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TECHNICAL REPORT

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Orienting paleomagnetic drill cores using a portable GPS compass

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Abstract: A portable Global Positioning System (GPS) compass was devised for orienting paleomagnetic drill cores and field test measurements were conducted. Orientation of drill cores has been done by magnetic compasses, sun compasses, and backsighting using landmarks. We modified a lightweight marine GPS compass to be mounted on an orientation device and directly measure azimuths, and compared them to measurements made with a magnetic compass, sun compass, and backsighting. Tests on our campus for a site with open sky above showed a root-mean-squared (rms) error of 0.39°, which is less than what is noted on the specifications of the GPS compass, and a difference of −0.1° ± 1.1° (average ± rms) between the GPS and sun azimuths for 11 direction measurements. However, the site between buildings showed an average deviation of 11.4° from the sun azimuth due to multipath effects. When tested on drill core sampling of historical lavas in a volcanic island, the GPS azimuths were deviated only by 0.4° ± 2.3° from the sun azimuths at a flat coastal site with open sky above, indicating that the GPS azimuths are as accurate as the sun azimuths. On the other hand, the GPS compass could not provide azimuths at vertical outcrops in forests due to the small number of satellites captured and multipath effects. If other Global Navigation Satellite Systems (GNSS) satellites are captured and false signals caused by multipath are eliminated, portable GNSS compasses, which operate regardless of rock type, weather, or geographic situation, would replace other methods of orienting drill cores.

Keywords: GPS compass, Oriented samples, Sampling, Paleomagnetism

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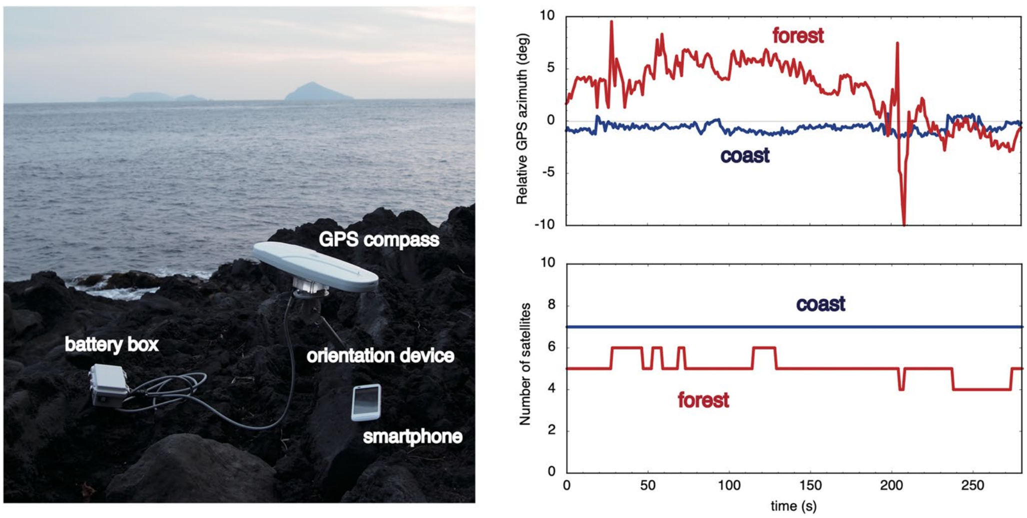
Graphical Abstract



Introduction

Paleomagnetic or archeomagnetic secular variations are currently modeled based on spherical harmonics series as the recent geomagnetic field (e.g., Korte and Constable 2011; Brown et al. 2021), which requires more accurate and reliable paleomagnetic field data to be accumulated. Orienting paleomagnetic samples at outcrops is an indispensable initial step for uncovering remanence directions and greatly affects the accuracy of resulting paleomagnetic field directions. Drilled cores by hand-carried engine or electric drilling devices can be more precisely oriented than block samples (Turner et al. 2015), therefore directional secular variation studies have relied on the drill cores especially from igneous rocks. Orientations of drill cores are usually determined by azimuth and plunge. Although plunge is unambiguously determined with an inclinometer, measuring azimuth angles needs more careful examination by a combination of magnetic or other kinds of compasses.

Magnetic compasses are most often used to measure the azimuth of drill cores because they are compact, easy to handle, and more importantly they can operate irrespective of weather or surrounding conditions. Present magnetic declination values at sampling sites can be drawn from regional or global geomagnetic field models (e.g., Alken et al. 2021). The azimuth measured by a magnetic compass is expected to be properly corrected by the declination value, but measuring azimuth of paleomagnetic samples by a magnetic compass is inherently problematic. In particular, strongly magnetized igneous rocks such as basalts can generate a magnetic field strong enough to alter localized field even within a single outcrop. The magnetic north is usually checked by a sun compass or backsighting at sampling sites, taking some distance from outcrops. However, the orientation of each drill core is rarely examined by a combination of several independent orienting methods.

