Journal of Archaeological Science: Reports 35 (2021) 102688

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

The DistoX2: A methodological solution to archaeological mapping in poorly accessible environments

Katarina Almeida-Warren [a,b,1,*], David R. Braun [c,2], Susana Carvalho [a,b,d,e,2]

[a] Primate Models for Behavioural Evolution Lab, Institute of Cognitive and Evolutionary Anthropology (ICEA), University of Oxford, Oxford, UK
[b] Interdisciplinary Center for Archaeology and Evolution of Human Behaviour (ICArEHB), Universidade do Algarve, Faro, Portugal
[c] Center for the Advanced Study of Human Paleobiology, Anthropology Department, George Washington University, Washington, DC, USA
[d] Centre for Functional Ecology (CEF), Coimbra, Portugal
[e] Gorongosa National Park, Sofala, Mozambique

ARTICLE INFO

Keywords:
Low-cost spatial mapping
Point provenience
Archaeological recording
Surveying
Field methods

ABSTRACT

Spatial information is crucial to archaeological field research. From the plane-table to the total station, recent technological advances have enabled data collection to become fully digital and highly accurate. Nevertheless, the recent expansion of archaeological expeditions to novel environments often incompatible with modern mapping equipment, e.g. tropical forests or ephemeral shorelines, calls for further methodological innovations. Such projects, as well as those under logistic or financial limitations, are still largely reliant on more time consuming, less accurate, traditional approaches, e.g. offset or tape and compass methods. The DistoX2 is a digital, highly portable, and versatile hand-held instrument originally developed for speleological surveys where total stations and DGPSs are not feasible. However, the potential of the DistoX2 system as a spatial mapping tool in above-ground contexts has been surprisingly overlooked. Here, we present a first assessment of the applicability of the DistoX2 for archaeological mapping in non-speleological environments. We investigate precision and accuracy in controlled above-ground settings relative to two common methods of data collection – total station, and tape and compass. We test the relative precision of the DistoX2 when mounted on a tripod or operated in hand-held mode and discuss its applicability, and potential combined used, in the context of other increasingly popular methods – GNSS and SfM photogrammetry. With a mean error of ≈5.00 cm for horizontal readings and ≈2.00 cm for vertical readings, the DistoX2 is considerably more accurate than the tape and compass method (μ ≈ 67.00 cm horizontal; μ ≈ 3.00 cm vertical). While the DistoX2 exceeds the error thresholds of projects that require high spatial sensitivity (e.g. Palaeolithic excavations), it provides a reliable, low-cost and more accurate alternative to many projects that resort to more traditional methods. This fills an existent methodological and financial gap amongst the growing diversity of archaeological expeditions.

1. Introduction

Spatial mapping has been a key component of archaeological research and documentation for over 100 years (Wheatley and Gillings, 2002). It helps determine the spatial relationships between archaeological objects and features, and the stratigraphic contexts in which they are found, crucial for the interpretation of an archaeological site or assemblage and its possible relationship to others (McPherron, 2005).

While mapping techniques in accessible urban or open environments are well established, it is not standardized throughout all archaeological settings – ranging from highly accurate total station systems, to analogue tape and compass methods. The pursuit of a universal methodology, compatible with all archaeological environments, has become more urgent in the last decades, as archaeological research expands to the exploration of cave sites, tropical forests and non-human primate records (Haslam et al., 2009; Mercader, 2002a,b, Trimmis, 2015, 2018; Carvalho and Almeida-Warren, 2019). The challenges of these new environments, particularly in terms of accessibility, have made the

* Corresponding author at: Primate Models for Behavioural Evolution Lab, Institute of Cognitive and Evolutionary Anthropology (ICEA), University of Oxford, 64 Banbury Rd., Oxford, OX1 6PN, UK.
E-mail address: katarina.almeida-warren@anthro.ox.ac.uk (K. Almeida-Warren).

[1] This is the main author and contributor.
[2] These authors contributed equally to this work.

https://doi.org/10.1016/j.jasrep.2020.102688
Received 26 June 2020; Received in revised form 9 November 2020; Accepted 20 November 2020
Available online 28 December 2020

implementation of many modern archaeological mapping methods unfeasible, thus limiting the potential of comparison across different datasets.

Mapping in the pre-digital era was achieved using a variety of methods and tools such as the plane table, the manual theodolite, or varying combinations of measuring tapes, levelling aids, and a compass (Dibble, 1987; Historic England, 2017; Wheatley and Gillings, 2002). While some of these methods are still used today, technological developments in engineering and Global Navigation Satellite Systems (GNSS) in the last decades have revolutionized the speed, accuracy and automation of mapping techniques, evolving from simple analogue approaches, to fully digital total station theodolite (TST) systems, and, more recently, to Real-Time Kinematic (RTK) GNSS, terrestrial laser scanning (TLS), and photography-based surveys, such as Structure from Motion (SfM) photogrammetry (Dibble, 1987; Jo and Hong, 2019; Kjellman, 2012; Martínez-Fernández et al., 2020; McPherron, 2005; Pearson et al., 2015; Roosevelt, 2014; Willis et al., 2016).

However, archaeology in extreme or poorly accessible environments, such as underground cave systems with narrow passages and densely forested landscapes with difficult terrain, has until recently been largely limited to the tape and compass method (Almeida-Warren et al., 2018; Trimmis, 2018). Also known as the distance-azimuth method, it typically involves the use of one measuring tape to measure the horizontal distance between a fixed reference point (datum) and the object of interest, a second tape to measure the vertical distance between the first tape and the object, and a compass to determine the direction of the object from the datum relative to North (Carvalho and Almeida-Warren, 2019). An alternative method (tape-compass-clinometer) measures the direct distance between the datum and the object, replacing the second tape with a clinometer to determine the inclination of the first tape (Ballesteros et al., 2013; Redovniković et al., 2014). While highly portable and effective, these methods lack the precision of more contemporary archaeological methods and are more time consuming both at the data collection level, recorded by hand, as well as data entry from paper to a digital format.

The limitations of such methods are particularly acute in primate archaeological research where standardized methods are needed to make meaningful comparisons between human and non-human primate records within an evolutionary context. Primate archaeologists study living non-human primates often in remote environments, such as densely vegetated high-canopy forests requiring daily travel of several kilometres on foot, and ephemeral shorelines where data collection is conditioned by the tides (Carvalho et al., 2008; Carvalho and Almeida-Warren, 2019; Haslam et al., 2016). They also face the additional challenge of working at ‘living sites’, which are still visited by the study species, often requiring minimal disturbance and rapid removal of equipment when subjects appear (Carvalho et al., 2011).

While a critical part of primate archaeology research deals with extant technological behaviour, the research questions mirror many of the spatial queries of traditional archaeology: how are archaeological objects spatially related to each other? How do assemblages change over time? Is there inter and intra-site variation? (Carvalho et al., 2008; Carvalho and Almeida-Warren, 2019; Falótico et al., 2019). Thus, like with traditional archaeology, precision in these contexts is essential for accurate mapping of archaeological objects and features.

The DistoX is a customized hand-held electronic laser distance measurer (e.g. Leica Disto A3; Leica Disto X310) retrofitted with a compass and clinometer. It was developed for mapping cave systems to replace the traditional time-consuming and labour-intensive method of manual measurements and paper sketches (Heeb, 2008). It is a compact (55 × 31 × 122 mm), light-weight instrument (150 g), which can be paired with an Android or Windows device, making it a highly versatile fully digital system for spatial data collection (Heeb, 2014). Further technical information including assembly instructions can be found here: https://paperless.bheeb.ch/.

Performance tests in cave settings have revealed that the DistoX system (X1 model) is considerably more accurate than the tape and compass method, and presents readings more comparable to total station measurements (Ballesteros et al., 2013; Redovniković et al., 2014). More recently, the DistoX1 has successfully been used to document archaeological remains found in caves on Kithera Island and Kastoria in Greece (Trimmis, 2018, 2015).

Nevertheless, while the DistoX has been adopted as one of the main speleological tools for mapping cave systems (see Trimmis, 2018), its potential in archaeological settings has yet to be fully explored. The portable and relatively affordable nature of the DistoX system make it a suitable candidate to replace the tape and compass method, with the potential to bring archaeological data collection in challenging environments to a similar level and quality as that seen in major archaeological research projects around the world. The DistoX system could also benefit those archaeological projects with a limited budget, where a total station or other modern alternative equipment, although viable in practice, may be too costly financially (Table 1).

To date, very little empirical literature exists on the performance of the DistoX method for capturing spatial provenience information. All equipment tests have, so far, been restricted to cave settings, and have provided limited statistical assessments (see Ballesteros et al., 2013; Redovniković et al., 2014, 2016). Here we test the latest model of the DistoX – DistoX2 – in controlled open-air settings. We assess performance in terms of precision, as well as accuracy relative to two common methods of spatial data collection – total station, and tape and compass.

Table 1
Practical details of common mapping methods compared to the DistoX2.

