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Performance of three GPS collars to monitor goats' grazing itineraries on mountain pastures

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ABSTRACT

Despite more than 15 years of GPS use in studies with domesticated animals, surprisingly little high-resolution data was collected on grazing itineraries of livestock. It seems as if each research group has its preferred GPS tracking equipment, but little comparative data about the reliability of different types of collars are available. This study provides such data for three very different GPS collars that were tested on a human observer's back and on herded goats in the rugged Hajar Mountains of northern Oman. At a set logging interval of 15 s, the obtained number of position fixes per minute varied from 2.3 to 3.8 and differed significantly ($P < 0.001$) between the three devices in obstructed terrain while differences were negligible ($P > 0.05$) in open terrain. The large variations between the devices in the obtained latitude, longitude and particularly the altitude data were likely due to differences in the factory-made basic setup of the GPS receivers which placed specific weights on signal reliability and trigonometric properties. In the topographically disrupted study environment, recorded values of the position dilution of precision (PDOP) proved to be of little use as indicators of position quality as they were poorly related to the precision of latitude, longitude and altitude values obtained. If accurate altitude data are required, such as for studies on animals' energy expenditure, separate recording of variations in barometric pressure at the same time intervals as those of the GPS collars is recommended.

1. Introduction

In the Hajar Mountain range in northern Oman, for centuries goats have been the most important livestock species in the predominantly agro-pastoral systems (Mandaville, 1977; Defremery and Sanguinetti, 1979; Nagieb et al., 2004; Zaibet et al., 2004). Today, the former nomadic husbandry system has been transformed to a semi-sedentary or fully sedentary system and goat numbers have increased substantially above historical records (Nagieb et al., 2004). Therefore, since 30 years considerable attention has been devoted to the problem of overgrazing of the sparsely vegetated mountain pastures surrounding the spring-fed oasis settlements (Mandaville, 1977). Although farmers feed their goats with cultivated green feeds such as maize (*Zea mays* L.), sorghum (*Sorghum bicolor* Moench) and alfalfa (*Medicago sativa* L.) and with concentrate feeds such as dates (*Phoenix dactylifera* L.), dried sardines and cereal by-products, goats' diets still contain a high proportion of plants ingested on the steep slopes and the plateaus of mountains surrounding the oasis settlements (Schlecht et al., 2008). Given the difficult accessibility of these mountain pastures, continuous manual observation of the animals' grazing itineraries is

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difficult or even impossible. One alternative to closely monitor grazing itineraries is the day-long recording of the exact geographical position (latitude, longitude and altitude) and time using a global positioning system (GPS). By superimposing this information on high-resolution terrain, soil or vegetation maps, detailed information about grazing ranges and the animals' spatial interaction with the natural environment can be extracted. In addition, the GPS recordings also allow calculation of the distances covered by grazing animals, which, on mountainous pastures can be separated into a horizontal and a vertical component. Since the energy expenditure for these two types of movements differs significantly (Lachica et al., 1997), separate information on horizontal and vertical distances covered is also of value if one wants to assess the animals' energy expenditure.

A major determinant for the utility of the collected data is the accuracy and precision of the geographical positions recorded by the GPS device, which can be quantified statistically. Thereby accuracy is defined as the closeness of a set of coordinates to the true location, while precision is defined as the proportion of locations within a pre-defined quantile (Hulbert and French, 2001). The accuracy of GPS recordings mainly depends on four factors: (i) the satellite geometry at the time of recording; (ii) the obstruction of satellite signals by physical obstacles; (iii) the number of channels of the GPS device (which determines the number of satellites signals the device can maximally track at one time); (iv) the apparatus' precision mode (which determines whether a geographical position is recorded when less than four satellite signals are captured at one time). Although all GPS devices that record data at the same time and location are similarly exposed to the effects of the first two factors, the way they handle these differs due to the latter two factors which thus define the final accuracy of a device's recordings. Given the site-specific dimension of the mentioned errors, the suitability of the GPS device to be used in an animal study (and elsewhere) should therefore be tested *ex ante* (Moen et al., 1996,1997,1998; Rempel et al., 1995; Rodgers et al., 1996; Hulbert and French, 2001; Agouridis et al., 2004), especially where terrain features such as overhanging cliffs and steep mountain slopes can obstruct satellite signals. Given the above, the present study aimed at comparing three commercially available GPS-based tracking collars for their precision in recording latitude, longitude and altitude of positions visited by goats during their daily grazing itinerary in the particularly rugged northern Hajar Mountains of Oman. The data obtained might help other scientists to make more informed decisions about the type of device to be used under conditions similar to those of our study area.

