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BRITISH ECOLOGICAL SOCIETY Ecological Solutions and Evidence

PRACTICAL TOOLS

Comparing the accuracy and precision of smartphone and specialist handheld GNSS receivers for use in ecological fieldwork

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Abstract

1. Smartphones are handheld computers and multichannel communication devices that carry an array of sensors and can link with specialist external devices. These powerful tools have an established role in biological recording and ecological surveying. The ability to geolocate accurately is frequently essential to ecological fieldwork. This field study aimed to test the performance of a compact/handheld surveyor-grade GNSS receiver, functioning as an external sensor, compared to smartphones' inbuilt GNSS receivers and a standard-grade external GNSS receiver.
2. We devised a series of survey protocols to test the horizontal accuracy of GNSS receivers in static and dynamic scenarios typical of ecology fieldwork, estimating the horizontal distance of GNSS measurements under 'open sky' conditions from a base station geolocated with centimetre accuracy. Protocols were designed to test the capabilities of GNSS receivers; the absolute horizontal accuracy and precision in static surveys and performance in dynamic surveys, walking a transect with frequent changes of direction, or roaming across the survey area, requiring the GNSS to rapidly re-establish a position fix.
3. In all survey protocols, the surveyor-grade GNSS performed significantly better with lower horizontal distance estimates at the 50th centile and more consistent performance at the 95th centile than the other GNSS receivers, giving median distance estimates of 0.5–1.1 m. The median horizontal accuracy of inbuilt GNSS receivers in this trial was 0.9–3.4 m under 'open sky' conditions.
4. *Practical implication*: The smartphone GNSS receivers that we tested were accurate to within a few meters. Linking the smartphone with a moderately priced compact/handheld external GNSS receiver significantly improved performance.

KEYWORDS
biological recording, ecology, fieldwork, geolocation, GNSS, smartphone, survey

1 | INTRODUCTION

Ecologists require mobile computing for 21-century biological recording (August et al., 2015); the widespread adoption of smartphone apps for navigation and mapping (Google, 2024; What3Words, 2024), and species recording (iNaturalist, LLC, 2014) has presented unique opportunities by allowing data entry whilst in the field (Gibson et al., 2024), with built-in GNSS (Global Navigation Position Systems) receivers providing accurate location metadata attached to recordings from cameras and microphones. External devices can be linked to smartphones producing powerful research tools; examples include high-frequency microphones (Blackburn & Unger, 2019) and thermal imaging cameras (Unger et al., 2019) for bat detection, and a fisheye lens adapter on a smartphone camera yielding hemispherical photographs of tree canopy structure (Cameron et al., 2021).

Smartphones are widely available for use by researchers and citizen scientists; over 80% of the population across China, Europe and North America were using smartphones and mobile internet by 2022 (GSMA, 2023). The smartphone has been widely adopted by volunteers and staff members as a data logging tool during a peatland restoration programme on Chat Moss, Greater Manchester, UK (Lancashire Wildlife Trust, n.d.), the inbuilt GNSS being used for capturing geo-tagged photographic time series, mapping and site monitoring (Osborne et al., 2021). Plant species translocations are recorded digitally via the versatile Epicollect5 data-gathering platform (Aanensen et al., 2009; CGNS Team, 2019–2022), which facilitates efficient data logging and improves workflow with secure data transfer for desk-based processing. Increasing use has driven the requirement for high accuracy geolocation to log translocations of individual plants for subsequent follow-up (Hartley, 2023). During the post-release monitoring of a large heath butterfly (*Coenoympha tullia*) species reintroduction programme (Osborne, 2022; Osborne et al., 2024; Osborne & Coulthard, 2022) the flights of individual butterflies were accurately tracked using GNSS, to establish the fine-scale relationship between point occupancy and environmental data obtained from geolocated survey quadrats and habitat island perimeters geolocated from walked transects. These studies necessitated meter-scale absolute horizontal accuracy of geolocation, together with the rapid reestablishment of position-fix whilst roaming across the nature reserve and tracking butterflies in flight. During these studies mapping applications were used extensively to plan the site surveys. More broadly, the use of geographical information systems (GIS) has been advocated for the selection of random survey points for ecological field work (Kermorvant et al., 2019), in preference to commonly used 'haphazard' sampling protocols, such as random walks (Smith et al., 2017). Clearly defining the study area (based on a site map) prior to the site visit, results in good sample-coverage across the study area and the randomization process yields a spatially balanced, statistically valid sample. However, the spatial scale of the survey is constrained by the resolution of the geolocation data, potentially limiting the use of this method for fine-scale habitats—having a clear picture of the horizontal accuracy and precision of the GNSS device employed to geolocate survey points is therefore essential.