Method	Weight	North	Functionality	Cost
Tape and compass	1–3 Kg	Magnetic North	Analogue or Semi-digital	$20–200[1]
Total station	4–10 Kg	Programmed by user	Fully digital	$4,000–10,000
GNSS/RTK GNSS	2–10 Kg	True North	Fully digital	$1,500–20,000
Photogrammetry	1–8 Kg	Programmed by user	Fully digital	$200–1,500
DistoX2	0.5–3[2] Kg	Magnetic North	Fully digital	$280–500[2]

[1] if using a digital compass
[2] depending on digital accessories chosen (e.g. mobile or tablet device), and whether tripod is included

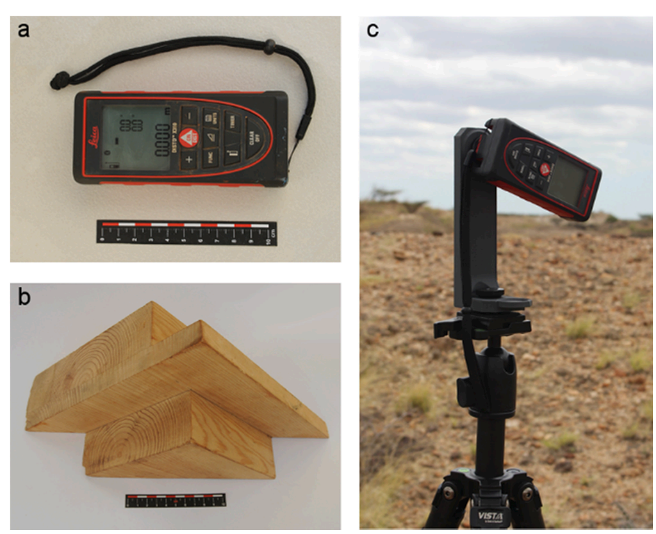

Fig. 1. DistoX2 and accessories: a) DistoX2 instrument (Photo: F. Tátá Regala); b) Disto calibration block (Photo: F. Tátá Regala); c) Custom-made tripod adapter (Photo: K. Almeida-Warren).

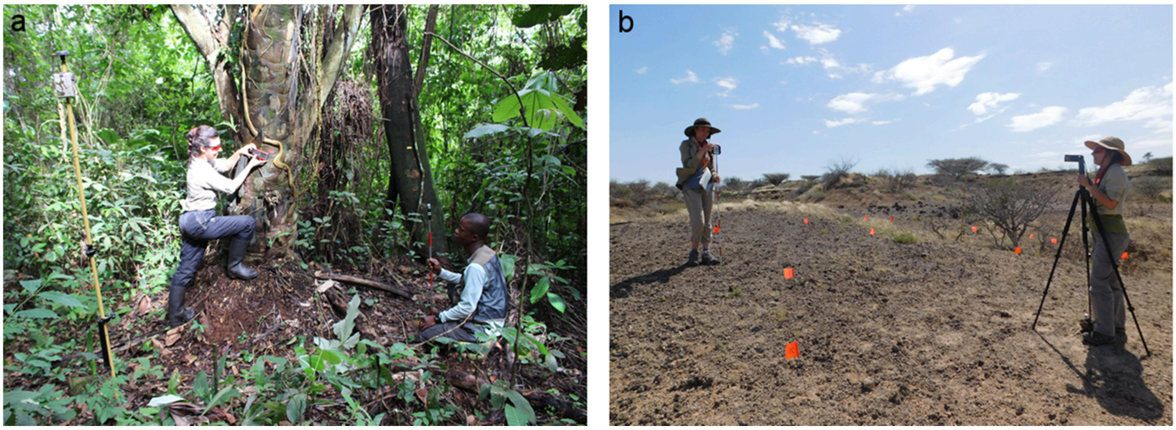

Fig. 2. DistoX2 setup options: a) Hand-held mode (Photo: V. Mamy); b) Tripod mode (Photo: C. Daniel).

1.1. The DistoX2

1.1.1. Technical summary

The DistoX2 is the latest model of the DistoX system (Fig. 1a). It is a hand-held electronic measuring device composed by a Leica DistoX310 laser distance meter retrofitted with a tilt-compensated (3D) digital compass, clinometer, and a Bluetooth module for wireless data transfer (Heeb, 2014). It was originally developed in 2008 as a paperless alternative to mapping the internal structures of caves, where more typical digital spatial mapping instruments, such as GPS/GNSS modules and total stations, are not viable (Heeb, 2008; Redovniković et al., 2014; Trimmis, 2018). Spatial mapping in forested environments, presents similar challenges to the cave settings – total stations are too heavy and bulky to carry manually in dense vegetation over large distances, and canopy cover is often too dense to achieve GPS readings at a sufficiently low resolution for accurate spatial mapping.

The DistoX2 provides instantaneous distance, inclination and azimuth readings. It can be used as a hand-held device without other supporting accessories or mounted on a tripod for additional stability; and measurements can be taken directly towards the target object or aimed at a reflector of fixed height placed on the target location (Fig. 2). It can function as a stand-alone instrument, but its performance is optimal when used in tandem with an external mobile device such as a phone or tablet (Redovniković et al., 2016). Data can be uploaded via Bluetooth connection onto a compatible data management application (Heeb, 2014). The currently available applications, both open-access, are PocketTopo for Windows OS (Heeb, 2008), and TopoDroid for Android OS (Corvi, 2016), which allow data management and organisation by project, data visualisation, and export in a variety of formats including .csv and .klm. These applications were designed for mapping speleological contexts, but can be adapted to archaeological settings (e.g. Trimmis, 2015, 2018), although a tailor-made application that integrates common archaeological data collection specifications (e.g. grid systems, digital finds/feature forms, conversion between angle readings and XYZ measurements) would help make the data collection process more streamlined. General DistoX2 technical specifications are presented in Table 2.

Table 2
Disto X2 technical specifications as per Heeb (2014).

	Range	Resolution	Precision
Distance	0.05 – >100 m	Magnetic North	0.2 cm[1]
Azimuth	0 – 360°[2]	0.1°	0.5° RMS[3]
Inclination	±90°	0.1°	0.5° RMS[3]

[1] up to 10 m.
[2] relative to magnetic North.
[3] after successful calibration.

In order to achieve the best results, regular calibration of the DistoX2 is essential to correct for spatial and temporal magnetic shifts, particularly when starting a project in a different geographic location or after long periods of inactivity (Heeb, 2013). Calibration is possible free-hand or with a calibration block (Fig. 1b) and the calibration function available on the Android or Windows software interface (Heeb, 2013; Regala, 2016, 2015).

It is important to note that azimuth readings are always relative to magnetic North and need to be corrected for magnetic declination (deviation from true North) (Redovniković et al., 2014). Magnetic declination fluctuates over time and is different depending on geographic location. Historic and current magnetic declination data can be consulted by coordinate location on the National Centers for Environmental Information website (https://www.ngdc.noaa.gov/geomag-web/).

1.1.2. Previous tests

Performance tests of the DistoX1 system in cave settings relative to the tape, compass and clinometer (TCC) method, and the total station revealed that, although less accurate than the total station, the DistoX1 is considerably more accurate than the TCC method (Ballesteros et al., 2013; Redovniković et al., 2014). Tests in El Pindal Cave (Spain), demonstrated that the DistoX1 measurements deviated from the total station readings by 0.72 m ± 0.04%, while the TCC measurements deviated by 9.18 m ± 11.64% (Ballesteros et al., 2013). Tests in cave Veternica (Croatia) mapping out a series of points along a 565.44 m traverse showed TCC deviations of up to 2.06 m in vertical distance from the total station baseline, while the DistoX1 only diverged by a maximum of 0.56 m (Redovniković et al., 2014). Horizontal distance error presented more exaggerated results, with TCC error ranging 0 – 30 m, and the DistoX1 error remaining consistently under 0.5 m. While not specified in the paper, the wide range for TCC error is likely due to the fact that the effect of angle measurement error and resolution (i.e. from compass and clinometer) is exacerbated as the distance from the measuring station increases, whereby at 0 m angle error would be negligible, but at 500 m the divergence from the true position would be considerable. One would expect a similar effect on the DistoX1, albeit to a lesser degree due to greater instrument accuracy and precision. However, data of these measurements were not provided in the publication.

Only one article has been published so far on the performance of the latest model of the DistoX – DistoX2 – where it was compared to the total station using two different post-processing applications (Redovniković et al., 2016). Both tests revealed similar results, with DistoX2 error ranging 0.07 – 0.24 m for horizontal measurements, and 0.00 – 0.03 m for vertical measurements. However, the test was only conducted on 14 physical control points, 8 of which were included in the study. The remainder of the publication focuses on comparing point clouds generated from photogrammetry using the 8 control points taken with the DistoX2, with points clouds produced from the equivalent total station data. In this case, for the 900 000 common generated points, measurement deviation between the DistoX2 and the total station point clouds was found to be largely under 0.04 m (Redovniković et al., 2016).

While previous empirical work has gone some way in testing the DistoX performance, and providing evidence supporting the DistoX as a better system than the tape and compass method for spatial mapping in cave settings, it has relied on small sample sizes (between 2 and 38 test points) and all have used different methodological protocols, which limits the potential/feasibility of collating and homogenizing the various results. Given the potential of the DistoX system as a spatial mapping method in above-ground scenarios we conduct a series of tests in controlled outdoor settings to assess the DistoX2 performance relative to the total station and tape and compass methods. We also test the relative precision of the DistoX2 when mounted on a tripod, as compared to when operated in hand-held mode. This data will not only complement the current literature on the performance of the DistoX system, but will also assess its capacity for spatial data collection across all non-aquatic environments, and for bridging the gap in methodological discrepancies between the optimal and the most challenging archaeological settings.

2. Methods

We tested the DistoX2 at two main levels: precision in both hand-held and tripod modes; and accuracy relative to the total station and to the tape and compass method. Tests were conducted in three geographically distinct open-air settings: Bossou, Guinea (L1); Koobi Fora Base camp, East Turkana, Kenya (L2); and University Parks, Oxford, United Kingdom (L3). L1 and L2 are field sites where the DistoX2 has been used for recording modern wild chimpanzee tool-use sites and Plio-Pleistocene archaeological surface assemblages, respectively. All DistoX2 measurements were taken with the aid of a reflector to avoid interference caused by low-lying vegetation or other foreground objects obstructing line of sight. Test points were allocated to cover a range of distances and location within a 15-metre radius of the DistoX2 position and were marked with numbered pin-flags. The DistoX2 was calibrated with a calibration block at each measurement location prior to tests. Data was imported and processed on a Samsung Android tablet using the TopoDroid application (Corvi, 2016).