2. Materials and methods

2.1. Study site

The study was carried out in the Jabal al Akhdar Mountain range of the Hajar Mountains in northern Oman. The climate in this area is arid with annual rainfall varying from 100 mm to 340 mm (Gebauer et al., 2007); however, successive years of very low or no rainfall are common. During the cooler period of the year (October to March) daily temperatures average 20.1 °C at 1000 m a.s.l. and 14.2 °C at 2000 m; during the months of April to September average temperatures of 29.4 °C and of 23.2 °C were recorded at 1000 m and 2000 m, respectively.

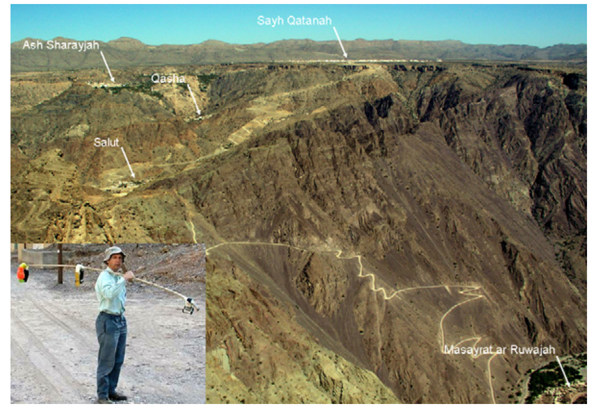

Fig. 1 – Watershed in the rugged Jabal al Akhdar Mountains of northern Oman in which the study was conducted, showing the villages of Masayrat ar Ruwajah (1030 m a.s.l.), Salut (1550 m), Qasha' (1640 m) and Ash Sharayjah (1900 m) and the main town of Sayh Qatanah (1965 m). The inserted image shows the setup to test the three GPS-receivers.

To test the equipment, an altitude gradient from 1000 m to 2000 m was chosen in the watershed from Masayrat ar Ruwajah (23°02′37″N, 57°40′13″E, 1030 m) through Salut (23°03′14″N, 57°39′31″E, 1550 m) and Qasha' (23°04′00″N, 57°39′50″E, 1640 m) to Ash Sharayjah (23°04′10″N, 57°39′30″E, 1900 m), situated in the neighborhood of the town of Sayh Qatanah (Fig. 1). In this area, irrigated agriculture on terrace fields of annual food crops, forages and perennial tree crops such as predominantly date palm (*Phoenix dactylifera* L., 1000 m), pomegranate (*Punica granatum* L., 1500–2000 m), peach (*Prunus persica* L.), walnut (*Junglans regia* L.), apricot *Prunus armeniaca* L.) and roses (*Rosa damascena* L., 1800–2500 m) is combined with goat husbandry.

2.2. GPS rovers

Three types of commercially available GPS rovers were used for the present study. Two of them had explicitly been developed for animal tracking studies, while the third device was of more a universal use and had been fitted into a self-designed collar made from nylon tissue. All three collars were slim, light and easy to secure around a goat's neck. Care was taken to make sure that the antenna position of each rover was located on the unobstructed top portion of the animal's neck and would not move regardless of the animals position on the mountain slopes or when brushing against an obstacle. For a perfect fit of the collars adhesive tape was employed wherever necessary.

The tracking collar GPS_H[2] consisted of a μ-Blox 16-channel GPS receiver and a UHF[3] Telemetry Beacon powered by two

[2] Brand names of the devices can be obtained from the authors upon request.
[3] Ultra high frequency.