Previous studies have determined the average horizontal accuracy of various GNSS receivers during static surveys in mixed environments; for smartphone GNSS receivers—6.50 m (Garnett & Stewart, 2015), 6.55 m (Senanayake et al., 2018), 7–13 m (Merry & Bettinger, 2019)—and for compact/handheld GNSS receivers—1.4–19.6 m (Wing et al., 2005), 4–26 m (Abdi et al., 2014), 3.65–4.77 m (Garnett & Stewart, 2015), 2.07 m (Senanayake et al., 2018)—and in dynamic testing, median distance from the true line approximately 2 m (Ucar et al., 2014). However, these studies of the accuracy of consumer-grade GNSS are now 5–10 years old and GNSS technology has evolved significantly during this time (Yasyukevich et al., 2021), potentially offering useful improvements in performance. To have full confidence in the reliability of commonplace consumer-grade GNSS technology for use in professional or research settings it is necessary to gain an objective assessment of the horizontal accuracy of the most exact position measurements and additionally the precision (distribution or spread) of inexact position measurements (Menditto et al., 2007). Smartphones are now widely available to ecologists; these versatile tools offer numerous advantages for increased efficiency and innovative working practices in ecological fieldwork.

In order to gain improvement on the performance of consumer-grade GNSS technology, for fine-scale work, we identified an economically priced compact/handheld surveyor-grade GNSS receiver; the device links via Bluetooth (Figure 1a) and replaces the function of the smartphone's internal GNSS receiver, hence conserving the phone's battery life, an additional benefit during prolonged field use. This field study aimed to

1. validate the horizontal accuracy and precision of the surveyor-grade GNSS receiver and to test the hypothesis that its performance is significantly better than commonly used control devices—smartphones' inbuilt GNSS receivers and a standard-grade external GNSS receiver;
2. determine the performance of the GNSS receivers in static surveys and additionally assess performance in dynamic situations, replicating common working practices in ecological fieldwork, whilst challenging the capability of the GNSS receivers; and
3. provide an updated appraisal of the reliability of representative models of compact consumer-grade GNSS receivers.

2 | METHODS

Survey protocols were devised to test four GNSS receivers, two newer models and two devices approximately 10 years old; compact/handheld GNSS receivers compatible with iPhones, the Bad Elf Surveyor BE-GNSS-3300 GNSS receiver ('BES') (~£720, Bad Elf LLC, CT 06107–2401) (released 2018) and Bad Elf for Lightening Connector BE-GNSS-1008 ('BELC') (~£150, released 2013), also the inbuilt GNSS receivers of two commonly used smartphones, iPhone 12 Pro ('iP12') (Apple Inc., CA 95014) (released 2020) and iPhone 6 Plus ('iP6') (released 2014).

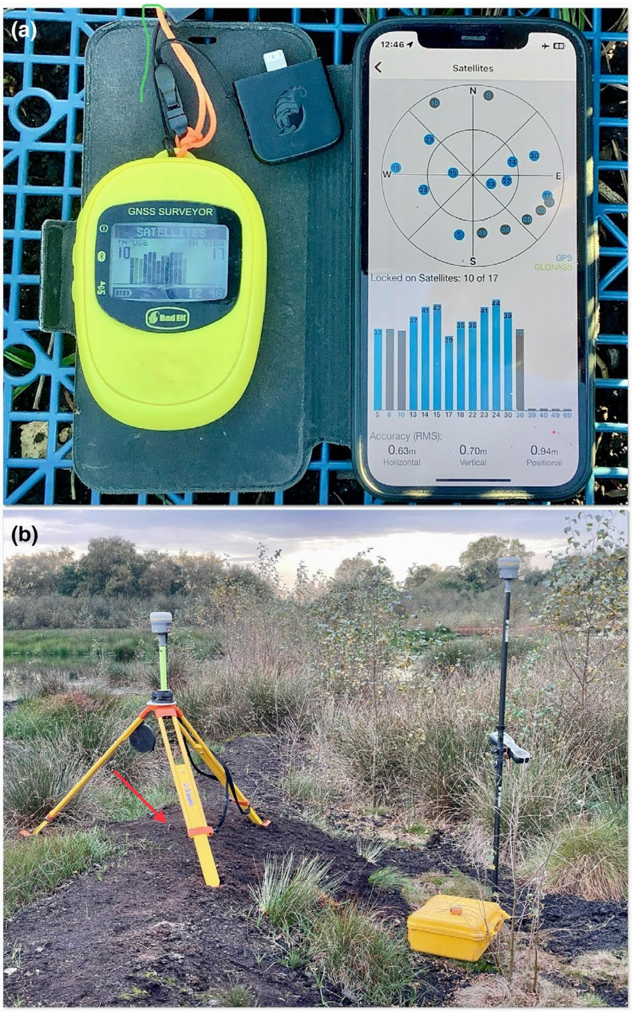

FIGURE 1 (a) Mobile GNSS receivers, iPhone, Bad Elf for Lightening Connector (BELC) (black) and Bad Elf Surveyor (BES) (yellow). The app shows data transmitted from the BES via Bluetooth—the available satellite constellation (grey) and the strongest satellite signals (light blue) used for trilateration and estimated horizontal accuracy. (b) Tripod mounted Trimble R10 located vertically above the base station ground peg (red arrow), the R10 Rover and the narrow east–west running bund—the south–north running bund is visible left off the ground peg.