2.1. Precision

The precision test served to determine variation between successive measurements taken of the same point. This helps establish the level of relative error a single measurement might have. While the technical specifications of the DistoX2 provide information regarding instrument precision, we wanted to verify this data in a real-world scenario, and to compare results between the two different device setups. Test data were collected from a total of 100 points – 50 points were documented in L1 using hand-held setup whereby the researcher was manually holding the DistoX2 positioned on the established datum; the other 50 points were documented in L3 using the tripod setup whereby the DistoX2 mounted on a tripod and set on a 5-second timer so the researcher could release their hands from the device before the measurement was taken. Each of the 100 points was recorded successively 5 times to determine device precision.

We designed a custom-made tripod mount with the help of Science Oxford, composed of a 3D-printed piece and non-magnetic bolts for fixing (Fig. 1c). See Appendix A for details on the design and a link to the 3D-model where downloads for printing are freely available.

2.2. Accuracy

Accuracy tests served to assess the performance and measurement errors of the DistoX2. In this case we use the total station measurements as a baseline and statistically compared the deviation in measurements (absolute error) of the DistoX2 with that of the tape and compass method in relation to a total station system. The DistoX2 accuracy relative to the total station was tested at L2 and L3. At L2 we collected 50 test points using a Leica Builder 505 (angular accuracy = 5″; distance accuracy = 2.0 mm) with a CPR111 True-Zero prism (constant = 0.0 mm; centring accuracy: 2.0 mm). At L3 we collected another 50 test points using a Leica TS06 (angular accuracy = 2″; distance accuracy = 1.5 mm), paired with a GPR111 prism (constant = 0.0 mm; centring accuracy: 2.0 mm). All total station points were recorded using the prism except for the datum and Disto position which were recorded by direct laser. Because control points with precise coordinate data were unavailable at either of the locations, the total station North was set to the magnetic North readings of the DistoX2, to avoid introducing further error from an additional measuring device. For this reason, we did not have to correct the DistoX2 readings for magnetic declination.

Tape and compass data were only collected for the 50 test points established at L3. We used a standard 30 m tape (resolution = 0.2 cm) to measure horizontal distance, a 5 m retractable tape (resolution = 0.1 cm) to measure vertical distance, and the in-built 3D digital compass of a Garmin Oregon 700 (resolution = 1.0°; reported accuracy = 2.0°, calibrated before use) to measure azimuth. The north reference was set to the default – true north – and azimuth readings were converted to a magnetic north reference based on declination information for the date of recording (Magnetic Model EEM2017 version 0.914, Declination = −0.752 decimal degrees). A string, plumb-bob and spirit level were used to keep the horizontal tape level to the datum. Although we recognize that using a digital compass with greater resolution and accuracy would directly improve the accuracy of this method, we wanted to reproduce a realistic scenario, using the equipment that is typically employed.

2.3. Statistical analyses

All statistical analyses were calculated in RStudio Version 1.1.383 (R Studio Team, 2017, 2017). We employed non-parametric tests as most data distributions were returned as not normal following a Shapiro-Wilk tests in R (‘shapiro.test()’ function). For the precision tests we calculate the average deviation from the mean for each set of five measurements taken for each test point. Comparisons of average deviation between the two methods were computed using a two-sample Wilcoxon signed-rank test (non-parametric equivalent to the two-sample *t*-test). For accuracy tests, comparison of errors between the different methods was computed with paired Wilcoxon tests. Errors were calculated as the absolute difference ($|\Delta|$) between each pair of measurements being compared. 3D error values were calculated as the Euclidean distance between test and reference XYZ coordinates for each test point.

Raw angular and distance errors between methods were also compared using paired Wilcoxon tests. Here, total station XYZ coordinate outputs were converted to angular and distance measurements to serve as a baseline for the comparison of raw errors (angles and distances) between the two methods; and inclination values from the DistoX2 were converted to vertical distance (Z) to enable direct comparison with the tape and compass method.

Angular and distance measurements recorded by the DistoX2 were converted into XYZ coordinates in R using the following trigonometric equations:

$$X = \sin\alpha \times (\cos\beta \times d)$$

$$Y = \cos\alpha \times (\cos\beta \times d)$$

$$Z = \sin\beta \times d,$$

where $\alpha = \textit{azimuth}$, $\beta = \textit{inclination}$ and $d = \textit{distance}$

Angular and distance measurements recorded using the tape and

Table 3
Raw DistoX2 precision results in hand-held and tripod modes. Values calculated from the average deviation.

	Hand-held mode				Tripod mode			
Measurement	mean	median	IQR	95% CI	mean	median	IQR	95% CI
Azimuth (°)	0.069	0.048	0.046	0–0.284	0.023	0.032	0.032	0–0.048
Distance (m)	0.006	0.005	0.003	0–0.014	0.002	0.003	0.003	0–0.005
Inclination (°)	0.023	0.032	0.048	0–0.048	0.009	0.000	0.000	0–0.048

Table 4
DistoX2 precision results in hand-held and tripod modes converted into XYZ format. Values in metres, calculated from the average deviation.

	Hand-held mode				Tripod mode			
Axes	mean	median	IQR	95% CI	mean	median	IQR	95% CI
X	0.005	0.005	0.005	0–0.011	0.002	0.003	0.002	0–0.005
Y	0.006	0.005	0.004	0–0.016	0.002	0.003	0.002	0–0.006
Z	0.002	0.001	0.003	0–0.007	0.001	0.000	0.000	0–0.007

compass method were converted into XYZ coordinates using the following trigonometric equations:

$$X = \sin\alpha \times d$$

$$Y = \cos\alpha \times d$$

$$Z = h,$$

where $\alpha = azimuth$, $d = distance$ and $h = height$

For the conversion of total station XYZ coordinates to angular and distance measurements, azimuths were calculated in R: unsigned angles between the vectorized coordinates and a fixed point ($x = 0$, $y = 1$) representing North, were computed using the 'angle.calc' function of the Morpho package (version 2.8; Schlager et al., 2020); then converted from radians to degrees using the 'rad2deg' function of the REdaS package (version 0.9.3; Maier, 2015); finally, angles were converted to a 360° format by subtracting the output from 360 where the original X coordinate was negative. Horizontal distance between the datum and each test point was calculated in QGIS (version 2.18.4) using the inbuilt Distance Matrix tool.

Major outliers for all data were defined as outliers that fell below the first quartile (Q1) subtracted by three times the interquartile range (IQR) or above three times the IQR added to the third quartile (Q3). Level of significance was set at $p < 0.05$.

3. Results

3.1. Precision

Overall, the precision test of the DistoX2 using the raw data output (angles and distance) yielded, on average, sub-degree and sub-centimetre precision for both hand-held and tripod modes (Table 3). Nevertheless, comparison between modes revealed that the average deviation values of the tripod mode were significantly lower than the reported values for the hand held mode, demonstrating that the tripod mode yields greater precision (Wilcoxon signed-rank test, Az: $z = 4.63$, $w = 1905.5$, $p < 0.01$; Dist: $z = 5.84$, $w = 2078.5$, $p < 0.01$; Inc: $z = 3.36$, $w = 1678.5$, $p < 0.01$).

For ease of interpretation we also converted the data into linear XYZ measurements, where the DistoX2 in tripod mode was found to be two-times more precise than the hand-held alternative with an average deviation of < 0.75 cm (95% CI) for all axes (Wilcoxon signed-rank test, X: $z = 4.78$, $w = 1943.5$, $p < 0.01$; Y: $z = 5.30$, $w = 2019.0$, $p < 0.01$; Z: $z = 4.19$, $w = 1854.0$, $p < 0.01$) (Table 4; Fig. 3).

3.2. Accuracy

The accuracy tests of the DistoX2 relative to the total station system were performed at two different locations. At L2 the DistoX2 errors

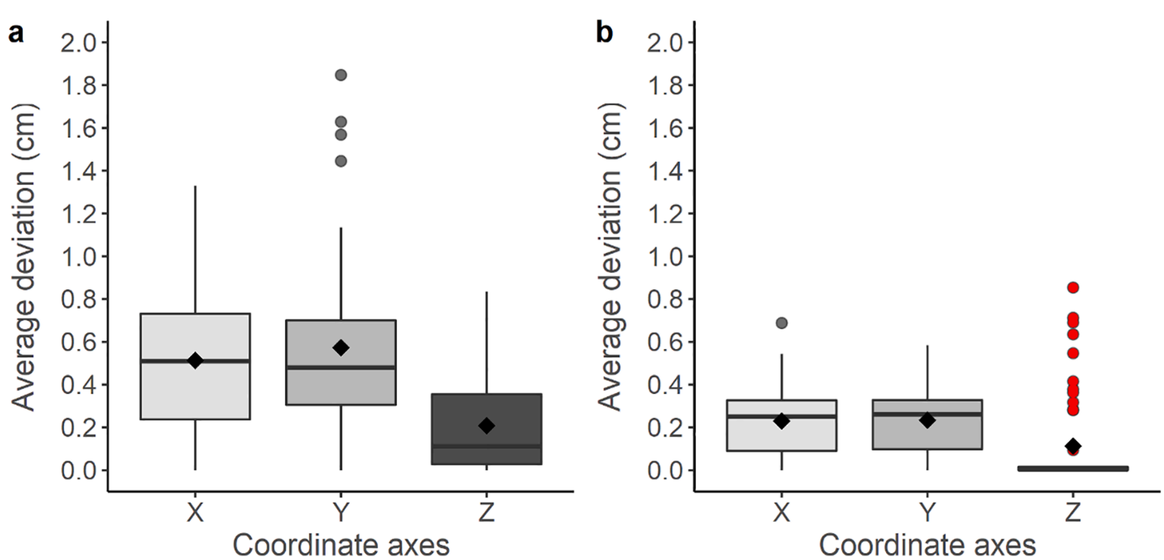

Fig. 3. DistoX2 precision: a) Hand-held mode; b) Tripod mode. Mean values represented by the diamond symbol, and major outliers indicated in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
DistoX2 accuracy relative to the total station at the two different test locations: L2 (Koobi Fora, Kenya) and L3 (Oxford, UK). Values in metres, calculated from the absolute error; 3D error calculated as Euclidean distance.