standard AA 1.5 V batteries. The components were placed in a 3 mm extruded aluminum housing of 89 mm width, 85 mm length and 32 mm height which was mounted on a polyester harness of precisely adjustable circumference. Altogether, the equipment had a gross mass of 498 g and stored the following data: date, time, latitude, longitude, altitude (collected above the ellipsoid and subsequently converted to above sea level), numbers of satellites tracked, the number of satellites used for each position calculation, and the (estimated) accuracy of position determination, expressed through the horizontal and vertical error, in meters, as derived by built-in algorithms from the horizontal and vertical dilution of precision (HDOP and VDOP[4]). GPS_H has a storage capacity of 4000 RINEX[5] data locations or alternatively up to 65,000 positional locations if *ex post* differential correction of data is not envisaged. For improved data accuracy, GPS_H calculates a location from as many visible satellites as possible (over-determination) rather than calculating a location from the best 3 or 4 satellites. According to the manufacturer, mean accuracy of raw data is <5 m, the range (95% quantile) being 0.3–16 m off the true position. After differential correction using post-processing, the location error typically narrows down to 3.6 m and the precision (95% quantile) improves to 0.3–13 m (Hulbert and French, 2001). Although the apparatus was also equipped with a sensor for ambient temperature and an activity sensor that can measure the angle of deflection of the collar from the horizontal level in the pitch and roll planes, these two functions were not used in the present study. The logging interval of GPS_H was set to 15 s (equivalent to 4 position fixes per minute) whereby the average time GPS_H takes to obtain a position fix has been factory-set to 24 s. The captured data was downloaded to a laptop PC using wireless radio communication (5 m range) via the UHF receiver in the collar and a (stationary) UHF beacon. The UHF communication system was also used to program GPS_H (definition and upload of logging rate and position mode from the computer). The elevated temperatures prevailing in the study region were within the range of the device's operating range (−20 °C to +54 °C with a data retention range of −40 °C to +60 °C).

Tracking collar GPS_S consisted of a 12-channel GPS receiver powered by two Li batteries of 3–3.6 V, 10 Ah. The components were placed in a sturdy casing and mounted on a polyester harness of precisely adjustable circumference. Gross mass of the collar was 610 g. Information stored by GPS_S was: date, time, latitude, longitude (UTM, WGS84 format), altitude, 2D/3D navigation, position dilution of precision (PDOP[4]), number of satellites, carrier-to-noise ratio and battery voltage used for each position calculation. The device had a total storage capacity of 65,536 non-differential GPS positions; at the time the study was carried out *ex post* differential correction of positions with data of our base station (see below) through RINEX data was not yet possible. Although being able to track up to six satellites, GPS_S always calculates a position from the best 3 or 4 satellites (2D/3D mode). According to the manufacturer, mean accuracy of raw data is 5 m. Similar to GPS_H, GPS_S also contained a temperature and an activity sensor, but these functions were not used. The device which had an operating temperature from −40 °C to +80 °C and a data retention range of −50 °C to +120 °C was set to a logging interval of 15 s.

The GPS_G has been used previously by Schlecht et al. (2004,2006) to track grazing orbits of cattle and small ruminants in western Africa and yielded reliable results under the widely open sky conditions commonly found within this region. It is a 6-channel receiver with an external antenna of 4 cm diameter and 10 mm height weighing 720 g. In our experiment it was powered by four 3000 mAh 1.5 V Li batteries (Ultimate Lithium, Energizer, St. Louis, MO, USA) providing GPS power for up to 10 h. The device was placed in a pocket from nylon tissue mounted on a self-made collar of adjustable size. The logging interval of GPS_G was set to 15 s. Positions were logged in line feature mode, with the following parameters stored: date, time, latitude, longitude and altitude (UTM, WSG84 format), and horizontal and vertical position error, in meters, derived by internal algorithms from the horizontal and vertical dilution of precision, as in the case of GPS_H. The rover position mode automatically changed from three-dimensional to two-dimensional mode if less than 4 satellites were tracked (3D/2D mode), using the last recorded altitude for the next 2D positions until the signals from a fourth satellite were received. The elevation mask for the rover antenna was set at 15°, the PDOP mask was set to a value of 8 and the signal-to-noise ratio (SNR) mask to a value of 4. According to the manufacturer, positions logged with the described setup are typically between 2 m and 5 m off their true position after differential correction (Hurn, 1993). The operating temperature of the device ranged from −10 °C to +50 °C with a data retention range of −20 °C to +70 °C.

The location data recorded by GPS_G and GPS_H were differentially corrected *ex post* (post-processed) with recordings of a 12-channel Trimble Pathfinder Pro XRS used as a Base Station, installed on the top of an unobstructed roof at Sayh Qatanah (23°04′44″N, 57°40′35″E, 1975 m), the major settlement on the Jabal al Akhdar plateau. The base station recorded positions at intervals of 1 s during 24 h per day with the PDOP and SNR mask set at a value of 6. The position readings of 7 days were averaged and used to determine the true position (reference position) needed for post-processing. To avoid recording failures due to electricity cut-offs, a continuously charged 12 V, 45 Ah car battery was used as power backup.

