location, the purpose of the scanning, the time of year, supply and demand etc., but a rough estimate based on our experiences with the commission of many LiDAR projects over the years, indicate that LiDAR from drones is currently 10 to 20 times more expensive as LiDAR from aeroplane or helicopter. This situation is bound to change over time, as more demand for LiDAR from drones will result in more providers and thus more competition. There is also reason to believe that an increased demand for this service will result in more companies developing and selling equipment, an aspect that will reduce investments in equipment and accordingly lower prices. This is a well-known development when new technology is introduced to the market and recognizable from when LiDAR was introduced almost 20 years ago and today. Drone scanning is not suitable for mapping very large areas. Battery capacity is still a restriction, as it only allows for approximately 30 minutes in the air before one must land and change the battery. It is possible to cover circa 1 km^2 in 30 minutes and therefore approximately 15 km^2 in an ordinary working day. In most countries there are regulations demanding line of sight, which means that the person operating the drone must have eye contact with the drone at any time when flying. This limits flying time and range, especially in forested areas where sight is limited by vegetation. Thus, the operator must stand in an elevated spot or move around to find suitable places that allow line of sight. Moreover, drones are more vulnerable to weather conditions, especially strong wind, compared to larger, more stable platforms.

3 Conclusion

The test presented here has given useful experience with the use of LiDAR from drones for archaeological purposes. LiDAR from drones offers a new and very interesting way of approaching remote sensing in archaeology. This is a pioneering test, which has demonstrated that drone scanning is promising but that new studies must be carried out in order to fully understand its real potential. There is still reason to believe that flying at a low altitude will result in better vegetation penetration abilities and consequently improved possibilities for filtering the data in off-ground and ground points – i.e. laser returns from the actual ground surface and not from the top of low vegetation. So far, price is perhaps the most limiting factor, in addition to challenges related to the efficient coverage of large areas. As long as line of sight is legally required in many places, this is probably the most severe obstacle in terms of practical hindrances. However, there is reason to state that the emergence of LiDAR scanning from drone represents an important contribution to archaeological remote sensing and that we can expect a lot of interest in this opportunity in the years to come.

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Table 1. Data acquisition parameters. The 0.7 and the 10 p/m^2 data sets are from 2007. In consequence they are referred to as 2007/0.7 and 2007/10, respectively. The latter is also referred to as 'the 2011 study data set'.

	2007/0.7	2007/10 (2011 study)	2015	2016
Ground point/m2	0.7	10	2	22
Date	April	August—September	November	July
Instrument	Leica ALS50-II	Leica ALS50-II	Leica ALS70	Riegel VUX-1
Platform	Aircraft	Aircraft	Aircraft	Drone
Flight altitude	1350 m.a.g.	790 m.a.g.	1560	120 m.a.g
Pulse frequency (Hz)	78 000	119 000	60 000	550 000

Table 2. The 13 archaeological features that were omitted in the 2011 study compared with 2016 data

Id	Category	Number of ground points 2007/10 scanning (2011 study)	Number of ground points 2016 scanning	Increase number ground point (multiplication factor)	Visible on UAV LiDAR generated DTMs?
38	Charcoal pit	34	123	3.6	Yes
60	Charcoal kiln	90	1047	11.6	Yes
67	House foundation	102	2536	24.9	No
72	Charcoal kiln	332	2778	8.4	No
77	House foundation	55	432	7.9	No
80	House foundation	31	598	19.3	Yes
91	House foundation	97	2126	21.9	No
95	House foundation	48	951	19.8	No
99	House foundation	85	1875	22.1	No
101	Charcoal kiln	520	4074	7.8	Yes
116	Charcoal pit	98	118	1.2	No
123	Charcoal kiln	274	2478	9.0	No
124	Charcoal kiln	358	3700	10.3	No

Table 3. This figure shows the relation between positive and negative detections (Yes/No), respectively, and the increased number of ground points from 2011 to 2016 (multiplication factor)