	Disto X2 – L2				Disto X2 – L3			
Axes	mean	median	IQR	95% CI	mean	median	IQR	95% CI
X	0.041	0.038	0.022	0.011–0.078	0.054	0.039	0.046	0.001–0.175
Y	0.025	0.022	0.022	0.001–0.061	0.051	0.048	0.059	0.002–0.130
Z	0.022	0.019	0.020	0.001–0.059	0.023	0.021	0.023	0.001–0.061
3D	0.057	0.055	0.024	0.028–0.093	0.089	0.073	0.064	0.018–0.184

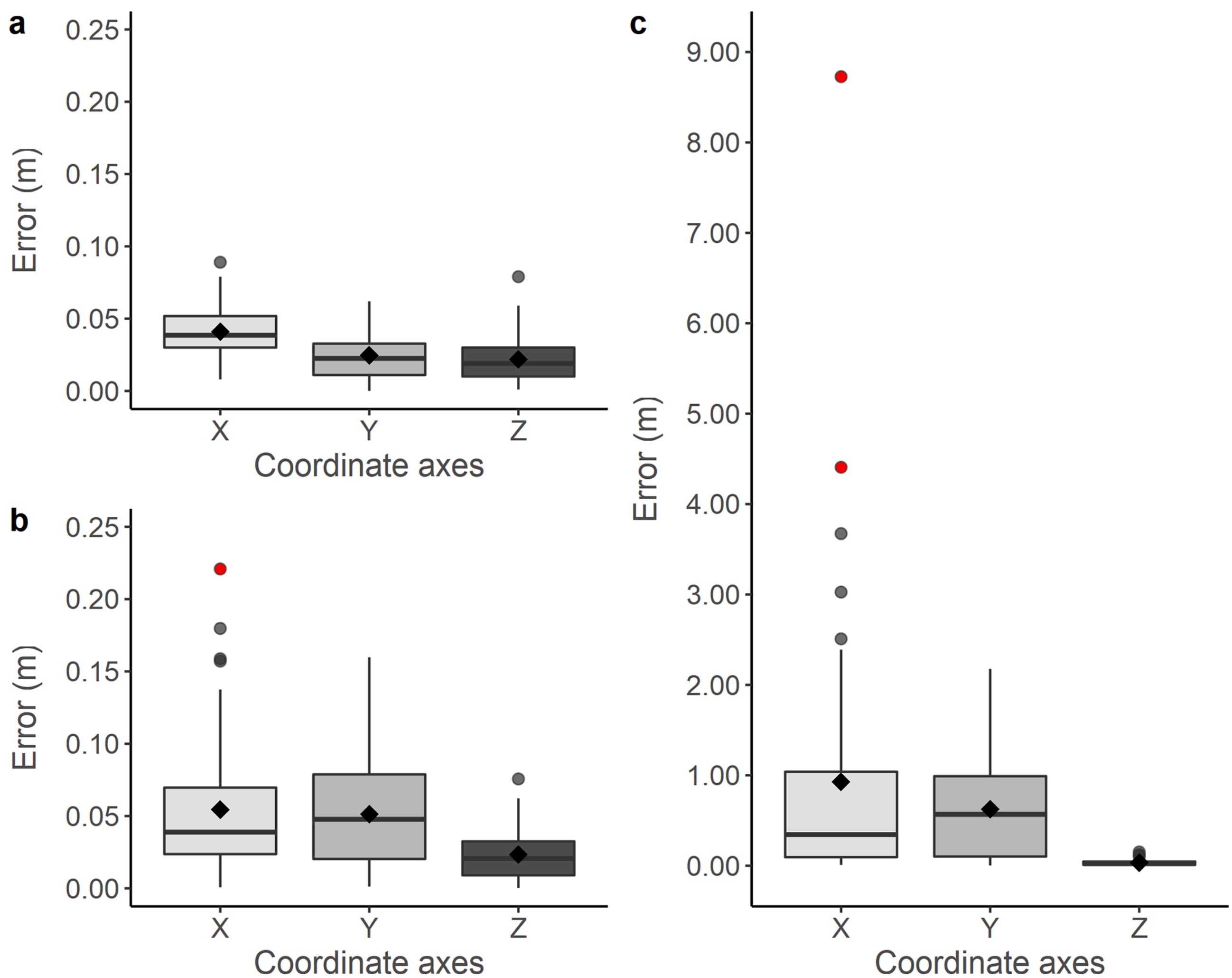

Fig. 4. Accuracy of the tested methods: a) DistoX2 at L2; b) DistoX2 at L3; c) Tape and compass method at L3. Values reported as absolute errors. Mean values represented by the diamond symbol, and major outliers highlighted in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6
Tape and compass accuracy relative to the total station with and without major outliers. Values in metres, calculated from the absolute error; 3D error calculated as Euclidean distance.

	TC – all data				TC – excluding major outliers			
Axes	mean	median	IQR	95% CI	mean	median	IQR	95% CI
X	0.928	0.344	0.945	0.012–4.242	0.693	0.332	0.795	0.011–2.936
Y	0.626	0.568	0.888	0.003–1.837	0.637	0.602	0.908	0.003–1.852
Z	0.034	0.023	0.036	0.001–0.117	0.034	0.022	0.034	0.001–0.118
3D	1.277	0.834	1.367	0.032–4.287	1.056	0.799	1.100	0.032–3.07

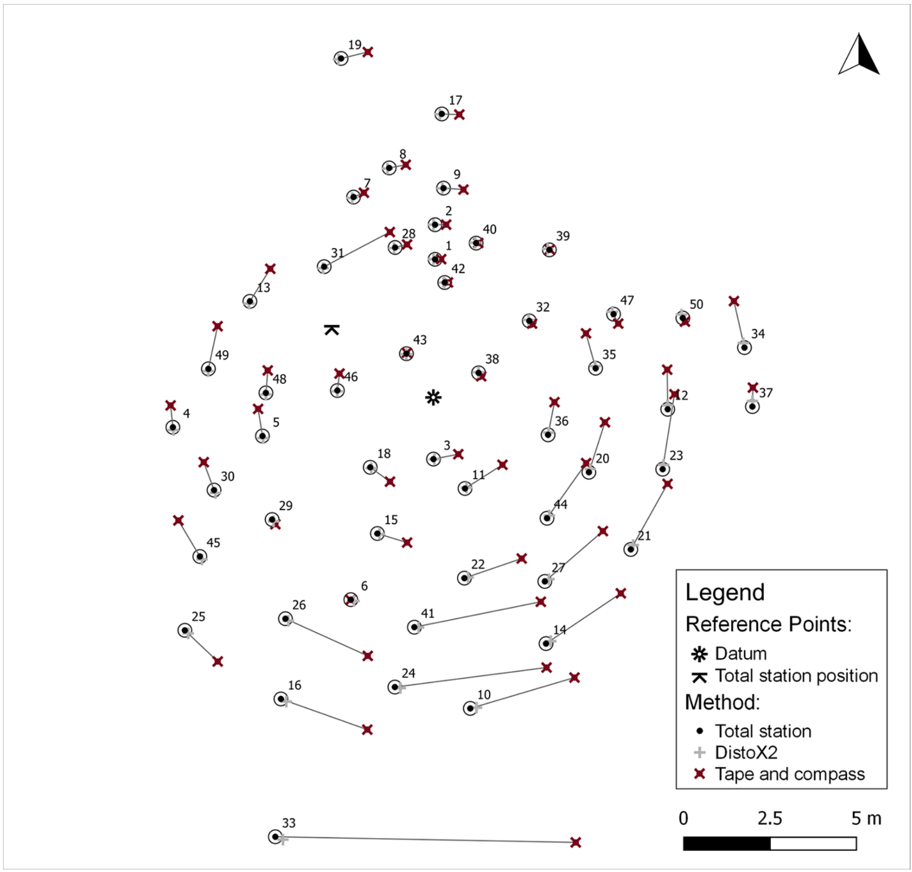

Fig. 5. 2D-plan of the test points at L2 mapped using the three different methods: total station, DistoX2, and tape and compass. Open circles represent a 20-cm buffer around the total station measurements. Lines illustrate the linear error between the tape and compass and total station methods where error is greater than 20 cm.

ranged 0–0.10 m for all axes (Table 5, Fig. 4a). At L3 the DistoX2 presented somewhat higher errors, ranging 0–0.20 m for the X and Y axes, 0–0.10 for the Z axis, and 0.02–0.20 for the overall 3D error (Table 5; Fig. 4b). However, these results were only significantly different for the Y axis and the composite 3D error (Wilcoxon signed-rank test, X: $z = -0.32$, $w = 1203$, $p = 0.75$; Y: $z = -3.37$, $w = 760$, $p < 0.01$; Z: $z = -0.46$, $w = 1183$, $p = 0.64$; 3D: $z = -3.28$, $w = 773$, $p < 0.01$).

Accuracy tests of the tape and compass relative to the total station conducted at L3 produced sub-metre average errors for the X and Y axes, with several points exceeding the one-metre error threshold, while error values for the Z axis were largely within the 0–0.1 m range (Table 6).

Paired comparisons between the error values of the two methods tested at L3, demonstrated that the DistoX2 is significantly more accurate than the tape and compass method (Paired Wilcoxon test, X: $z = -5.96$, $v = 20$, $p < 0.01$; Y: $z = -5.88$, $v = 28$, $p < 0.01$; Z: $z = -2.52$, $v = 376$, $p < 0.01$; 3D: $z = -6.06$, $v = 9$, $p < 0.01$). The level of significance was maintained even when the most extreme outliers were removed (Paired Wilcoxon test, X: $z = -5.82$, $v = 20$, $p < 0.01$; Y: $z = -5.74$, $v = 28$, $p < 0.01$; Z: $z = -2.63$, $v = 331$, $p < 0.01$; 3D: $z = -5.93$, $v = 9$, $p < 0.01$; Table 6, Fig. 4c). Fig. 5 shows a map of the coordinate positions of each test point taken with the three different methods.