2.3. Experimental setup to compare GPS position and altitude records

The three GPS collars were mounted at a spacing of 0.7 m onto a wooden bar of 2 m length, which was carried horizontally by an observer and turned around regularly to avoid any bias (Fig. 1). On 19 March 2005 the three devices were switched on in the morning at 7:30 a.m. local time and carried initially along the grazing itinerary of Masayrat's goat herd, where obstruction of satellite signals was judged to be highest, due to the

[4] The PDOP, position dilution of precision, is a measure of the GPS receiver/satellite geometry. Components of PDOP are the HDOP (horizontal DOP) and the VDOP (vertical DOP). Combining PDOP with TDOP (time clock offset) yields GDOP (Geometric DOP). Low DOP values indicate better relative geometry and higher corresponding accuracy.

[5] Receiver independent exchange format: special data format for easy exchange of GPS data between receivers of different types or brands.

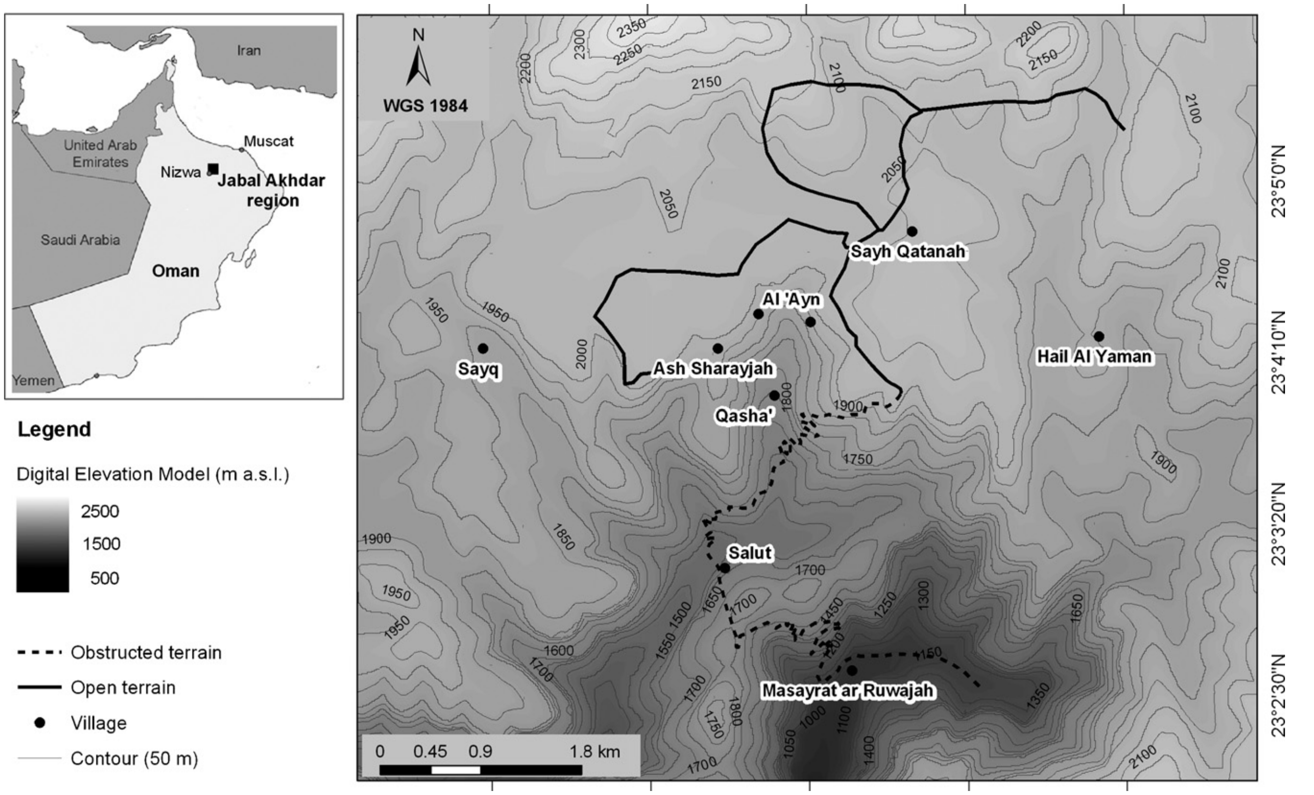

Fig. 2 – Overview of the study area on Al Jabal al Akhdar with the GPS tracks (right map) obtained in the logger comparison and location of the study area within Oman (left map).