Devices were placed in a close array on a light mesh plastic tray (Figure 1a), mounted horizontally, facing upwards and on the same level so as not to block signals from available satellites to adjacent receivers. GNSS receivers were located within a 10 cm radius of the tray's centroid and the arrangement and orientation of the array varied between protocol repetitions to mitigate any possible local interference from adjacent devices and the operator. Devices were carefully isolated from the internet and each other by switching off Wi-Fi, mobile and Bluetooth, apart from an extra device used to record data received from the BES via Bluetooth. All four receivers were tested at the same time (in preference to performing a series of individual tests) to ensure closely identical atmospheric conditions, satellite constellations (the GNSS receivers having differing ability to lock onto multiple satellites across the various satellite networks) and movement patterns during dynamic tests. GNSS point data were recorded using the myTacks app. (Stichling, 2021-2023) and .gpx files were exported when there was an available Wi-Fi connection.

All measurements were taken on Little Woolden Moss peatland restoration site (53.45, −2.47). This provided 'open sky' GNSS reception, being flat, without buildings or tree canopy cover. A central 'base station' was marked with a ground peg at the intersection of two low peat dams (bunds), with low scrub approximately five meters to the west and north (Figure 1b). A transect running approximately eastward along one bund was established by measuring 12 m and marking the end station with a ground peg ('point ew'). A second transect running approximately southward along the perpendicular bund was established by measuring 12 m and marking the end station ('point sn') with a ground peg. The position of the three reference points were accurately geolocated using a tripod-mounted Trimble R10, a mapping-grade GNSS receiver (Trimble Inc. CO 80021; Figure 1b), centered on the base station ground peg with a second R10, in rover configuration, at the transect end stations. A 5-h static survey was conducted taking one GNSS measurement per second—after post-processing this yielded an absolute horizontal geolocation for each of these datum points with centimetre accuracy.

Three separate surveys were undertaken with each survey protocol repeated on five occasions, on separate days: (A) Fixed base station survey to test the absolute horizontal accuracy and precision (Menditto et al., 2007) of the GNSS receivers during static use; the receiver array was placed on a 60 cm high horizontal table, with the array centroid vertically above the base station ground peg and GNSS measurements recorded for 15 min—approximately 900 GNSS measurements. (B) Walked transect survey to test the horizontal accuracy and precision of line recording by repeatedly walking a short transect (Figures 1b and 4), also the ability of the GNSS receivers to rapidly adjust to changes in direction and orientation; the receiver array was held at head height and the 'ew' transect walked 10 times, following the narrow top of the bund, at a medium pace, between the base station and ew ground pregs, rotating the array through 180 degrees with every turn at the end of each walk of the transect. This transect protocol was repeated for the 'sn' transect—approximately 300 GNSS measurements in total. (C) Roaming point survey to test the ability of GNSS receivers to accurately reestablish geolocation within a timeframe of 10–40 s whilst recording points during surveying or work activity; the receiver array was placed on a 60 cm high horizontal table with the array centroid vertically above the base station ground peg, then, with recording paused, the GNSS fix disrupted by moving 10 m away from the base station (watching the position marker on-screen move away from the base station), before returning to the base station; after 10 s of equilibration 30 seconds of GNSS measurements were recorded. This process was repeated 10 times, moving away from the base station in rotation, north, south, east, west—approximately 300 GNSS measurements in total. Before each survey repetition, each receiver was checked to ensure that it had established a stable position fix. GNSS measurements were recorded at a rate of one per second throughout. Measurements were conducted in good weather conditions (no precipitation and low windspeed) on separate days between October 2023 and January 2024 to assess the performance of GNSS receivers under a variety of satellite constellation configurations and conditions in the upper atmosphere (ionosphere and troposphere), which interfere with the GNSS radio signal (Klobuchar & Kunches, 2003).

Coordinate reference system (CRS) transformations were conducted using a high-accuracy (2 cm) conversion tool (Wilton-Jones, 2021). Data processing was performed in R (v.4.0.4) (R Core Team, 2021) using Rstudio (v.1.4.1106) (R Studio Team, 2021). GPX tracks were imported into R using the 'htmlTreeParse' function in package 'XML' (Lang and CRAN Team, 2013) and then the longitude and latitude coordinates of position measurements extracted using the 'xpathSApply' function. For each GNSS position measurement, the distance from the fixed datum was estimated; in the fixed base station trial and roaming point trial, Euclidean distances from the base station were calculated using the 'spDistsN1' function in package 'sp' (Pebesma & Bivand, 2012). In the transect survey, the perpendicular distance from the transect line was calculated using geometry and trigonometry functions in base R.