Comparison of raw angle and distance errors between the DistoX2 and the tape and compass methods provides some insight into the nature of the stark discrepancy in accuracy (Table 7). While statistical significant differences were apparent for all measurement (Paired Wilcoxon test, Az: $z = -6.06$, $v = 9$, $p < 0.01$; Dist: $z = -5.75$, $v = 41$, $p < 0.01$; Z: $z = -3.53$, $v = 271$, $p < 0.01$), it is clear that the higher values and variance of the azimuth error of the tape an compass method is the principal contributor, suggesting that the compass used is a driving cause of the lower accuracy of this approach. While resolution and reported accuracy of the compass accounts for this in part, additional random error was likely introduced by the general imprecision of the whole system – compass orientation is done by hand and relies on the visual aptitude of the human eye for alignment with the measuring tape, with the compass changing location between each measurement. By comparison, the DistoX2 and total station are in fixed positions and use exact guides (e.g. reflector, prism) and visual aids (e.g. laser, magnifier) to record orientation. Thus, even with the highest attention to detail, the tape and compass method is more prone to extrinsic errors that could result in a higher incidence and range of erroneous measurements.

Angular errors translate into linear errors that increase with distance. This effect is particularly apparent for the tape and compass method, which also demonstrates high variance in error values reflecting the inconsistent nature of this method (Fig. 6). While the DistoX2

Table 7
Raw measurement accuracy of the DistoX2 and tape and compass methods relative to the total station baseline. Values calculated from the absolute errors.

	DistoX2				Tape and Compass			
Measurement	mean	median	IQR	95% CI	mean	median	IQR	95% CI
Azimuth (°)	0.769	0.761	0.364	0.386–1.146	11.323	8.824	14.389	0.21–31.989
Horizontal distance (m)	0.007	0.006	0.008	0–0.017	0.015	0.015	0.005	0.008–0.024
Vertical distance (m)	0.016	0.014	0.014	0.001–0.045	0.034	0.022	0.036	0.001–0.117

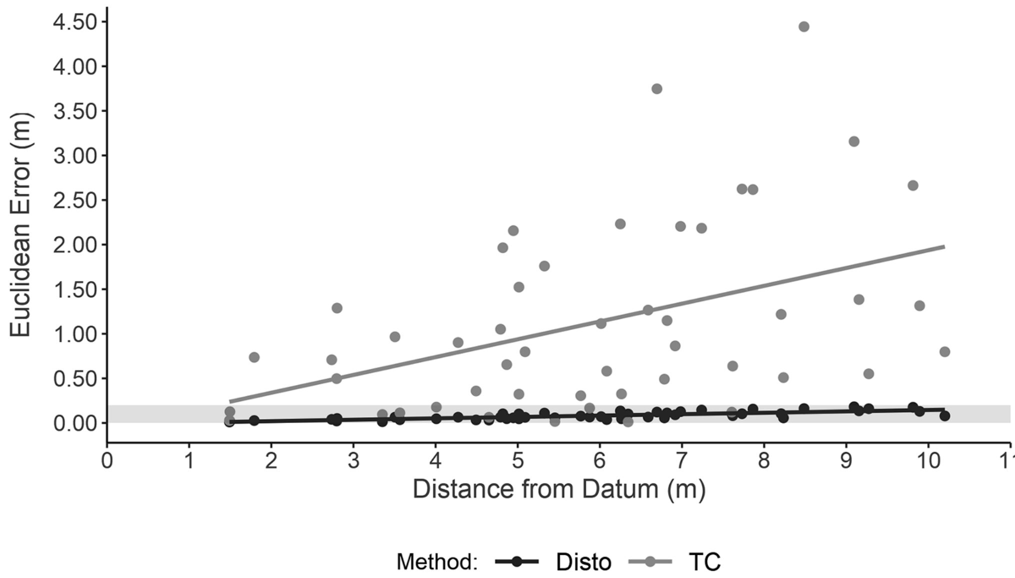

Fig. 6. 2D linear distance error between each test method and the total station baseline relative to distance from datum. Grey bar indicates the 0.0 – 0.2 m error range.

measurements ae also affected by this trend, the effect is far less extreme due to its higher precision, accuracy, and corresponding lower error dispersal.

4. Discussion

4.1. Observations on overall performance

In addition to the current study, the authors have had extensive experience in using all three survey methods in a range of real-world archaeological settings. KAW and SC have previously used the tape and compass method during primate archaeological fieldwork at wild chimpanzee sited in Tanzania and Guinea. SC also used the total station to record several chimpanzee nut-cracking sites in Guinea, and DRB uses it extensively for documenting Plio-Pleistocene excavations throughout Africa. More recently, KAW has used the DistoX2 to map chimpanzee tool sites in Guinea, as well as document surface material from Plio-Pleistocene deposits in Kenya. The following observations are a reflection on our collective experiences.

The DistoX2 system proved to be an easy to use, highly versatile instrument. While initial calibration required time and often several attempts before reaching acceptable calibration levels, the spatial data collection itself was fast and extremely efficient, and to a similar degree to the total station. It was only less so, in bright sunlight conditions when it was difficult to see the laser beam for targets beyond ~10 m, although laser enhancement glasses help mitigate this. The fact that data was recorded automatically in digital format and could be viewed in real time on a tablet was another major advantage of this system. Exporting and loading the data to a computer was also easy and intuitive.

Another major advantage of the DistoX2 was that it uses magnetic north as point of reference, and, once calibrated, it is ready to use anywhere within an approximately 100 km radius. This, combined with its small size and portability, enables mapping of several sites consecutively and instantaneously in a short period of time. In contrast, a total station generally needs to be "told" where North is, usually with the aid of a minimum of two fixed geo-referenced points. This means every site needs at least two geo-reference points, and every mapping session requires the total station to be setup and referenced relative to the known points. For multi-site projects covering large areas, the whole process from setup to completion of data collection can take up a considerable amount of research time (Fitts, 2005), although the use of a self-tracking (robotic) total station can help overcome the more nuanced logistical challenges of large-scale surveys (Holdaway and Fanning, 2008). While we did not document the exact recording times for each of the discussed methods, previous tests in cave settings have reported that a survey with the total station took a total of 48 h and three people, while the same survey was achieved with the DistoX in five hours by two people (Redovniković et al., 2014). Lastly, learning to use the DistoX2 system was relatively easy and took less than a day of training. In contrast, the total station often requires extensive training and a high level of expertise, which may pose additional limitations for archaeological projects with logistic and financial constraints.

Spatial mapping using the tape and compass method was the most time consuming, often requiring readjustments of the tape and levelling string. Between two people measuring and recording, where each person was handling multiple objects at the same time, it was also necessary to confer and redo measurements on several occasions to ensure accurate recording. The compass was also highly sensitive to movement and could display divergent readings for any given target point, providing greater potential for erroneous measurements. These factors, combined with the high range of error uncovered during data analysis, indicate that the tape and compass method is the least reliable and most prone to random human and instrument errors. While the addition of a third person dedicated solely to recording the measurements, the application of tension, sag and temperature corrections to distance measurements, and the use of a more accurate digital compass would have improved data quality and collection efficiency, this would not have been a realistic representation of most archaeological operations that use this method.

Total station real-world accuracy under field conditions is estimated at around ±0.05 – 0.10 cm (Sapirstein, 2016). This not only allows for highly accurate provenience data, but also enables the detailed recording of object orientation and slope required for high-profile excavations, such as those in Palaeolithic contexts (McPherron, 2005; Peng et al., 2017). While the DistoX2 observes a much higher error threshold (around ±0.10 – 15.00 cm), it can be considered a suitable method for archaeological projects that do not demand sub-cm accuracy – e.g. surface surveys, recovery excavations, community projects. It could also complement the total station and other current methods in large-scale projects where both excavations and surface surveys are taking place

Table 8
Summary of specifications and practical information of current and novel mapping methods.

	Tape and compass	Total station	RTK GNSS	Ground-based photogrammetry	DistoX2
Accuracy[1]	0–300 cm	< 0.5 cm	0–2 cm	0–5 cm	0–15 cm
Distance range	~ 20 m	~ 4 km	~ 15 km (Base and Rover RTK) ~ 100 km (RTK network)	~ 300 m	~ 100 m[2]
Weight	1–3 Kg	4–10 Kg	2–10 Kg	1–8 Kg	0.5–3[3] Kg
Speed	Slow	Moderate	Moderate	Slow	Fast
Operating time	10–26 hrs[4]	8–30 hrs	8–30 hrs	4–15 hrs	2–3 days[5]
Expertise required	Low	High	Moderate-High	Moderate-High	Moderate
Optimal conditions	Any	Open spaces	Overground with open sky	Any	Overground, underground
Practical limitations	Not suitable in locations with steep terrain unless used in tandem with a clinometer	Not suitable in underground settings with restrictive access	Not suitable in forested conditions. Requires a Base and Rover system or access to an RTK network with good cell service	Not suitable in locations with many vertical obstacles, dense vegetation or contrasting light conditions	Not suitable in locations with very strong sunlight or high magnetic interference
Cost	$20–200[6]	$4,000–10,000	$1,500–20,000[7]	$200–1,500[7]	$280–500[3]

[1]Reported as absolute error.
[2]Up to 10–15 m in bright sunlight.
[3]Depending on digital accessories chosen (e.g. mobile or tablet device), and whether tripod is included.
[4]Unlimited if using a fully analogue system.
[5]Up to two weeks for low to moderate usage.
[6]If using a digital compass.
[7]Depending on additional accessories, and whether a subscription to software and/or correction service is needed.

over a large geographic area.