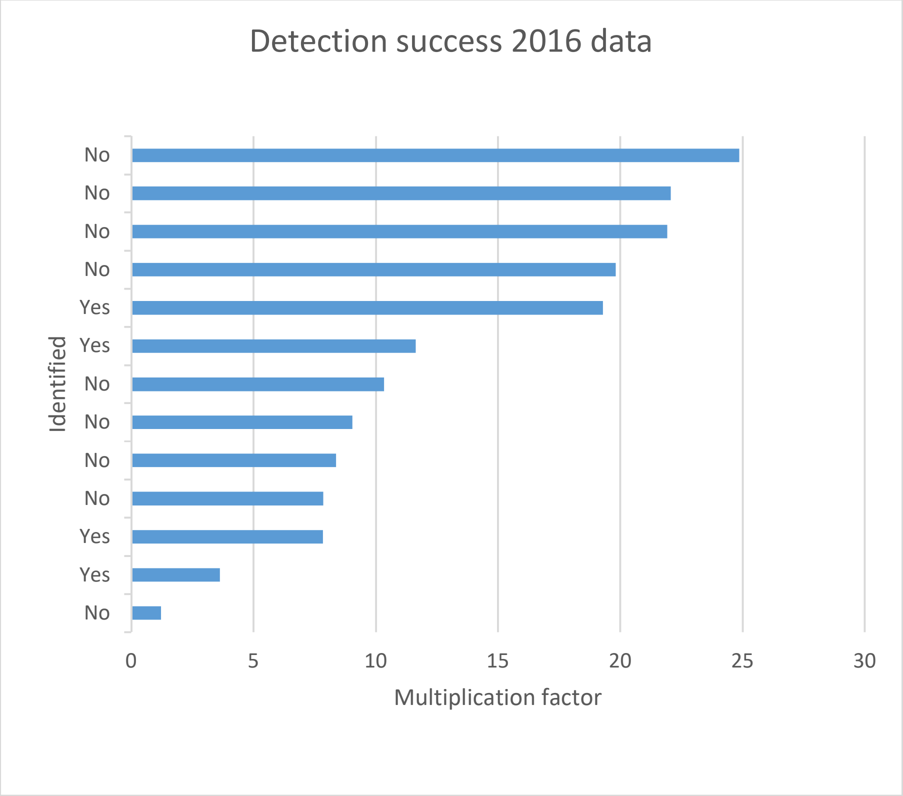

Table 4. The measurements of the archaeological features included in the study

ID	Category	Field diameter	0.7 p/m^2 diameter	2 p/m^2 diameter	22 p/m^2 diameter	Field height	0.7 p/m^2 height	2 p/m^2 height	22 p/m^2 height
5	Grave mound	8	8.9	8.8	8.7	1	0.7	0.9	1
6	Grave mound	11	14.1	12.6	13.2	1.5	1.1	1.1	1.3
7	Grave mound	5.5	7	5.3	5.5	1	0.3	0.6	0.6
8	Grave mound	6	8	7	7	1	0.6	0.6	0.8
22	Grave mound	16.2	16.4	16.9	16.7	1.5	1.4	1.4	1.5
32	Grave mound	12	11.7	10.5	11.3	1.4	0.8	0.8	1.2
33	Grave mound	13	13.2	13.1	12.9	1.6	1.7	1.7	1.6
83	Grave mound	17	18.4	18	17.3	3	2.7	3.2	3
ID	Category	Field diameter	0.7 p/m^2 diameter	2 p/m^2 diameter	22 p/m^2 diameter	Field depth	0.7 p/m^2 Depth	2 p/m^2 depth	22 p/m^2 depth
10	Charcoal pit	6	0	6	6	0.4	0	0.4	0.4
12	Charcoal pit	4.4	5	5.8	6.4	0.4	0.2	0.2	0.4
13	Charcoal pit	4.8	4.9	5	5.1	0.5	0.1	0.3	0.4
15	Charcoal pit	5.2	5	4.8	5.2	0.3	0.2	0.2	0.3
39	Charcoal pit	8.3	0	9.1	9.5	0.8	0	0.8	0.8
54	Charcoal pit	8.3	10.8	0	9.5	0.8	0.5	0	0.8
63	Charcoal pit	11.1	12.6	12.5	12	0.9	0.6	0.9	0.8
65	Charcoal pit	10.6	10.8	11.6	11.1	0.8	0.6	0.9	0.8
97	Charcoal pit	8.8	11.2	9.2	9.9	1	0.6	0.9	0.9
113	Charcoal pit	9.6	14.8	12.5	9.5	0.6	0.8	0.5	0.7
116	Charcoal pit	10.3	0	9.5	9.5	0.6	0	0.5	0.6
125	Charcoal pit	9.7	5.9	9.1	9.3	1	0.4	0.7	0.5
128	Charcoal pit	5.5	0	8.4	6.3	1.2	0	1.2	1.3

Table 5. The average accuracy of measurements in percentage

	0.7 p/m^2	2 p/m^2	22 p/m^2
Diameter grave mounds	85.81	91.46	92.89
Height grave mounds	70.94	77.61	89.05
Diameter charcoal pits	54.95	78.71	89.74
Depth charcoal pits	39.04	76.22	91.07