Orienting each drill core by a sun compass or backsighting is a time-consuming and demanding task. Sunlight enough to operate a sun compass is not always available as it is hampered by clouds, trees or rocks surrounding a sampling site. Backsighting needs distinct landmarks such as sharp mountain peaks or isolated rock bodies that are often difficult to adjust direct sights from an orientation device. An alternative device for independently determining azimuths is a Global Positioning System (GPS) compass; weather condition is no longer a problem to operate, and the signal come from basically overhead, consequently not blocked by surrounding trees or rocks. Lawrence et al. (2009) introduced a GPS compass composed of two GPS receivers for use in Antarctica where sunlight is not readily available. This GPS compass was a large piece of equipment to transport so that each drill core was indirectly oriented using the laser beam with respect to the baseline of the two GPS receivers.

GPS compasses, sometimes called satellite or Global Navigation Satellite Systems (GNSS) compasses, have been used, for example, for automatic solar tracking systems (Wu et al. 2022), for heading in ship navigation (Kakihara 2002; Felski et al. 2020), and more recently for navigation in urban areas (Dabrowski et al. 2020). In this study, a marine GPS compass with two antennas was modified so that it could be directly placed on an orientation device of a drill core. We measured the time variation of the orientation data from the portable GPS compass at a site with open sky above and a site between buildings to determine the initialization time and how it is affected by the surrounding conditions. To find out how accurately drill cores are oriented by the GPS compass, the azimuths were compared with those by sun compass, magnetic compass, and backsighting at sites with different locations, such as on the coast or in the forest.

Methods

A compact GPS compass (ssV-102, Hemisphere GNSS Inc.), which was originally developed for vessel navigation and only 0.98 kg in weight, was attached with an acryl block to be directly mounted on an orientation device of a drill core (Fig. 1). The orientation device has a rotatable turntable with a scale of 1° increments, on which a Brunton compass is usually placed. Because the GPS compass is directly mounted on the orientation device, errors in azimuth caused by indirect connections between the orientation device and the GPS compass can be avoided (Lawrence et al. 2009; Cromwell et al. 2013). The plastic housing [40.5(length) × 15.0(width) × 6.4(height) cm)] accommodates a single board with two GPS antennas to find the direction as well and the position.

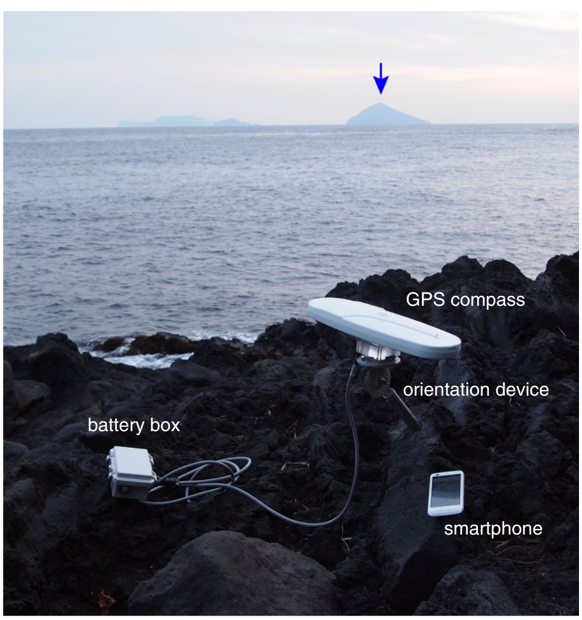


Fig. 1 A portable GPS compass mounted on an orientation device of a paleomagnetic drill core. A battery box supplies DC 12 volts by ten AA rechargeable batteries through a wire, and a smartphone acquires the GPS data through Bluetooth wireless connection. An arrow points to the landmark for backsighting

Electric power of DC 12V was supplied by a waterproof battery box containing ten AA rechargeable batteries. The battery box was modified after the original one supplied by TIMBERTECH Co.,Ltd. To the battery box, the power cable carries back GPS data that were then transmitted by a Bluetooth antenna and received by an Android-based smartphone. Alternatively GPS data can be transferred through a serial port from the battery box to a personal computer.

The GPS compass ssV-102 receives the L1 signal of the GPS system for position and direction measurements (Misra and Enge 2011), but does not receive signals from other GNSS such as Glonass or Beidou. According to the manufacturer's specification, the horizontal position accuracy is 1 m in the differential GPS mode using the Satellite Based Augmentation System (SBAS). The direction between the two antennas 27 cm apart is determined by decoding the phase of L1 carrier waves (wavelength = 19 cm), and the heading accuracy is 0.75° in root-mean-square (rms) as noted in the specification. To use dual phase difference at least four satellites are required for determining the heading. It takes a few minutes for initialization to resolve carrier phase ambiguity (Kakihara 2002). The data protocol is NMEA0183 (Langley 1995), and the National Marine Electronics Association (NMEA) messages ($PSAT,HPR: direction data, $GPGGA: position and other supplemental data) were saved as text files on the smartphone and later transferred to a personal computer for processing. The direction and position data were captured at 1 Hz, and the elevation angle mask was varied up to 45°, although it is usually set to 5°.