A similar statistical analysis was repeated for each survey protocol to compare the distance estimates from the four GNSS receivers within each survey protocol. As an initial exploration of the data, density plots were generated, with the 'bin-width' set to 0.1 m. To concisely describe the median accuracy of distance estimates the 50th centile of the Euclidean/radial distance (RD50) was reported. To describe the precision of distance estimates (excluding outliers) the 95th centile of the Euclidean/radial distance (RD95) was reported; comparable 50th centiles and 95th centiles were adopted for the perpendicular distance from the transects in the walked transect survey. Maximum distance estimates were also reported to quantify the extent of outlier distance estimates. Distance estimates at the 50th centile and 95th centile were determined for each repetition and, based on the number of GNSS measurements in each group, the weighted mean and weighted standard deviation of these grouped centile estimates calculated using the 'wtd.mean' function and the 'wtd.var' functions in package 'Hmisc' (Harrell Jr, 2019).

For each survey, the difference between the distributions of distance estimates from the four GNSS receivers across all five

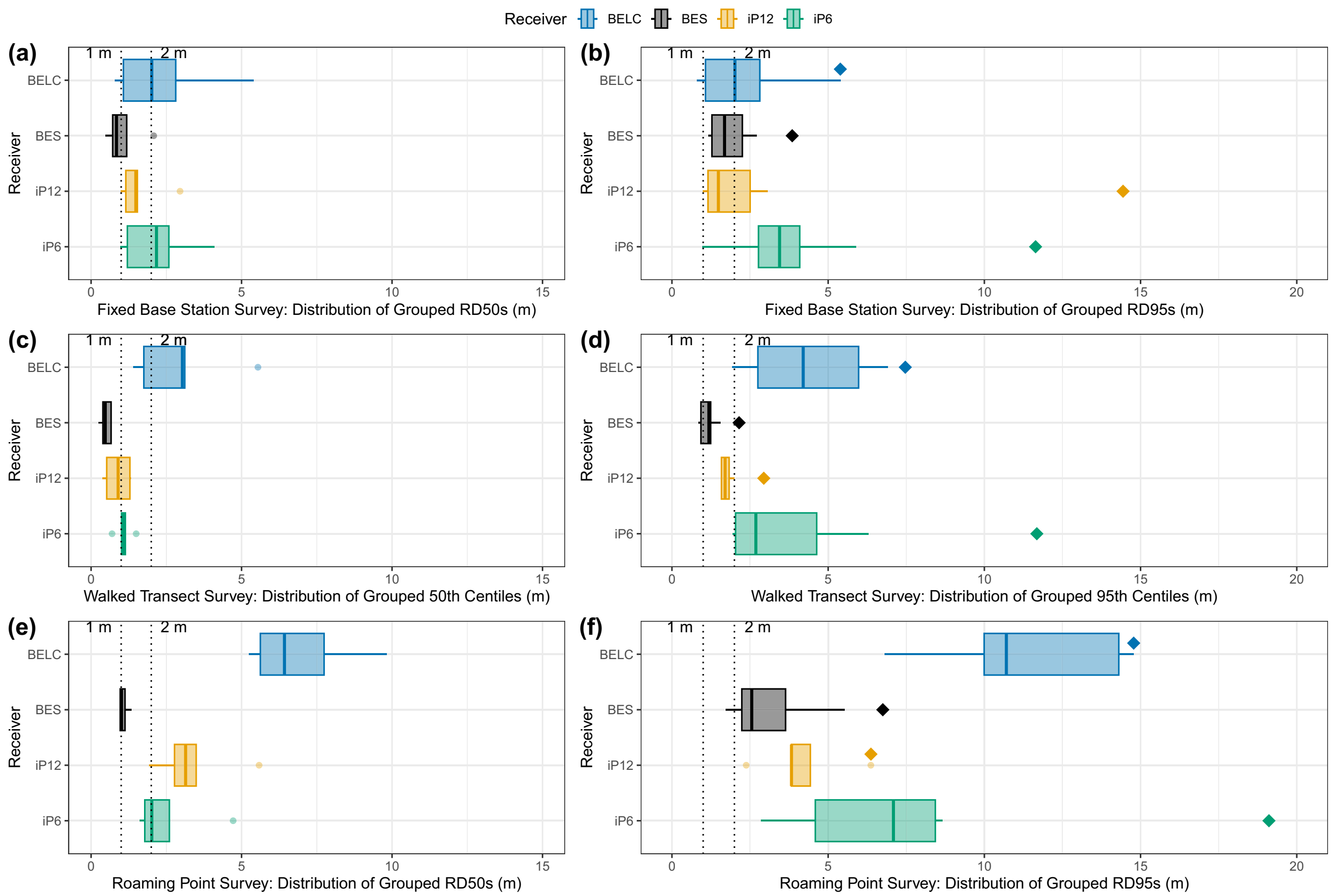

FIGURE 2 Boxplots of grouped results showing distance estimates from the datum at the 50th and 95th centiles; (a and b) fixed base station survey, (c and d) walked transect survey, (e and f) roaming point survey. Maximum individual distance estimates are shown as diamonds in (b, d, f). BELC indicates Bad Elf for Lightening Connector, BES indicates Bad Elf Surveyor, iP12 indicates iPhone 12 Plus and iP6 indicates iPhone 6 Plus. BES has the lowest distance estimates overall.

repeat measurements, and the interaction of receiver*repeat were compared using permutational analysis of variance (PERMANOVA) (Anderson, 2014) using the 'adonis2' function in package 'vegan' (Oksanen et al., 2020) with a Euclidean dissimilarity distance matrix. The difference in the distribution of distance estimates between pairs of receivers across all five repeat measurements was analysed using the 'pairwise.adonis2' function in package 'pairwiseAdonis' (Martinez Arbizu, 2017) with the strata set to 'receiver'.

The distribution of longitude and latitude measurements in the fixed base station survey were tested for normality using the shapiro.test function in base R and tested for difference from the base station datum using the one-sample Wilcoxon rank sum test in base R. The directional bias of each receiver was estimated using trigonometry functions in base R.

3 | RESULTS

The distribution of grouped 50th and 95th centile distance estimates, and the maximum individual distance estimates are shown in Figure 2. The BES demonstrates the most consistent horizontal accuracy and precision in all three surveys—in the static survey, RD50 1.1 ± 0.6 m, RD95 1.8 ± 0.6 m, with the iP12 performing better than the older receivers (Supporting Information S1). Density plots demonstrating the overall distribution of distance estimates are shown in Supporting Information S2.

The horizontal accuracy and precision of GNSS measurements for BES are demonstrated in Figures 3–5 and plots comparing all four GNSS receivers are demonstrated in Supporting Information S3–S5.