steep slopes of the surrounding 1000 m high rock walls. On this trip, which ended at 1 p.m., the observer then followed the different altitude lines of the grazing orbits of the goat herds of Salut and Qasha' until reaching the relatively flat and open Sayq plateau[6] (2000 m a.s.l.) near Sayh Qatanah. Here, another trip along a typical herd track (Schlecht et al., 2008) was performed from 14:40 p.m. to 17:00 p.m. (Figs. 1 and 2).

On 29 October 2005, the same observer conducted a second 74 min experiment with a similar setup from 8:06 a.m. to 9:29 a.m. At this time only GPS_G and GPS_S were used but a barometric altimeter (Alpin 3, Ciclosport GmbH, Krailling, Germany) with a non-volatile memory of 46,080 data points and a precision of ±1 m was used to cross-check the height recordings of the two GPS devices. The altitude covered ranged from 1560 m to 1990 m in the same watershed of the Jabal al Akhdar Mountains with its deep valleys and steep cliffs.

On October 30 and 31 a third experiment was conducted by placing two barometric altimeters into the pockets of two self-made tracking collars holding each a GPS_G. Subsequently, the collars were mounted on the neck of two goats of the village herd of Qasha'. All devices were switched on immediately before the goats left the village in the morning (7:55 a.m. on 30 October 2005 and 7:27 a.m. on 31 October 2005). After the herd's return in the evening (5:40 p.m. on 30 October 2005 and 5:30 p.m. on 31 October 2005), the collars were removed from the animals and all data downloaded to a laptop computer. On the first day, 382 min and 412 min of valid altitude recordings between 1280 m and 1700 m were obtained. On the second day valid GPS data (410 min) were obtained from only one goat moving across mountain ranges of 1600 m to 1960 m. Assuming that the recordings of the calibrated altimeter in the absence of weather changes in this climatically high-pressure area were correct, the absolute difference in altitude (average value per minute) between the altimeter and the GPS was ascribed to GPS errors caused by poor satellite geometry and/or quality of signal capture.

2.4. *Data analysis*

All data obtained from the GPS rovers and the altimeter were pre-processed in Microsoft Excel. Since the different devices never registered a position at exactly the same time (the second), the absolute divergence in these recordings between the three combinations of GPS devices was calculated on the basis of the average value for latitude, longitude and altitude of every minute of recording. The following dependent parameters were compared in an ANOVA using the Proc GLM procedure of SAS V8.1 (SAS, 2000) to determine the effect of GPS device (independent variable) and number of satellites tracked, horizontal and vertical position error, number of recordings per minute and PDOP values (co-variables) on the absolute divergence (in meters) between longitudinal, latitudinal and altitude recordings of all combinations of rovers (GPS_S

[6] The correct local name of this plateau is 'al Ronda', however it is referred to as Sayq plateau in the publication of Mandaville (1977).

versus GPS_H, GPS_H *versus* GPS_G and GPS_G *versus* GPS_S). The statistical analysis of the results of the second and third experiment was also based on the average altitude recordings per minute of the GPS devices and the barometric altimeter. The ANOVA tested the effect of the GPS type (independent variable, fixed effect) and average PDOP per minute (co-variable) on the absolute difference in altitude (dependent variable, in meters) between the recordings of the calibrated barometric device (supposed to deliver the true altitude) and the GPS.

3. Results and discussion

The total recording time for the comparison of the three GPS collars was 7.45 h (447 min), of which 311 min (70%) were spent climbing up the steep slopes from Masayrat ar Ruwayjah via Qasha' and Ash Sharayjah to Sayh Qatanah (thereafter referred to as 'obstructed terrain' where reception of GPS satellite signals was hampered by partial cliff cover) and 136 min were spent on the flat, undisturbed Sayq plateau (thereafter referred to as 'open terrain', Figs. 1 and 2).