We performed test measurements of the GPS compass on the Kyotanabe campus of Doshisha University (lat. = 34.7966°N, lon. = 135.7638°E) at two sites with open sky and between buildings. The open sky site was located in the middle of a softball field. At the site between two parallel three- and four-story buildings, which are spaced about 13 m apart and running approximately east–west, the elevation angles of the buildings were 46° and 63°, respectively. A granite block was plastered and drilled, and the orientation device was inserted into the hole for test measurements on the campus. During field sampling of drill cores GPS compass measurements were taken for a total of 37 cores at three coast sites and three forest sites in Izu Oshima, a volcanic island located about 100 km south of Tokyo, Japan. Historical basaltic lava flows that erupted between fourteenth and eighteenth century were collected. Many paleomagnetic studies have been conducted on these lava flows (e.g., Nagata et al. 1963; Yoshihara et al. 2003; Mochizuki et al. 2004).

Azimuths were also measured by sun and magnetic compasses for comparison with the GPS compass. The sun compass was operated using the Brunton compass mounted on the turntable of the orientation device (Ueno et al. 1997), contrary to commonly used gnomon. The time required for calculation of the sun compass azimuth was determined by a radio watch receiving JJY time signals transmitted at 40 kHz by National Institute of Information and Communications Technology (NICT). The magnetic strike was also measured with the same Brunton compass. Declination corrections were based on the International Geomagnetic Reference Field (IGRF) model (Alken et al. 2021). For drill cores, azimuths were also obtained by backsighting using the Brunton compass at sites with a clear view of sea stacks or islands that would serve as target landmarks (Fig. 1). Azimuths between the sampling sites and the targets were calculated using digital maps after sampling. At additional three sites in Izu Oshima, measurements by sun and magnetic compass and backsighting were performed for comparison. The azimuths measured by sun, GPS, magnetic compasses, and backsighting are referred to as sun, GPS, magnetic, and backsighting azimuth, respectively.

Results

Test measurements on our campus

On our campus, we estimated the initialization time of the GPS compass at the site with open sky. GPS signals from 7 to 11 satellites could be detected for about 5 min after the GPS compass was turned on (Fig. 2). However the latitude and longitude changed dramatically with the number of satellites, and the direction shifted gradually and was not stable. Therefore, we considered that it would take about 5 min to initialize the GPS compass and decided not to record data for the first 5 min.

We measured GPS and magnetic azimuths relative to the sun azimuth, as rotating the turntable of the orientation device by approximately 30°. After 5 min of initialization with the GPS compass, about 1800 directional data were acquired at 1 Hz for about 30 min for each heading, and the averages and rms were calculated for the 11 headings (Fig. 3, Additional file 1: Table S1). There seems to be no obvious dependence of the relative GPS and magnetic azimuths on the sun azimuth. Although the sun azimuth itself contains errors, the two differences are in the range of $\pm 2.5°$. The averaged rms of the GPS azimuth is 0.39°, which is less than the value of 0.75° in the manufacturer's specification. Averaged over the 11 headings, there is no significant discrepancy between the three pairs from the sun, GPS and magnetic azimuths (Additional file 1: Table S1). The averages and rms represent the accuracy and precision of the GPS compass in open sky, and those of the magnetic compass where strongly magnetized rock body is absent.

Temporal variations of the GPS azimuths relative to the sun compass and the numbers of satellites that were able to capture the GPS signal are shown in Fig. 2 for the open sky site and the site between buildings. In both cases, the elevation mask was set to 5°. Except for the first 5 min of initialization, the azimuths at the open sky site stayed within a few degrees from the sun azimuth, whereas the GPS azimuths at the site between buildings showed large deviations from the sun azimuth varying widely from 5° to 19°. The number of satellites was stable at 8 or 9 in the open sky site, whereas it kept fluctuating between 5 and 8 at the site between buildings.

Figure 4 shows the time-averaged GPS azimuths and satellite counts with their rms for the open sky site with an elevation mask from 5° to 45°, compared to the site between buildings with an elevation mask of 5°. The average deviations from the sun azimuth were less than 1° and the rms were small for the elevation masks from 5° to 35°, but at 45° the average deviation was increased to 3.28° and the rms was 2.83°. The numbers of satellites were around 8 for the elevation angles from 5° to 25° and the variation was small. At 35° it was decreased to 5 ± 1.5, and it was only 4 and did not change with time at 45°. Despite the relatively large number of satellites 6.2 ± 0.8 at the site between buildings, the GPS azimuth deviation $11.39° \pm 2.97°$ was extremely large. Although the site between buildings seems to be receiving signals from sufficient number of satellites, the directional deviation should be due to the multipath effect, in which false signals are reflected by the buildings rather than directly transmitted from the satellites to the GPS compass.

Orienting drill cores of historical lavas in Izu Oshima

At sampling sites in Izu Oshima, the GPS compass was turned on and stood by for approximately 5 min for initialization, then measurements were taken for about 5 min for each drill core to obtain an averaged azimuth. The elevation mask was set to 5°. Temporal variations of GPS azimuth and number of satellites at two sites situated on the coast and in forest are shown in Fig. 5. At the flat coastal site, the GPS azimuth varied less than 1° from the sun azimuth and the number of satellites remained constant at seven. At the forest outcrop, in contrast, the azimuth showed large variations of $\pm 10°$ and the number of satellites varied repeatedly between 4 and 6. The small number of satellites captured at the forest site is due to covering trees or the rock body that makes up the vertical outcrop. Multipath may induce the large deviations and variations of the GPS azimuth.