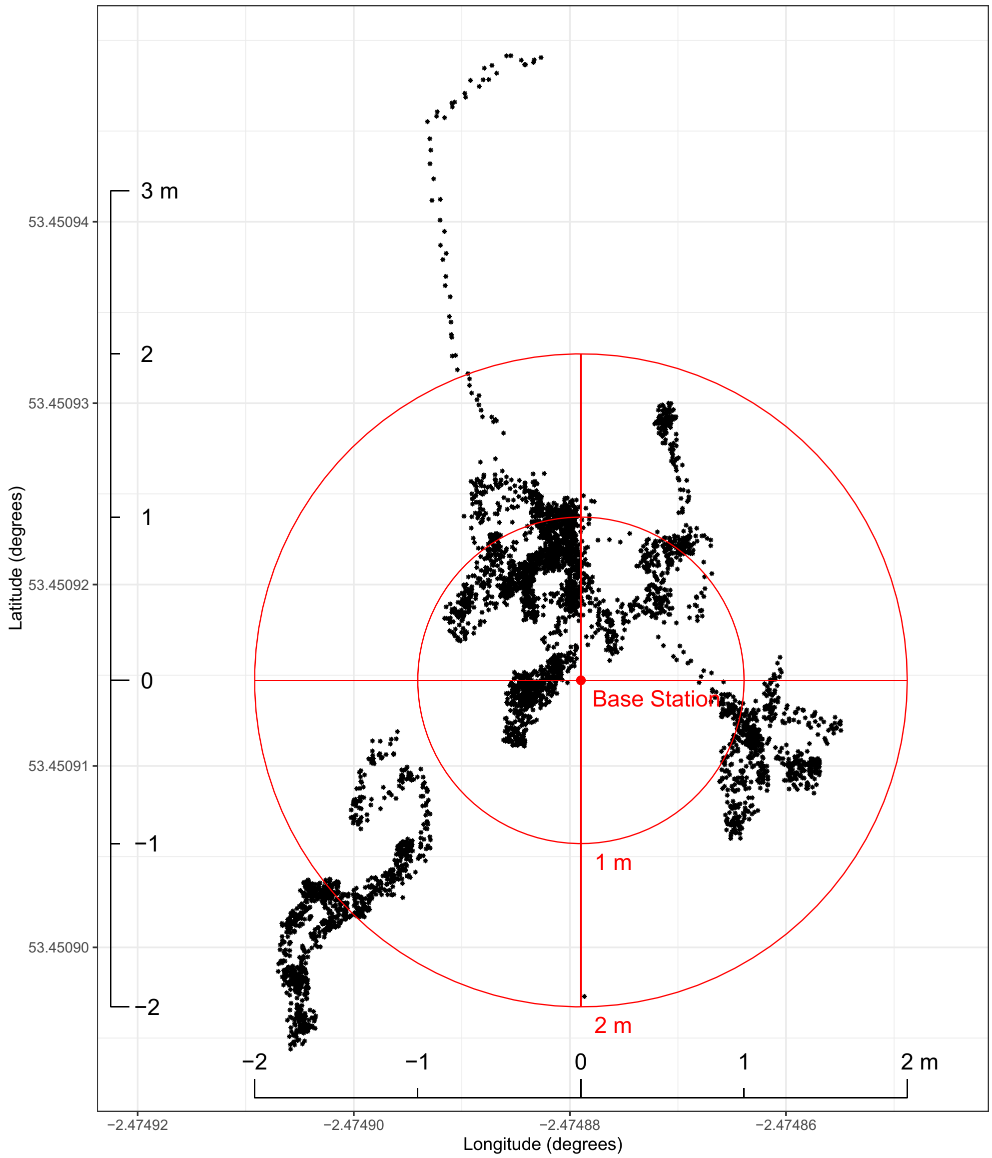

FIGURE 3 GNSS position measurements recorded by the Bad Elf Surveyor GNSS receiver (BES) during the fixed base station survey and 1 and 2 m radii (red) around the base station.