3.1. *Reception of satellite signals*

Despite the fact that for all three GPS devices the interval of position logging was set at 15 s, the theoretical number of 4 fixes per minute was often not obtained, particularly in the obstructed terrain, but a few times for unknown reasons also exceeded (Table 1). When expressing the position fixes per minute as a fraction of the theoretical number of fixes, GPS_H had the least fixes followed by GPS_G and GPS_S ($P < 0.001$), whereby the quality of the terrain (obstructed *versus* open) significantly influenced these results ($P < 0.001$). In the obstructed terrain, GPS_H did not capture any signal in 108 out of 311 min (35% of the time), while all positions were captured during the 136 min in the open terrain. Once signal contact was lost, this collar needed up to 15 min with continuous satellite contact to restart recording positions.

In the obstructed terrain GPS_S outperformed the other instruments, recording 4 fixes per minute during 185 min (59% of the time). In the open terrain, however, differences between the three collars were not significant ($P = 0.0599$) even if GPS_H tended to operate best with no missing fixes (Table 1). The comparatively low rate of fixes by GPS_H was likely due to its rather conservative (high precision) mode of operation in the over-determined mode. It was most likely the instrument's need of undisturbed signal reception for 24 s that led to the many missing fixes in the obstructed part of the study area.

3.2. *Closeness of latitude, longitude and altitude recordings*

To summarize relative differences of the three tested devices, we use the concept of 'closeness of data' rather than 'accuracy' and 'precision' that have been proposed by Hulbert and French (2001) to characterize GPS collars. Since there was no objective measurement of latitude, longitude and altitude for the observer's position at any point in time, the absolute difference in each of the three dimensions (average values per minute) for each combination of two GPS rovers was calculated. Thereby latitudinal, longitudinal and altitude data were compared on the basis of metric values. For the latitude (Fig. 3a), values registered by GPS_G were closest to those recorded by GPS_H, whereas the recordings of GPS_H and GPS_S differed on average by 8.2 m (Table 2). For the recordings of longitude (Fig. 3b) the average difference between GPS_G and GPS_H was again smallest and the difference between GPS_S and GPS_H with 15.5 m largest. The separate analysis of data for the obstructed and the open terrain yielded the same overall results, but the magnitude of difference was higher in the obstructed terrain and lower in the open terrain for the three combinations of loggers. Although GPS_S was recording solid latitudinal and longitudinal data quickly after being switched on, it took about 15 min before it had adjusted itself to the true altitude (Fig. 3c). The largest differences in altitude records were with almost

Table 1 – Characteristics of per minute position recordings of three different GPS collars used for goat tracking in the rugged Jabal al Akhdar Mountains of northern Oman

Parameter	GPS_G	GPS_H	GPS_S
Position fixes (*n*) per minute for			
Entire itinerary	3.4 ± 1.3	2.8 ± 1.7	3.9 ± 0.6
Obstructed terrain	3.3 ± 1.5	2.3 ± 1.8	3.8 ± 0.6
Open terrain	3.8 ± 0.6	4.0 ± 0.4	3.9 ± 0.5
Minutes (*n*) with *j* positions logged: entire time/obstructed terrain			
$j = 0$	47/45	108/108	4/2
$j = 1$	4/4	14/12	6/6
$j = 2$	7/6	20/20	5/4
$j = 3$	53/38	22/19	14/14
$j = 4$	334/216	278/150	418/185
$j > 4$[a]	2/2	5/2	0/0

Total recording time was 447 min, of which 311 min were spent in 'obstructed terrain' with reception of GPS satellite signals hampered by partial cliff cover and 136 min in 'open terrain' with unhampered signal reception. The number of position fixes per minute was set at 4 (equivalent to a 15 s logging interval). Values are means followed by ± one standard deviation.

[a] For unknown reasons, GPS_G and GPS_H were for 2 min and 5 min erroneously logging more than 4 positions per minute, meaning that the logging interval was shorter than the programmed 15 s.