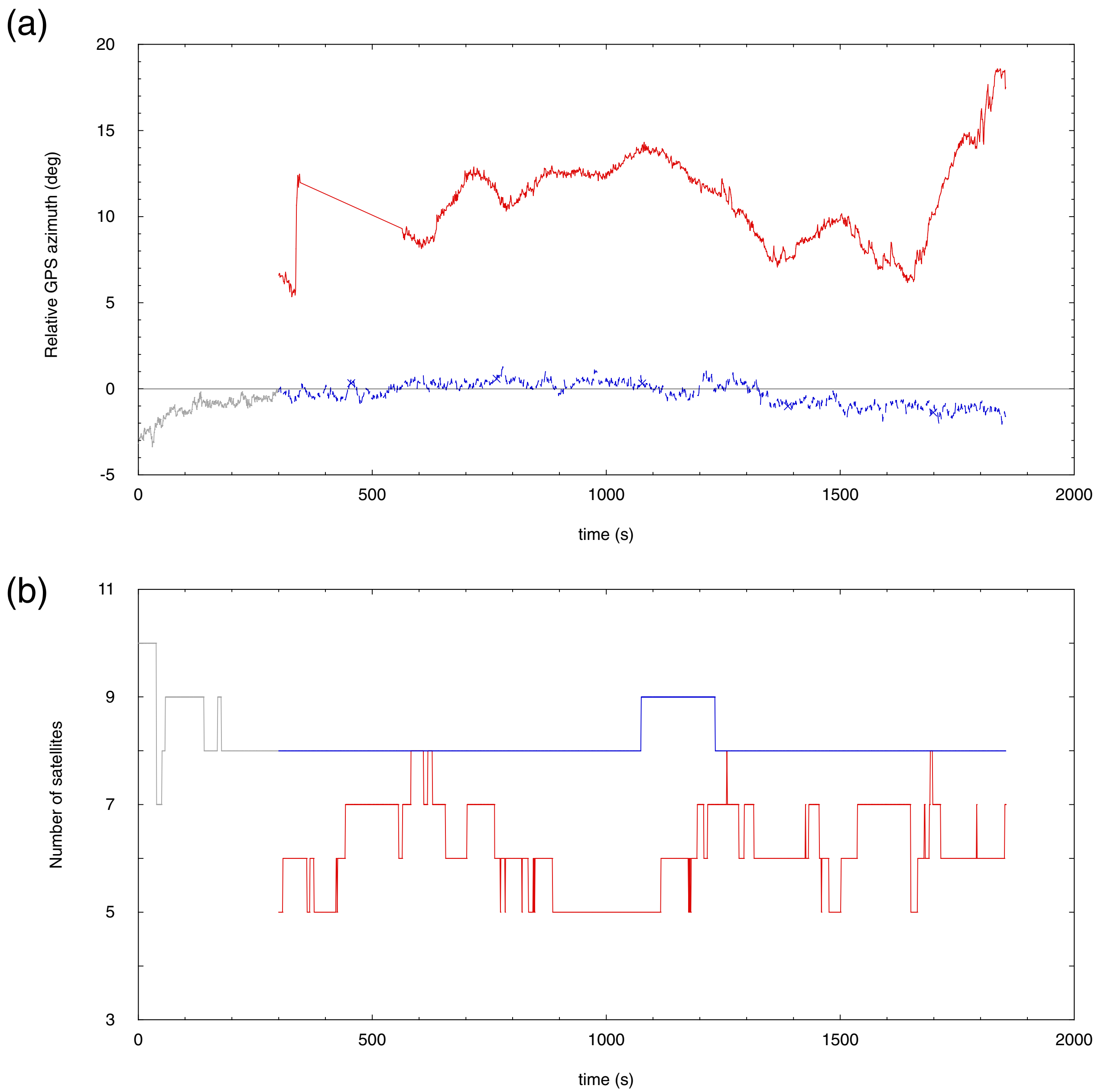


Fig. 2 Temporal variations of **a** azimuths measured by the GPS compass relative to the sun compass and **b** numbers of satellites captured for the GPS signals, at a site with open sky (blue) and a site between buildings (red). The first 5 min at the open site, shown in gray, did not give reliable azimuths due to initialization of the GPS compass. At the site between the buildings, data were not collected during the first 5 min

Time-averaged GPS azimuths and their rms were calculated for 35 drill cores at coastal and forest sites, and azimuths were not adopted if the rms were greater than 2° for the 5 min time series. The GPS azimuths were obtained for 22 of the 26 cores at the three coastal sites, but none of the 11 cores at the three forest sites yielded GPS azimuths (Additional file 1: Table S2). The difference between GPS and sun azimuths has the average of + 0.4° with a rms of 2.3°. Including magnetic compass and backsighting results at the other three sites where GPS compass measurements were not taken, the magnetic azimuth was − 1.8° ± 5.2° and the backsighting azimuth was − 0.2° ± 1.5° with respect to the sun azimuth (Fig. 6). The remaining three differences (GPS-backsighting, GPS-magnetic and magnetic–backlighting azimuths) were also determined. The three differences involving the