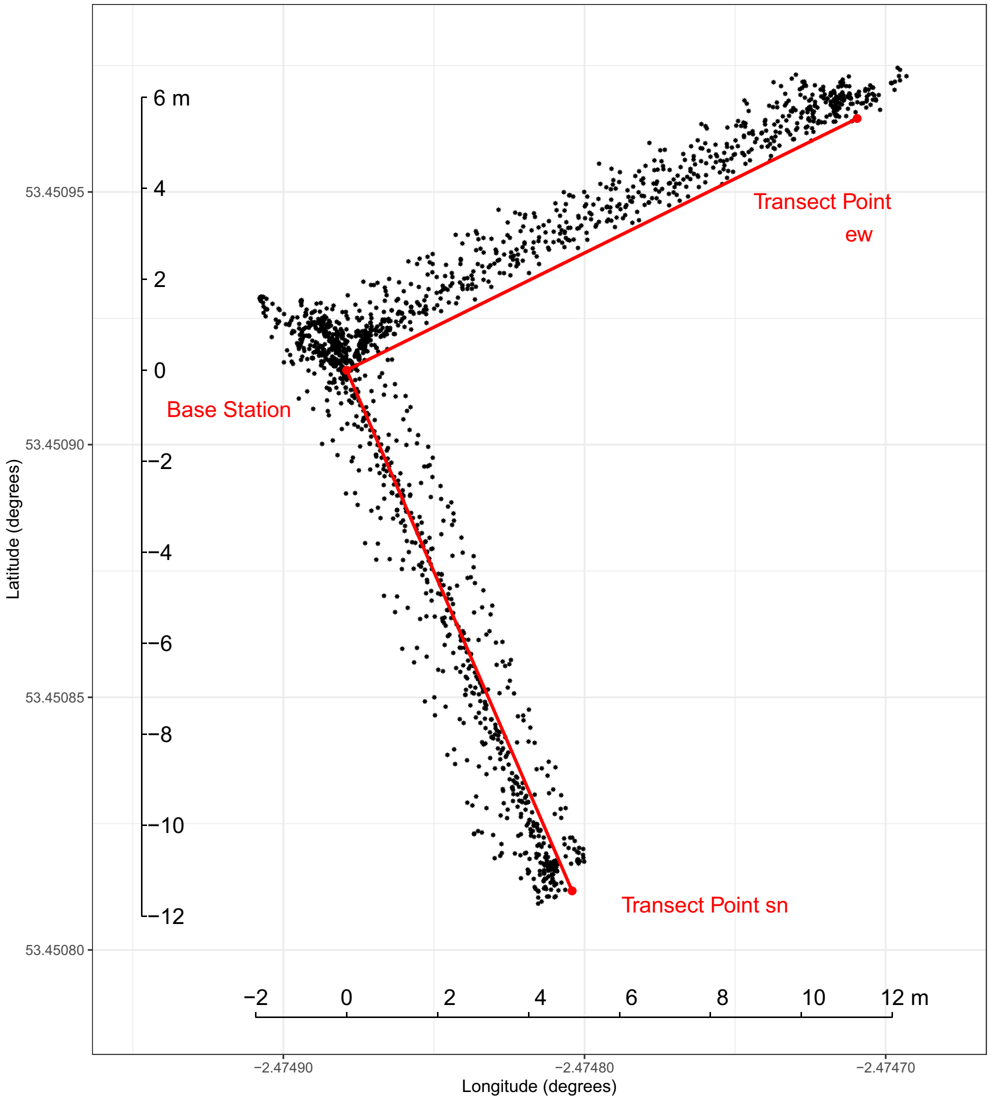

FIGURE 4 GNSS position measurements recorded by the Bad Elf Surveyor GNSS receiver (BES) during the transect survey and the ew and sn transect lines (red).