Nevertheless, the DistoX2 would be of most benefit to projects for which modern mapping techniques are incompatible, whether due to site characteristics, or logistical and budgetary limitations. Worldwide, there are many expeditions that, due to such conditions, still rely on older provenience techniques (Peng et al., 2017), including the tape and compass method tested here. The DistoX2 presents an affordable and versatile alternative to such methods while providing a tenfold improvement in accuracy as well as other benefits such as digital recording, speed and consistency. Thus, the DistoX2 narrows the error thresholds between the diverse range of archaeological projects, bringing those that would typically rely on traditional methods closer to the total station standard.

4.2. *Other methods*

While the focus of the present research was to test the performance of the DistoX2, we also consider two of the latest methods that are becoming increasing commonplace in archaeological research – photogrammetry, and high-accuracy GNSS. Extensive literature now exists on the performance of these approaches in open archaeological settings, many reporting high levels of accuracy and precision comparable to the total station (Fitts, 2005; Hill et al., 2019; Peng et al., 2017; Roosevelt, 2014; Sapirstein, 2016; Tripcevich and Wernke, 2010; Willis et al., 2016). Conditions permitting, at least one of these methods may be feasible for archaeological mapping in poorly accessible environments. Close-range photogrammetry, for example, has been successful in both underground and underwater settings, albeit to varying degrees (Chang et al., 2019; Jordan, 2017; Lee, 2018; Yamafune et al., 2017); and has been implemented for generating 3D-models of both natural and archaeological features in these environments (Dabove et al., 2019; Figueira et al., 2015; Unhammer, 2016; Yamafune et al., 2017; Perfetti et al., 2020). One of the great advantages of photogrammetry is that the core equipment required – a digital camera – is already part of the archaeologist's toolkit. Additional elements, such as tripods, access to SfM software, as well as material for identifying ground control points, can be acquired at relatively low cost. It is a great visual tool for complementing traditional excavation recording methods, reconstructing archaeological objects, and providing immersive 3D-visualisation for preservation and dissemination of cultural heritage. It can be implemented in almost all archaeological settings, except for forested environments (Willis et al., 2016), where low-lying vegetation and many vertical obstacles (trees) could greatly impact the feasibility of this method unless it is possible to clear large areas of vegetation.

Archaeological studies investigating accuracy of SfM photogrammetry have reported errors as low as 0.20 cm, ranging ~0.0–5.0 cm (Peng et al., 2017; Sapirstein, 2016; Willis et al., 2016). However, we highlight that most of these studies have scaled their SfM models with ground control points that were georeferenced using a total station or real-world coordinates, and very few tested the accuracy of point provenience data directly (i.e. compared the total station coordinates of predefined points with those yielded from photogrammetric data). Nevertheless, accuracy and precision of photogrammetry-generated models can be extremely variable as it is dependent on a variety of factors, including: the scale and texture of the subject, the image quality and degree of overlap among photos, the number of ground control points, the camera used, the accuracy of the scaling method (e.g. georeferenced control points, measurements between known points, object of known scale), and whether coded targets are included (Peng et al., 2017; Sapirstein, 2016). Thus, in order to achieve reliably consistent results requires expertise and strict protocols (Sapirstein and Murray, 2017). This is even more crucial when no other methods of spatial data collection are being used. In most fieldwork scenarios, SfM composites cannot be generated *in situ* in real-time, consequently failure to take sufficient overlapping photos covering the whole area of interest could result in complete loss of valuable data if the area is under active

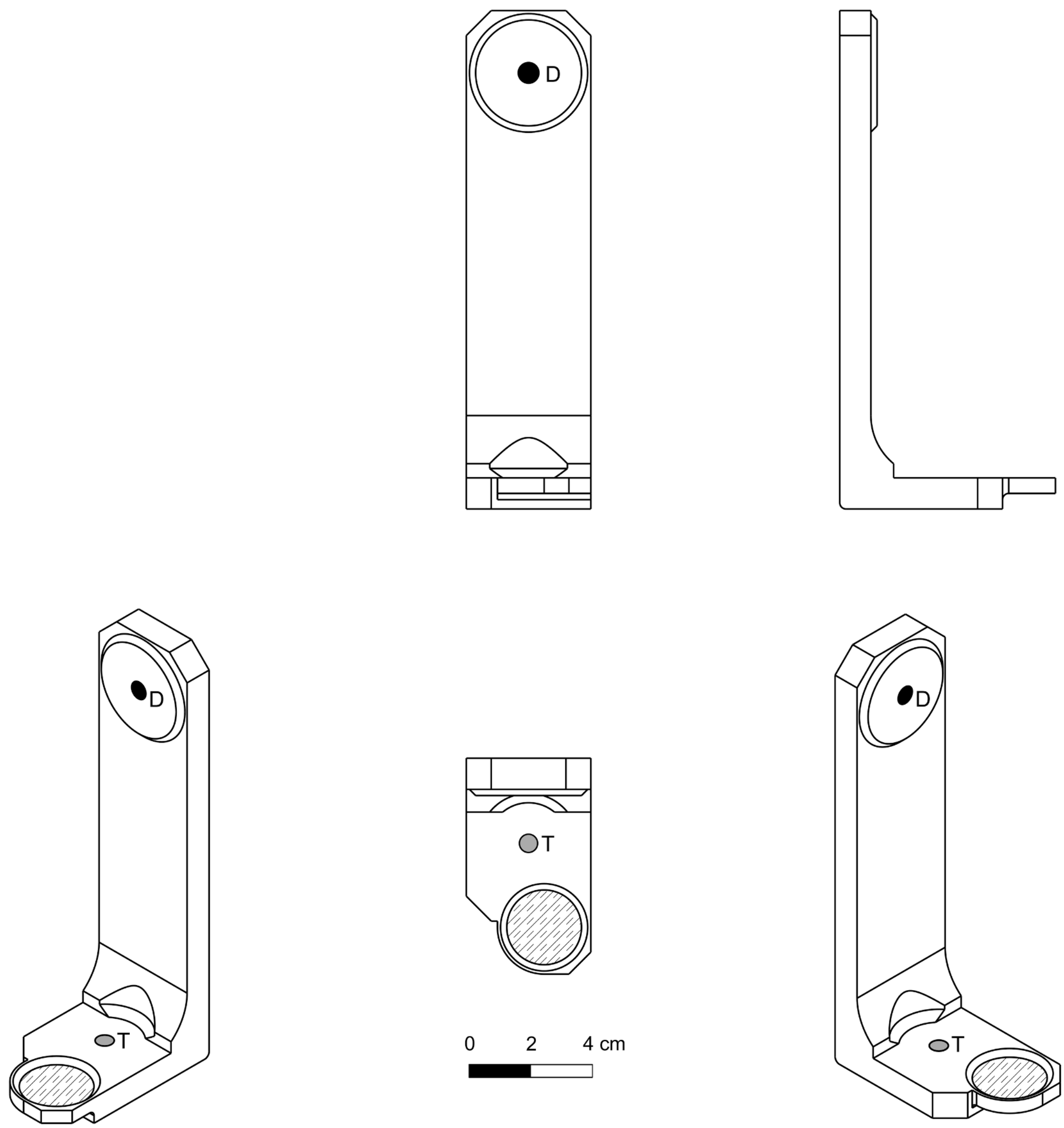

Fig. A1. Blueprint of DistoX2 custom-made tripod mount (Original composite by P. Riggs; with modifications by K. Almeida-Warren). Solid fill areas indicate screw attachments and connections to the DistoX2 (D), and tripod head (T). Hatch fill areas indicate surface for fitting a small circular spirit level.

excavation or a site of modern activity (e.g. an active chimpanzee nut-cracking site).

At a practical level, extracting spatial provenience of archaeological artefacts and features using SfM photogrammetry without the aid of a total station or a GNSS device, requires precise measurements of the distances between multiple ground control points or the inclusion of an object of known dimensions. It may also require the use of a camera boom to enable greater surface coverage and a shade to diffuse strong sunlight and reduce shadows. While the whole process, from taking the photographs, to generating the 3D-models, to extrapolating the desired spatial data, can be time-consuming and labour-intensive (Sapirstein and Murray, 2017), SfM photogrammetry may be a good alternative to the total station in archaeological projects that implement photogrammetry as part of the recording practices whether for digital archives or public outreach.

High-accuracy GNSSs technology is rapidly advancing, and such devices may well replace the total station in open-air settings in the coming decades, if not years. Currently, most RTK GNSSs range from sub-cm to 2 cm horizontal accuracy in optimal conditions (e.g. good satellite coverage, clear sky) (EOS Positioning Systems Inc., 2017; Hill et al., 2019; Pearson et al., 2015). However, this system requires connection to an RTK network (via cell signal) or nearby base station (Pearson et al., 2015), which are not always available or feasible in remote field sites. As an alternative, some GNSS companies offer subscription access to differential correction services (e.g. Atlas^{TM}; CenterPoint^{TM} RTX) that can provide base-station free corrections at accuracies as low as two centimetres (Ames et al., 2020; EOS Positioning Systems Inc., 2017). Nevertheless, the accuracy of such systems is still heavily conditioned by access to open sky and clear satellite geometry. One of the authors (KAW), who used an EOS Arrow Gold with Atlas H10 correction extensively during fieldwork in the Bossou (Guinea), found that the system performed very poorly under forested conditions. Often the device struggled to reach a reliable measurement (Fix solution frequency = 2.5%, n = 1324), with data outputs returning error values of $\approx$ 2.13 m HRMS and $\approx$ 4.00 m VRMS (Appendix B), despite observing each point for several minutes to half an hour. Battery life may also be a limitation if there is no daily access to a power source. In the case of the Emlid Reach RTK, battery autonomy is approximately 30 h (Hill et al., 2019), while for the EOS Arrow Gold it caps at around 8 h (EOS Positioning Systems Inc., 2017). In contrast, the DistoX2 can last 2–3 days of intensive data collection to approximately two weeks of low to moderate usage. While the cost of commercially available GNSS instruments is