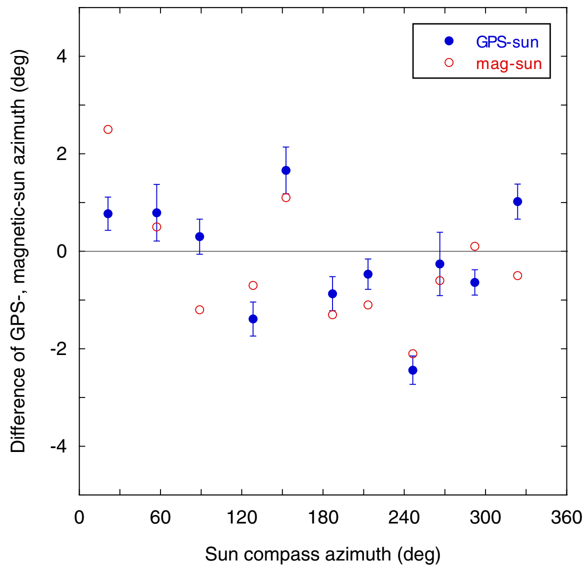


Fig. 3 Azimuths measured by the GPS and magnetic (mag) compasses relative to the sun compass for 11 different directions. At the measurement site the sky above is open and the elevation mask was set to 5°. For the GPS compass, azimuthal data were acquired for about 30 min at 1 Hz, and the root-mean-squares are indicated by vertical bars

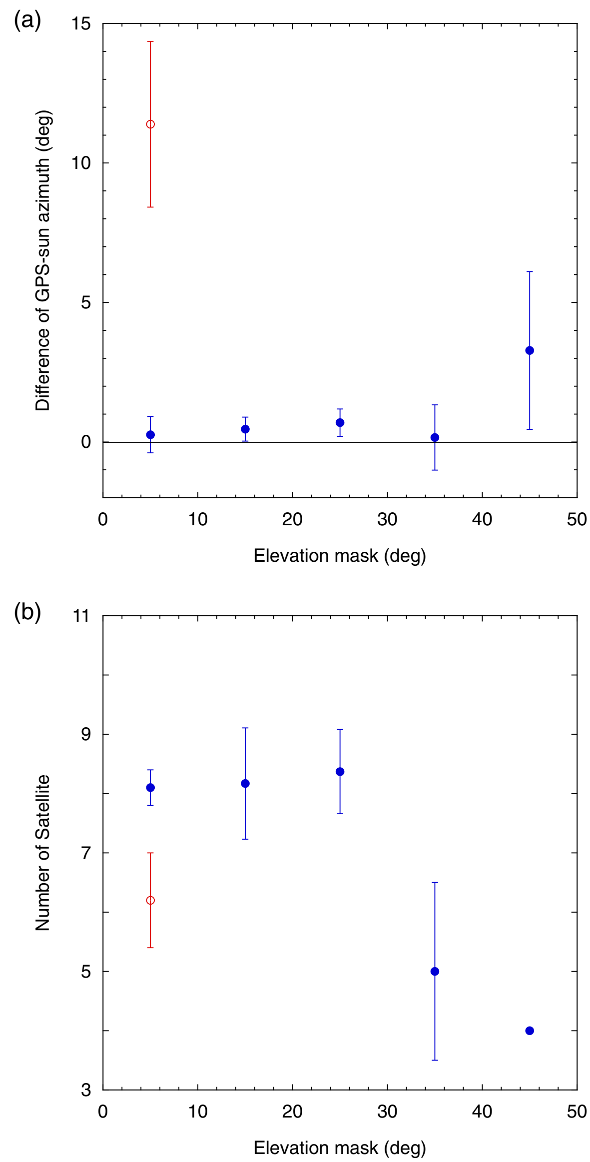


Fig. 4 **a** Azimuths and **b** numbers of satellites for varying elevation mask at a site with open sky (blue) and a site between buildings (red). The root-mean-squares are indicated by vertical bars. For 45°, the number of satellites was constant at four

magnetic azimuth showed larger deviations and larger rms than the other three differences. The GPS compass and backsighting have about the same accuracy and precision as the sun compass, but those of the magnetic compass are much poorer. The differences between the magnetic and sun azimuths are more than 10° in some cores, and even if taking averages for individual sites the site averages still exceed 2° at several sites. The historical lavas in Izu Oshima are strongly magnetized as shown by the natural remanent magnetization intensity of total average and rms 23.0 ± 11.8 A/m (Additional file 1: Table S2).

Discussion

As has been pointed out (e.g., Butler 1992; Turner et al. 2015), there are still problems with azimuths measured by a magnetic compass especially for strongly magnetized rocks. In test measurements on our campus, although magnetic azimuths were only corrected for declination using the global IGRF model, the deviations from the sun azimuth showed a maximum of 2.5° and an average of − 0.29° ± 1.21° for 11 directions (Fig. 3, Additional file 1: Table S1). These values are better than the normally considered magnetic compass accuracy of 3° (Tauxe 2010). This is because the measurements were taken at a place where no strongly magnetized rock is located nearby. When sampling rocks with low magnetization (e.g., sedimentary rocks), the combination of the magnetic compass and the declination correction by a global or regional model will lead to obtain a precise azimuth.