The PERMANOVA analysis demonstrates significant differences in GNSS receiver accuracy ($p = 0.001$) in all three survey protocols and significant differences in GNSS performance between repeat measurements in all three survey protocols ($p = 0.004$; Supporting Information S6). The pairwise PERMANOVA (Supporting Information S7) confirms significant differences between all pairs of GNSS receivers ($p = 0.001$), confirming the significance of the variations in performance observed between receivers (Figure 2).

In the fixed base station survey, the distributions of latitude and longitude measurements for all four GNSS receivers were significantly different from normal ($p < 0.001$) and the mean position was significantly different from the datum ($p < 0.001$). Directional bias; BELC 1.36 m at 12 degrees, BES 0.36 m at 276 degrees, iP12 1.00 m at 72 degrees, iP6 1.81 m at 113 degrees (Supporting Information S3 and S8).

4 | DISCUSSION

In this study, the specialist surveyor grade GNSS receiver performed significantly better than the control devices with lower horizonal distance estimates at the 50th centile and more consistent results at the 95th centile and maximum outlier, across all three survey protocols (Figure 2 and Supporting Information S1–S8). The newer smartphone performed more consistently (Figure 2) than the older devices which were 10 years old at the time of the study. All four receivers showed small, but statistically significant directional bias, which was least for the BES at 0.36 m (Supporting Information S3 and S8), with no overall clustering in cardinal direction, similar to previous studies (Merry & Bettinger, 2019). A significant part of the variation in our testing (Supporting Information S6) occurred between repeat measurements, illustrating the variability in GNSS performance as a potential source of error in geospatial work.

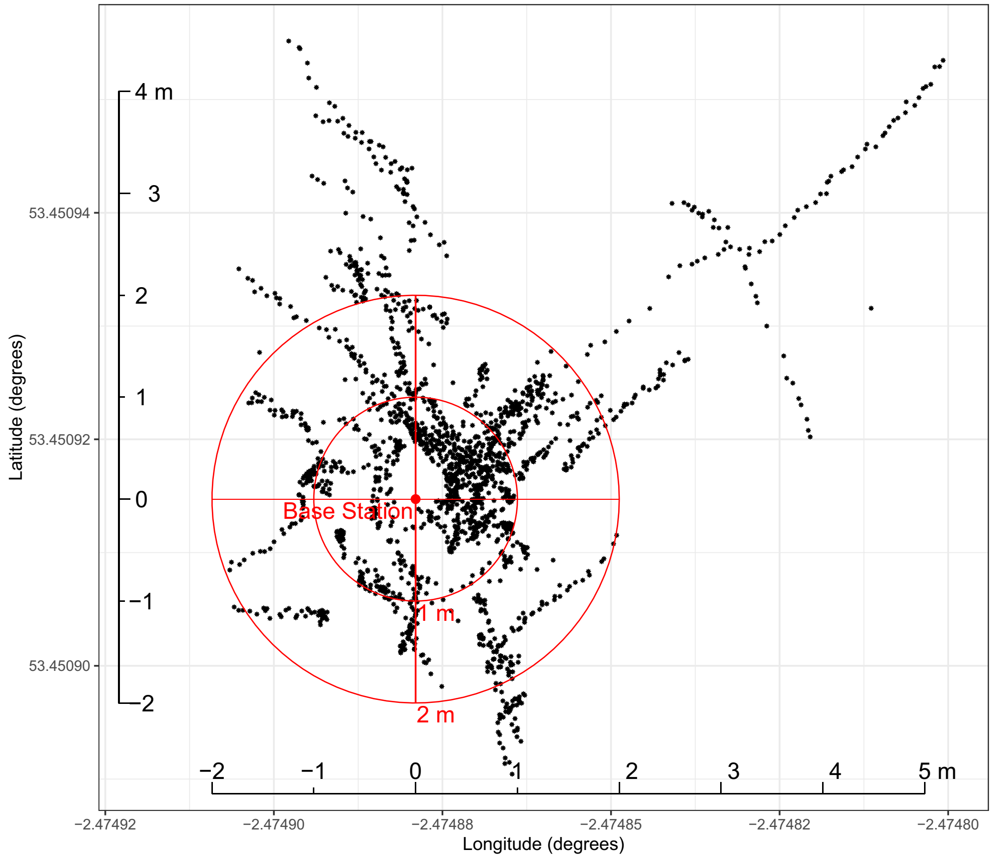

FIGURE 5 GNSS position measurements recorded by the Bad Elf Surveyor GNSS receiver (BES) during the roaming point survey and the 1 and 2 m radii (red) around the base station.