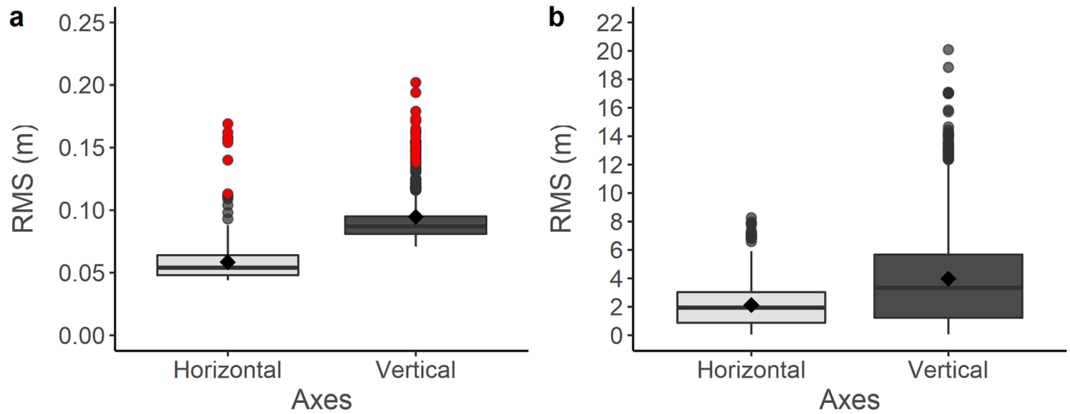

Fig. B1. Accuracy of the Arrow Gold GNSS Receiver as reported by the device during field surveys under two canopy conditions: a) open canopy; b) closed canopy. Values indicated as root mean square (RMS). Mean values represented by the diamond symbol, and major outliers highlighted in red.

becoming more and more affordable, a complete survey kit even at the lower end of the spectrum will range between $1,500 and $2,500. In projects with a limited budget, a GNSS device especially if requiring the added cost of periodic subscriptions to correction services may not be economically feasible (Ames et al., 2020).

Ultimately, the method used for collecting spatial provenience data is a decision that depends on the nature of the project – from the characteristics of the site (location, environment, scale, accessibility), archaeological significance/importance, funding available, and project duration, to the team size and the amount of logistical support. In some cases, the total station will be the only compatible option, while for others, practical or budgetary limitations will require the use of alternative methods. For ease of comparison, we provide a summary of key information as well as some practical limitations regarding each of the survey methods discussed in this study (Table 8).

While the current research has mainly focused on assessing the DistoX2 as a stand-alone data collection method, we would like to highlight that the DistoX2 could equally be used in tandem with other methods. Currently several archaeological projects employ a combination of total station, GNSS and/or photogrammetry, including expeditions directed by one of the authors – DRB – in Koobi Fora, Kenya. The DistoX2 system constitutes a new addition to the archaeologist's toolkit that can complement and facilitate the tailoring of spatial mapping strategies to the specific goals of an archaeological project.

5. Conclusions

Today, archaeological expeditions are becoming increasingly diverse, and the data collection methods used will depend on the requirements and limitations of the project at hand. While the total station should be the primary choice in most instances, especially when very high accuracy is required, many projects may not meet the conditions or means required to implement such a method, or other current alternatives. Yet, other projects may also seek to combine several mapping methods to fit their needs. The DistoX2 provides a methodological solution to those projects that would still typically resort to more traditional, analogue methods, but also constitutes a novel system that complements other commonly used methods in projects that benefit multiple approaches.

The DistoX2 presents a good level of precision both in hand-held and tripod modes. However, it is most precise when mounted on a tripod, where the mean precision is ≈ 2.00 cm for the X and Y axes and ≈ 1.00 cm for Z.

The conservative estimate for DistoX2 accuracy relative to the total station is ≈ 5.00 cm for 2D dimensions and ≈ 2.00 cm for the Z axis (≈ 6.00 cm for 3D composite). These values are better than the previously published results, although the errors fall under the same upper boundary (see Redovniković et al., 2016).

In contrast, the tape and compass method, with a mean error of ≈ 69.00 cm for the X axis, ≈ 64.00 cm for the Y axis, and ≈ 3.00 cm for the Z axis, is considerably less accurate than the DistoX2, particularly with respect to the X and Y axes. The fact that the analogue or digital compass used in the tape and compass method cannot be calibrated to the same rigour nor have the same resolution as the DistoX2, is a major disadvantage to this approach. Furthermore, unlike the DistoX2, data collection using this method is not an automated process, and therefore has greater propensity for human errors at the reading, recording, and data-entry levels. Despite being the most affordable, its high level of measurement error makes this method a poor option for spatial data collection and should only be used when alternative methods (including the DistoX2) are not viable options.

In sum, the DistoX2 presents several features that make it a suitable and affordable alternative to the more commonly used digital spatial mapping methods in archaeology, and to the tape and compass method: 1) small, light-weight and highly-portable device; 2) can be calibrated, ensuring more accurate readings than standard analogue or digital compasses; 3) more accurate and more efficient than the tape and compass method; 4) records measurements instantaneously onto a digital interface, that can be exported and uploaded to a laptop for analysis.

The DistoX2 combines the portability and affordability of the tape and compass method with the speed, accuracy and digital features of the total station. Its applicability in poorly accessible field-sites fills a critical gap in archaeological mapping methods, and enables greater standardization of spatial data collection across all human and non-human archaeological records.

CRediT authorship contribution statement

Katarina Almeida-Warren: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Visualization, Writing - original draft. **David R. Braun:** Conceptualization, Resources. **Susana Carvalho:** Conceptualization, Supervision, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We are grateful to V. Mamy, L. Goigbe, B. Zogbila, G. Zogbila, A. Curley, C. Costa, C. Daniel, N. Mann, N. Gitaw, K. O'Brien, Dr. J. Reeves and Dr. M. Bluteau for support during the data collection process; to F.

Tátá Regala, L. Meira Paulo and M. J. Pinto at AESDA (Associação de Estudos Subterrâneos e Defesa do Ambiente) for DistoX2 training, suggestions and technical support. We thank P. Riggs at Science Oxford for producing a custom-made tripod adaptor; Dr. L. Luncz and the Institute of Archaeology (University of Oxford) for kindly loaning their survey equipment during testing in Oxford. We also thank the Direction Nationale de la Recherche Scientifique, the Institut de Recherche Environmentale de Bossou (Guinea), Kyoto University Primate Research Institute, National Museums of Kenya, and the National Commission for Science, Technology and Innovation (Kenya), and the Koobi Fora Field School for research permissions and logistical support overseas.

This work was funded by the Fundação para a Ciência e Tecnologia (FCT) [grant number: SFRH/BD/115085/2016] to KAW, with support from the Programa Operacional Capital Humano (POCH) and the European Union; ICArEHB with support from FCT [grant number: UIDB/04211/2020]; the Boise Trust Fund (University of Oxford) to KAW; the National Geographic Society [grant number: EC-399R-18] to KAW; and a Philip Leverhulme Prize to SC.

Appendix A – Custom-made tripod mount

The DistoX2 tripod mount was conceptualized by KAW and Paul Riggs (Science Oxford), to enable a setup more in line with the total station system and standard archaeological data collection protocols. The piece is designed so that the DistoX2 can be mounted on a standard camera tripod over a fixed point and rotated along vertical and horizontal planes, covering all directions except for the area within the tripod legs. The rotation axes align with the origin of the laser (at the base of the DistoX2) and over the fixed point at the base of the tripod, so that the DistoX2 can be rotated while maintaining the fixed position of the laser source. The build is sturdy and lightweight, with a space at the base to fit a small circular spirt-level to aid with setup (Fig. A.1). The 3D file is freely available for download and printing through Thingivese (https://www.thingiverse.com/thing:4367548) where print instructions and related information can be found.

The connections with the tripod and the DistoX2 are made using common photography tripod adaptor components available from eBay and other sources:

– 1/4″ male to 1/4″ female screw adaptor for camera tripod flash bracket

– 1/4″ dual nuts tripod mount screw and camera flash hot shoe adapter

These pieces need to be non-magnetic (e.g. aluminium) so as not to interfere with the DistoX2′s internal compass.

Appendix B – Arrow Gold GNSS Receiver

Fig. B1.

References

Almeida-Warren, K., Braun, D.R., Matsuzawa, T., Carvalho, S., 2018. Mapping primate archaeology: new tools for standardizing spatial data collection across the primate order. Proceedings of the XXVIIth Congress of the International Primatological Society.

Ames, C.J.H., Shaw, M., O'Driscoll, C.A., Mackay, A., 2020. A multi-user mobile GIS solution for documenting large surface scatters: an example from the Doring River, South Africa. J. F. Archaeol. 45, 394–412. https://doi.org/10.1080/00934690.2020.1753321.

Ballesteros, D., Domínguez-Cuesta, M.J., Jiménez-Sánchez, M., González- Pumariega, P., 2013. Tape-compass-clinometer, DistoX or total station, what is the best method to elaborate a cave survey? A case study in El Pindal Cave, Spain, in: 8th International Conference (AIG) on Geomorphology, 27-31 August, Paris.

Carvalho, S., 2011. Diécké Forest, Guinea: Delving into Chimpanzee Behavior Using Stone Tool Surveys. In: Matsuzawa, T., Humle, T., Sugiyama, Y. (Eds.), The Chimpanzees of Bossou and Nimba. Springer Japan, pp. 301–312. https://doi.org/10.1007/978-4-431-53921-6_31.

Carvalho, S., Almeida-Warren, K., 2019. Primate Archaeology, in: Chun Choe, J. (Ed.), Encyclopedia of Animal Behavior. Elsevier, pp. 397–407. https://doi.org/10.1016/B978-0-12-809633-8.90156-0.

Carvalho, S., Cunha, E., Sousa, C., Matsuzawa, T., 2008. Chaînes opératoires and resource-exploitation strategies in chimpanzee (*Pan troglodytes*) nut cracking. J. Hum. Evol. 55, 148–163. https://doi.org/10.1016/j.jhevol.2008.02.005.