In sampling of historical basaltic lavas in Izu Oshima, however, the maximum deviation of the magnetic azimuth from the sun azimuth was 13.8° and the average was − 1.8° ± 5.2° for 55 drill cores (Fig. 6, Additional file 1: Table S2). Although the total average of azimuthal displacement is small, erroneous magnetic azimuths lead to declination errors of the mean paleomagnetic

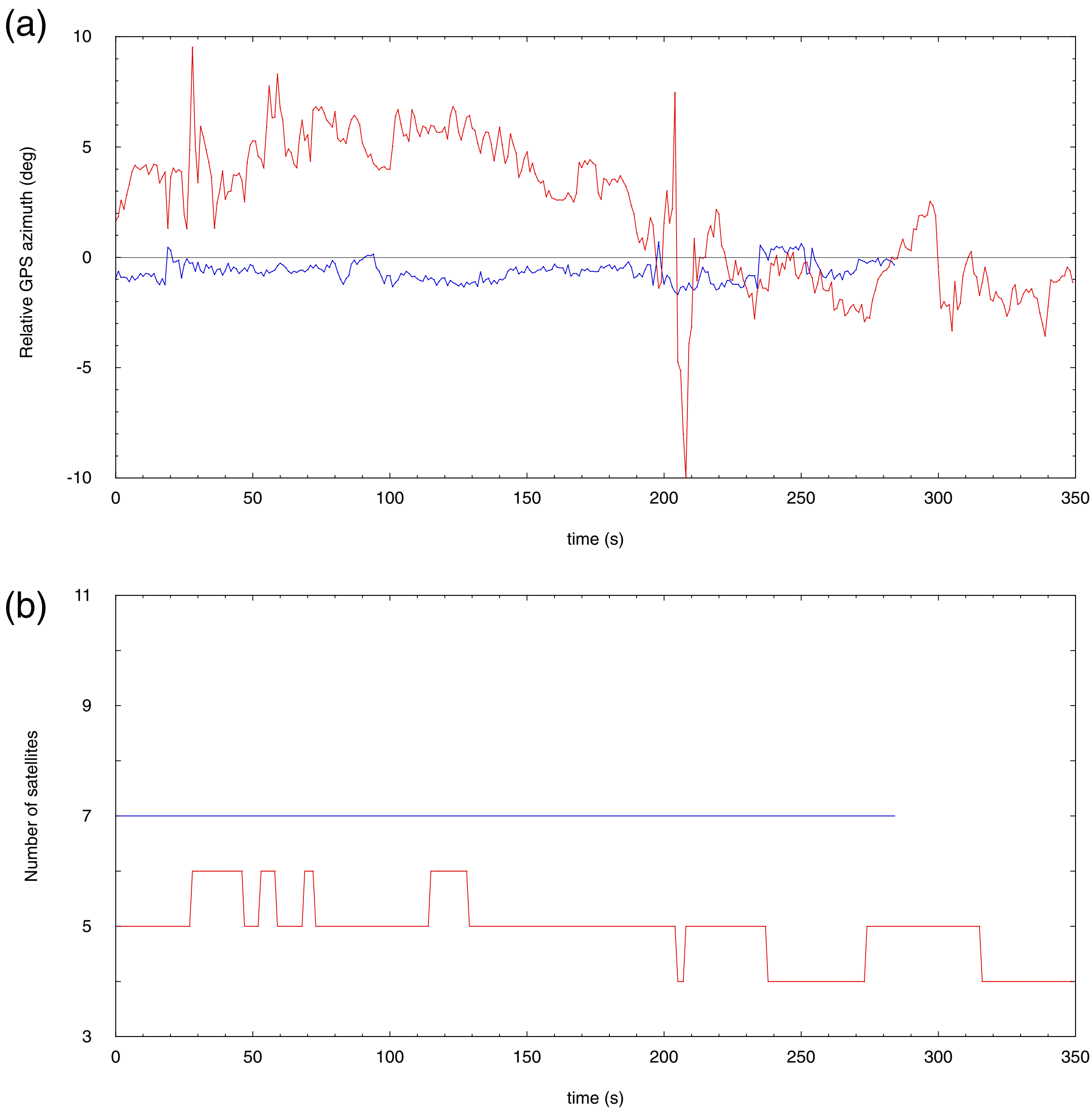


Fig. 5 Temporal variations of **a** azimuths measured by the GPS compass relative to the sun compass and **b** numbers of satellites captured for the GPS signals for drill cores at coast and forest sites. Blue indicates data at a coast site (site 28, core 250) where the sky above is open, red indicates data at a forest site (site 31, core 114) where the vertical outcrop is covered by trees. At both sites data were not recorded during the first 5 min for initialization of GPS compass

direction. The azimuth variation would result in uncertainties of paleomagnetic secular variation as well as paleomagnetic directions. The large deviations of the magnetic azimuths even within a single site are probably due to the strong magnetization of rocks very close to the magnetic compass on the orientation device (Additional file 1: Table S2). Therefore, examining the difference between the sun and magnetic compasses at one or a few points does not provide a reliable correction for azimuths of individual drill cores.