The horizontal accuracy and precision of the older GNSS receivers was better than anticipated from previous studies (Merry & Bettinger, 2019), although our study was conducted under optimal 'open sky' conditions. There is an ongoing evolution in GNSS technology, with increasing numbers of satellites available for trilateration as well as an improved carrier signal, which (within the constraints imposed by the GNSS receiver's outdated hardware) enhances the performance of the older GNSS receivers (Yasyukevich et al., 2021). The directional bias that we measured may result from the characteristics of the individual GNSS receivers, which are being tested at the operational limits for compact/handheld devices, but could be related to the GNSS network, interference from local conditions on the ground, or neighbouring devices in the array. Our current experiments were designed primarily to quantify and compare distance estimates from the datum—by testing the receivers in parallel our experimental design prioritised controlling measurement conditions (potentially introducing meter range errors as the position-fix 'drifts' from minute to minute). However, testing all the receivers together within an array, with devices displaced horizontally by up to 10 centimetres, constrained the absolute horizontal accuracy of distance estimates to 0.1 m.

There were several variables which had to be managed during data gathering, the importance of which could be investigated in future work. Smartphone mobile data were turned off, deactivating 'Assisted GPS' which uses cellular data to improve GNSS function. Additionally, we deactivated the 'point averaging function' in the recording app which potentially improves the precision of transect measurements. Whilst operating the array of GNSS receivers during the trial we attempted to minimise potential interference with GNSS reception caused by the operator shadowing devices from the sky, reducing the number of available satellites and hence GNSS performance—this effect appeared to be minimal but would be interesting to quantify.

With the continued to evolution of solid-state technology during the first quarter of the 21st century (Shalf, 2020), a range of devices has superseded the compact/handheld surveyor-grade GNSS receiver tested in this study—the more expensive models offering centimetre accuracy and the basic model having similar performance but costing approximately 25% less. Additionally, other manufacturers are now marketing similar quality devices. We appraised the performance of the inbuilt GNSS receiver in two models of one of the most widely used smartphones, as well as an older standard grade GNSS receiver; it was not possible to test all off the large and evolving range of makes and models of GNSS devices, however it would easily be possible for teams to set up datum points on campus or field sites to appraise their devices as we have outlined.

5 | CONCLUSIONS

The smartphones that we tested are powerful data-logging tools and the remarkable horizontal accuracy and precision of these widely available handheld GNSS devices encourages their use in ecological practice and research. Inbuilt GNSS receivers are currently accurate to within a few meters, which is sufficiently accurate for biological recording and routine navigation. For fine-scale geospatial work 'Pairing' the smartphone with a moderately priced compact/handheld external GNSS receiver significantly improves performance, when one-meter absolute horizontal accuracy is required.

AUTHOR CONTRIBUTIONS

Andrew Osborne conceived the ideas and design methodology. Andrew Osborne and Hannah Mossman collected the data. Andrew Osborne, Hannah Mossman and Emma Coulthard analysed the data. Andrew Osborne led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/2688-8319.70015.

DATA AVAILABILITY STATEMENT

Data and R scripts are available from Manchester Metropolitan University e-space https://doi.org/10.23634/MMU.00637959 (Osborne et al., 2025).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Supporting Information S1. Weighted means and weighed standard deviations (SD) for grouped distance measurements at the 50th and 95th centiles, and the overall maximum distance recorded.

Supporting Information S2. Density plots comparinging the frequency of estimates of the distance from the datum obtained from GPS position measurements during the three survey protocols; (A) fixed base station survey, (B) walked transect survey, and (C) roaming point survey.

Supporting Information S3. GPS points recorded in the fixed base station (53.450914719012, −2.4748789803808) survey.

Supporting Information S4. GPS points recorded during the walked transect survey; (A) transect between the base station and 'ew' transect point (53.450964541335, −2.4747094849943). (B) transect between the base station and the 'sn' transect point (53.4508116952, −2.4748041248861).

Supporting Information S5. GPS points recorded during the roaming point survey.

Supporting Information S6. PERMANOVA analysis comparing the difference in distance estimates between receivers, repeat measurements and their interaction during the three survey protocols.

Supporting Information S7. Pairwise PERMANOVA analysis, comparing the difference in distance estimates between pairs of GPS receivers during the three survey protocols.

Supporting Information S8. Analysis of the distribution of longitude and latitude position measurements (from all 5 repetitions aggregated) in relation to the base station datum (53.450914719012, −2.4748789803808) in the fixed base station survey.

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