Chang, A., Jung, J., Um, D., Yeom, J., Hanselmann, F., 2019. Cost-effective framework for rapid underwater mapping with digital camera and color correction method. KSCE J. Civ. Eng. 23, 1776–1785. https://doi.org/10.1007/s12205-019-1891-3.

Corvi, M., 2016. TopoDroid v.2.7.

Dabove, P., Grasso, N., Piras, M., 2019. Smartphone-based photogrammetry for the 3D modeling of a geomorphological structure. Appl. Sci. 9, 3884. https://doi.org/10.3390/app9183884.

Dibble, H.L., 1987. Measurement of artifact provenience with an electronic theodolite. J. F. Archaeol. 14, 249–254. https://doi.org/10.1179/009346987792208457.

EOS Positioning Systems Inc., 2017. Arrow Gold [WWW Document]. URL https://eos-gnss.com/wp-content/uploads/2017/11/eos-arrow-gold-revC-v4.pdf (accessed 3.12.20).

Falótico, T., Proffitt, T., Ottoni, E.B., Staff, R.A., Haslam, M., 2019. Three thousand years of wild capuchin stone tool use. Nat. Ecol. Evol. 3, 1034–1038. https://doi.org/10.1038/s41559-019-0904-4.

Figueira, W., Ferrari, R., Weatherby, E., Porter, A., Hawes, S., Byrne, M., 2015. Accuracy and precision of habitat structural complexity metrics derived from underwater photogrammetry. Remote Sens. 7, 16883–16900. https://doi.org/10.3390/rs71215859.

Fitts, W.R., 2005. Precision GPS surveying at Medieval Cottam, East Yorkshire. England. J. F. Archaeol. 30, 181–190. https://doi.org/10.1179/009346905791072387.

Haslam, M., Hernandez-Aguilar, A., Ling, V., Carvalho, S., De La Torre, I., Destefano, A., Du, A., Hardy, B., Harris, J., Marchant, L., Matsuzawa, T., McGrew, W.C., Mercader, J., Mora, R., Petraglia, M., Roche, H., Visalberghi, E., Warren, R., 2009. Primate archaeology. Nature 460, 339–344. https://doi.org/10.1038/nature08188.

Haslam, M., Luncz, L., Pascual-Garrido, A., Falótico, T., Malaivijitnond, S., Gumert, M., 2016. Archaeological excavation of wild macaque stone tools. J. Hum. Evol. 96, 134–138. https://doi.org/10.1016/j.jhevol.2016.05.002.

Heeb, B., 2014. The next generation of the DistoX cave surveying instrument. Cave Radio Electron. Gr. J. 88, 5–8.

Heeb, B., 2013. DistoX2 Calibration Manual [WWW Document]. URL https://paperless.bheeb.ch/download/DistoX2_CalibrationManual.pdf (accessed 5.30.19).

Heeb, B., 2008. Paperless Caving - An Electronic Cave Surveying System. Proc. IV Eur. Speleol. Congr. 130–133.

Hill, A.C., Limp, F., Casana, J., Laugier, E.J., Williamson, M., 2019. A New Era in Spatial Data Recording: Low-Cost GNSS. Adv. Archaeol. Pract. 7 (2), 169–177. https://doi.org/10.1017/aap.2018.50.

Historic England, 2017. Understanding the Archaeology of Landscapes: A Guide to Good Recording Practice, 2nd ed. Historic England, Swindon.

Holdaway, S., Fanning, P., 2008. Developing a landscape history as part of a survey strategy: a critique of current settlement system approaches based on case studies from Western New South Wales, Australia. J. Archaeol. Method Theory 15, 167–189. https://doi.org/10.1007/s10816-008-9051-y.

Jo, Y., Hong, S., 2019. Three-dimensional digital documentation of cultural heritage site based on the convergence of terrestrial laser scanning and unmanned aerial vehicle photogrammetry. ISPRS Int. J. Geo-Information 8, 53. https://doi.org/10.3390/ijgi8020053.

Jordan, J.H., 2017. Modeling Ozark Caves with Structure-from-Motion Photogrammetry: An Assessment of Stand-Alone Photogrammetry for 3-Dimensional Cave Survey. BSc Thesis. University of Arkansas.

Kjellman, E., 2012. From 2D to 3D: a photogrammetric revolution in archaeology? MSc Thesis University of Tromsø.

Lee, T.O., 2018. An Examination of Close-Range Photogrammetry and Traditional Cave Survey Methods for Terrestrial and Underwater Caves for 3-Dimensional Mapping. MSc Thesis. University of Southern California.

Maier, M.J., 2015. Package "REdaS.".

Martínez-Fernández, A., Benito-Calvo, A., Campaña, I., Ortega, A.I., Karampaglidis, T., Bermúdez de Castro, J.M., Carbonell, E., 2020. 3D monitoring of Paleolithic archaeological excavations using terrestrial laser scanner systems (Sierra de Atapuerca, Railway Trench sites, Burgos, N Spain). Digit. Appl. Archaeol. Cult. Herit. 19, e00156 https://doi.org/10.1016/j.daach.2020.e00156.

McPherron, S.J.P., 2005. Artifact orientations and site formation processes from total station proveniences. J. Archaeol. Sci. 32, 1003–1014. https://doi.org/10.1016/j.jas.2005.01.015.

Mercader, Julio, 2002a. Excavation of a Chimpanzee Stone Tool Site in the African Rainforest. Science (80-). 296, 1452–1455. https://doi.org/10.1126/science.1070268.

Mercader, J. (Ed.), 2002b. Under the canopy: the archaeology of tropical rain forests, Under the canopy: the archaeology of tropical rain forests. Rutgers University Press, New Brunswick.

Pearson, T., Ainsworth, S., Thomason, B., 2015. Where on Earth Are We? The Role of Global Navigation Satellite Systems (GNSS) in Archaeological Field Survey. Historic England, Swindon.

Peng, F., Lin, S.C., Guo, J., Wang, H., Gao, X., 2017. The application of SfM photogrammetry software for extracting artifact provenience from palaeolithic excavation surfaces. J. F. Archaeol. 42, 326–336. https://doi.org/10.1080/00934690.2017.1338118.

Perfetti, L., Fassi, F., Rossi, C., 2020. Low-cost digital tools for archaeology, in: Aste, N., Della Torre, S., Talamo, C., Adhikari, R., Rossi, C. (Eds.), Innovative Models for Sustainable Development in Emerging African Countries. Research for Development. Springer, Cham, pp. 137–148. https://doi.org/10.1007/978-3-030-33323-2_12.

R Studio Team, 2017. RStudio: Integrated Development for R.

Redovniković, L., Ivković, M., Cetl, V., Sambunjak, I., 2014. Testing DistoX Device for Measuring in the Unfavourable Conditions. In: 6th International Conference on Engineering Surveying, 3–4 April 2014. Czech republic, Prague, pp. 269–274.
Redovniković, L., Stančić, B., Cetl, V., 2016. Comparison of Different Methods of Underground Survey. In: International Symposium on Engineering Geodesy, 20–22 May 2016. Varaždin, Croatia, pp. 465–472.
Regala, F.T., 2016. AESDA - Calib: a calibrator for DistoX/X2 [WWW Document]. URL https://www.aesda.org/wp-content/uploads/2016/09/Calibrator-EuroSpeleo2016-adapted.pdf (accessed 10.2.19).
Regala, F.T., 2015. AESDA Calib - um calibrador para DistoX/X2, in: Proceedings of the 6th National Congress of Speliology. Alvados, Portugal, pp. 77–82. https://doi.org/10.1017/CBO9781107415324.004.
Roosevelt, C.H., 2014. Mapping site-level microtopography with Real-Time Kinematic Global Navigation Satellite Systems (RTK GNSS) and Unmanned Aerial Vehicle Photogrammetry (UAVP). Open Archaeol. 1, 29–53. https://doi.org/10.2478/opar-2014-0003.
Sapirstein, P., 2016. Accurate measurement with photogrammetry at large sites. J. Archaeol. Sci. 66, 137–145. https://doi.org/10.1016/j.jas.2016.01.002.
Sapirstein, P., Murray, S., 2017. Establishing best practices for photogrammetric recording during archaeological fieldwork. J. F. Archaeol. 42, 337–350. https://doi.org/10.1080/00934690.2017.1338513.
Schlager, S., Jefferis, G., Dryden, I., 2020. Package "Morpho.".
Trimmis, K.P., 2018. Paperless mapping and cave archaeology: a review on the application of DistoX survey method in archaeological cave sites. J. Archaeol. Sci. Reports 18, 399–407. https://doi.org/10.1016/j.jasrep.2018.01.022.
Trimmis, K.P., 2015. Fear of the light: mapping modern cave use strategies in Kythera Island Caves. Ethnoarchaeology 7, 141–156. https://doi.org/10.1179/1944289015Z.00000000031.
Tripcevich, N., Wernke, S.A., 2010. On-site recording of excavation data using mobile GIS. J. F. Archaeol. 35, 380–397. https://doi.org/10.1179/009346910X12707321242511.
Unhammer, O.F., 2016. Methodological evaluation of digital photogrammetry in a Middle Stone Age cave context. A case study from Blombos Cave, South Africa. MSc Thesis. The University of Bergen.
Wheatley, D., Gillings, M., 2002. Archaeology, space and GIS. In: Spatial Technology and Archaeology: The Archaeological Applications of GIS. Taylor & Francis, New York, pp. 1–18.
Willis, M.D., Koenig, C.W., Black, S.L., Castañeda, A.M., 2016. Archaeological 3D mapping: the structure from motion revolution. J. Texas Archaeol. Hist. 3, 1–36.
Yamafune, K., Torres, R., Castro, F., 2017. Multi-Image Photogrammetry to Record and Reconstruct Underwater Shipwreck Sites. J. Archaeol. Method Theory 24, 703–725. https://doi.org/10.1007/s10816-016-9283-1.