For basalt drill cores in Izu Oshima, the azimuthal difference between sun compass and backsighting was quite

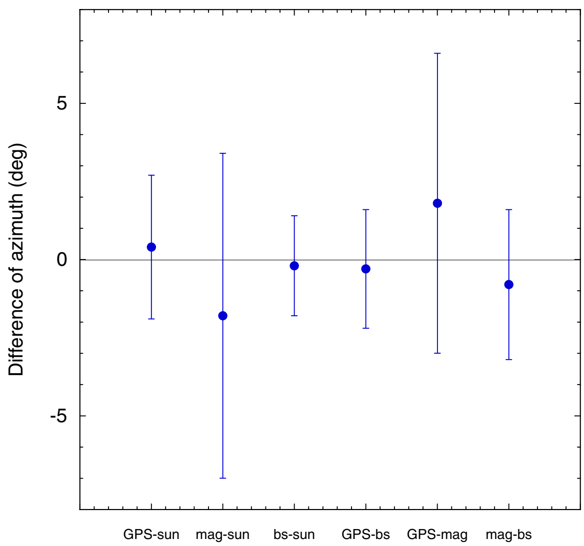


Fig. 6 Differences of azimuths measured by the sun, GPS, and magnetic (mag) compasses and backsighting (bs) for drill cores. The root-mean-squares are indicated by vertical bars

small $-0.2° \pm 1.5°$ (Fig. 6, Table S2). Since the difference between the GPS and sun azimuth was $+0.4° \pm 2.3°$, it would be argued that the three methods of the sun compass, backsighting, and the GPS compass provide almost equally accurate azimuths that were much more reliable than the magnetic compass. However, the sun compass could operate only at a few of the nine sites at the time of the first sampling. Unlike Antarctica where a GPS compass was tested by Lawrence et al. (2009), it is not extremely difficult to obtain sunlight necessary for the sun compass in Izu Oshima, but multiple site visits were needed for sun compass measurements taking into account weather conditions and the sunlight directions. Backsighting was possible only at three sites. This is because no distinct landmarks could be found at other sites, or because the elevation angles of landmarks, unlike the sun or GPS satellites, are generally low and landmarks could not be sighted from the orientation device. GPS compasses can capture satellite signals regardless of weather, time, or geographic conditions. Therefore GPS compasses would provide an alternative orientation method to the sun compass or backsighting in drill core sampling.

Using the GPS compass, we could obtain azimuths only at the flat and open coastal sites. At the forest sites, 11 cores at 3 sites were attempted, but we failed to obtain azimuths for all of the cores. To resolve carrier phase ambiguity and obtain azimuth from the baseline vector of the two antennas, at least four satellites are required, and the more satellites lead to the more accurate azimuths. However, at the forested sites, the number of satellites captured often dropped to four (Fig. 5). Even once the phase ambiguity of the carrier wave is resolved, recalculation of the baseline vector is needed when the number or placement of satellites changes, resulting in an error in the azimuth. In addition, as was evident in the test measurements at the site between buildings on the campus, even if the number of satellites captured was five or more, the multipath effect caused a large error in the azimuth (Fig. 2). At the forest sites, drill cores were collected in vertical outcrops without exception. Not only the trees but also the rocks that make up the outcrops acted as obstacles covering half of the sky, reducing the number of satellites captured and creating the multipath effect (Fig. 5). To increase the number of satellites, it would be effective to introduce a GNSS compass that can capture GNSS satellites such as GLONASS, Beidou or Galileo (Wu et al. 2021). Also it would be necessary to adopt an algorithm that removes false signals caused by the multipath effect (Liu et al. 2016).

Conclusions

A lightweight marine GPS compass was modified to allow direct orientation of paleomagnetic drill cores. Azimuths for historical lavas measured by this portable GPS compass at open coastal sites showed an accuracy and precision of $+0.4° \pm 2.3°$ relative to the sun compass. This GPS compass can azimuthally orient drill cores with accuracy comparable to sun compasses and backsighting at open sites. However, the GPS compass could not yield azimuths at forest sites. It would be necessary to increase the number of captured satellites, including GNSS satellites, and to develop algorithms to remove the effects of multipath. GPS compasses would replace magnetic and sun compasses and backsighting, as a portable tool for orientation that can be used regardless of rock type, weather, or geographic situation.

Abbreviations

GNSS: Global Navigation Satellite Systems; GPS: Global Positioning System; IGRF: International Geomagnetic Reference Field; NMEA: National Marine Electronics Association; SBAS: Satellite Based Augmentation System.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40623-022-01699-y.

Additional file 1: Table S1. Azimuths measured by sun, GPS and magnetic (mag) compasses for eleven different directions at the open sky site in the campus of Doshisha University. **Table S2.** Azimuths measured by sun, GPS, and magnetic (mag) compasses and backsighting (bs) for drill cores and natural remanent magnetization (NRM) intensity of historical lavas in Izu Oshima Island.

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Author contributions
KF devised the equipment, made field test measurements, and drafted the manuscript. TM made test measurements on the campus. Both authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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References

Alken P, Thébault E, Beggan CD, Amit H, Aubert J, Baerenzung J, Bondar TN, Brown WJ, Califf S, Chambodut A, Chulliat A, Cox GA, Finlay CC, Fournier A, Gillet N, Grayver A, Hammer MD, Holschneider M, Huder L, Hulot G, Jager T, Kloss C, Korte M, Kuang W, Kuvshinov A, Langlais B, Léger JM, Lesur V, Livermore PW, Lowes FJ, Macmillan S, Magnes W, Mandea M, Marsal S, Matzka J, Metman MC, Minami T, Morschhauser A, Mound JE, Nair M, Nakano S, Olsen N, Pavón-Carrasco FJ, Petrov VG, Ropp G, Rother M, Sabaka TJ, Sanchez S, Saturnino D, Schnepf NR, Shen X, Stolle C, Tangborn A, Tøffner-Clausen L, Toh H, Torta JM, Varner J, Vervelidou F, Vigneron P, Wardinski I, Wicht J, Woods A, Yang Y, Zeren Z, Zhou B (2021) International geomagnetic reference field: the thirteenth generation. Earth Planets Space 73:49. https://doi.org/10.1186/s40623-020-01288-x

Brown MC, Hervé G, Korte M, Genevey A (2021) Global archaeomagnetic data: the state of the art and future challenges. Phys Earth Planet Inter. https://doi.org/10.1016/j.pepi.2021.106766

Butler FR (1992) Paleomagnetism: magnetic domains to geologic terranes. Blackwell Scientific Publications, Hoboken

Cromwell G, Tauxe L, Staudigel H, Constable CG, Koppers AAP, Pedersen RB (2013) In search of long-term hemispheric asymmetry in the geomagnetic field: results from high northern latitudes: long-term hemispheric asymmetry. Geochem Geophys Geosyst 14:3234–3249. https://doi.org/10.1002/ggge.20174

Dabrowski PS, Specht C, Felski A, Koc W, Wilk A, Czaplewski K, Karwowski K, Jaskólski K, Specht M, Chrostowski P, Szmagliński J (2020) The accuracy of a marine satellite compass under terrestrial urban conditions. J Mar Sci Eng. https://doi.org/10.3390/jmse8010018

Felski A, Jaskólski K, Zwolak K, Piskur P (2020) Analysis of satellite compass error's spectrum. Sensors. https://doi.org/10.3390/s20154067

Kakihara T (2002) Application of GPS for fisheries. Fish Sci 68:1789–1792

Korte M, Constable C (2011) Improving geomagnetic field reconstructions for 0–3ka. Phys Earth Planet Inter 188:247–259. https://doi.org/10.1016/j.pepi.2011.06.017

Langley R (1995) NMEA 0183: a GPS receiver. GPS world 6:54–57

Lawrence KP, Tauxe L, Staudigel H, Constable CG, Koppers A, McIntosh W, Johnson CL (2009) Paleomagnetic field properties at high southern latitude. Geochem Geophys Geosyst 10:1005. https://doi.org/10.1029/2008GC002072

Liu S, Zhang L, Li J (2016) A dual frequency carrier phase error difference checking algorithm for the GNSS compass. Sensors. https://doi.org/10.3390/s16121988

Misra P, Enge P (2011) Global positioning system: signals, measurements, and performance. Ganga-Jamuna Press, Kathmandu

Mochizuki N, Tsunakawa H, Oishi Y, Wakai S, Wakabayashi K, Yamamoto Y (2004) Palaeointensity study of the Oshima 1986 lava in Japan: implications for the reliability of the Thellier and LTD-DHT Shaw methods. Phys Earth Planet Inter 146:395–416. https://doi.org/10.1016/j.pepi.2004.02.007

Nagata T, Arai Y, Momose K (1963) Secular variation of the geomagnetic total force during the last 5000 years. J Geophys Res 68:5277–5281

Tauxe L (2010) Essentials of paleomagnetism. University of California Press, Berkeley. https://doi.org/10.1525/9780520946378

Turner GM, Rasson J, Reeves C (2015) 5.04—Observation and measurement techniques. In: Schubert GBT (ed) Treatise on geophysics, 2nd edn. Elsevier, Oxford, pp 91–135. https://doi.org/10.1016/B978-0-444-53802-4.00098-1

Ueno H, Matsumoto T, Takeda T (1997) Applying the Sun's Azimuth for orientation on the paleomagnetic sample and determination of the declination of the geomagnetic field. Reports of the Faculty of Science, Kagoshima University 30:51–61

Wu M, Luo S, Wang W, Liu W (2021) Performance assessment of BDS-2/BDS-3/GPS/Galileo attitude determination based on the single-differenced model with common-clock receivers. Remote Sens 13:4845. https://doi.org/10.3390/rs13234845

Wu CH, Wang HC, Chang HY (2022) Dual-axis solar tracker with satellite compass and inclinometer for automatic positioning and tracking. Energy Sustain Dev 66:308–318. https://doi.org/10.1016/j.esd.2021.12.013

Yoshihara A, Kondo A, Ohno M, Hamano Y (2003) Secular variation of the geomagnetic field intensity during the past 2000 years in Japan. Earth Planet Sci Lett 210:219–231. https://doi.org/10.1016/S0012-821X(03)00123-7

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