Table 2 – Absolute divergence (△) in per minute position recordings of latitude, longitude and altitude between three different GPS collars used in the rugged Jabal al Akhdar Mountains, northern Oman

Parameter	GPS comparison			Fixed effects, P≤		
	G *versus* H	G *versus* S	S *versus* H	Logger	Terrain	Logger × terrain
Entire itinerary (*n*)	300	397	337	d.f. = 2	d.f. = 1	d.f. = 2
△Latitude (m)[a]	5.1 ± 15.1	5.1±22.0	8.2 ± 32.2	0.058	0.001	0.058
△Longitude (m)	6.6 ± 21.9	8.9 ± 34.9	15.5 ± 51.6	0.001	0.001	0.001
△Altitude (m)	11.4 ± 11.1	58.3 ± 139.0	42.6±55.5	0.001	0.001	0.022
Obstructed terrain (*n*)	166	264	203		n.a.	n.a.
△Latitude (m)[b]	0.0 ± 0.00	0.0 ± 0.00	0.0 ± 0.00	1		
△Longitude (m)[b]	0.0 ± 0.00	0.0 ± 0.00	0.0 ± 0.00	1		
△Altitude (m)	13.7 ± 11.0	72.4 ± 168.5	47.5 ± 69.6	0.001		
Open terrain (*n*)	133	133	134		n.a.	n.a.
△Latitude (m)	11.2 ± 21.0	15.3 ± 35.9	19.4 ± 45.8	0.149		
△Longitude (m)	13.3 ± 31.3	27.7 ± 56.0	39.8 ± 75.8	0.001		
△Altitude (m)	8.5 ± 10.5	30.3 ± 16.1	35.2 ± 18.1	0.001		

Total time of recording was 447 min of which 311 min were spent in 'obstructed terrain' with reception of GPS satellite signals hampered by partial cliff cover and 136 min in 'open terrain' with unhampered signal reception. Data show means ± one standard deviation. n.a.: not applicable.

[a] Conversion factor: 1 degree latitude = 102,100 m, 1 degree longitude = 110,713 m at the study location.

[b] For the obstructed terrain, the latitude/longitude deviations were minimal (in the range of millimetres; see also Fig. 3a and b), most probably because the GPS-receivers were carried mostly upwards on a relatively straight path (leading to the vertical differences), whereas in the open terrain also x/y distances were covered.

60 m detected between GPS_S and GPS_G while with 11 m differences were smallest between GPS_G and GPS_H (Table 2).

Calculated on a per minute basis, the PDOP averaged 4.7 (S.D. 3.9, $n = 264$) in the obstructed and 1.7 (S.D. 0.4, $n = 134$) in the open terrain. When using PDOP as a co-variable in comparing the difference in latitude, longitude and altitude between GPS_S *versus* GPS_G and GPS_H, respectively, the GPS combination (SG *versus* SH) lost its significant effect on the difference in latitude, longitude and altitude, whereas the effect of PDOP became significant at $P < 0.001$. The subsequent assumption that a low PDOP value would reflect a low and a high PDOP value a high absolute difference in the geographical positions recorded by two different collars could, however, not be confirmed as there was no linear relationship between PDOP and the absolute difference of latitude, longitude and altitude values registered by GPS_S from values registered by the other two devices ($r^2 < 0.1$ in all cases).

In addition to the geographical position, GPS_S and GPS_H also recorded the number of satellites used for each position fix. For GPS_H this variable averaged 5.0 (range from 4 to 8, $n = 166$) in the obstructed and 8.9 (4–11.8, $n = 133$) in the open terrain; the respective values for GPS_S were 4.5 (3–7.8, $n = 264$) and 9.7 (7–12, $n = 133$). While the divergence in altitude recordings was significantly different between the two logger combinations ($P < 0.001$), it was also significantly affected by the number of satellites tracked ($P < 0.001$).

The number of satellites used for a position fix became a highly significant co-variable ($P < 0.001$) in the comparison of the absolute divergence in latitude, longitude and altitude between GPS_H and GPS_S, respectively, *versus* GPS_G, while

Table 3 – Absolute divergence (△) between the altitude recorded by two types[a] of GPS collars (GPS_G and GPS_S) and a Ciclotronic Alpine 3 barometric altimeter mounted on a 2 m long bar (29 October) or on goats' necks (30–31 October) in the rugged Jabal al Akhdar Mountains, northern Oman

Date	Carrier	Collar type	*n*	PDOP[b]	Vertical error[c] (m)	△Altitude (m)	△Altitude, P≤ Logger, fixed effect	△Altitude, P≤ PDOP, co-variable
29 October	Person with bar	GPS_G(1)	68	4.4 ± 1.2	1.5 ± 1.3	213.5 ± 525.2	0.001	0.001
		GPS_S	135	5.3 ± 10.2	n.a.	89.8 ± 317.5		
30 October	Goat 1	GPS_G(1)	371	4.0 ± 1.4	1.2 ± 1.2	64.8 ± 245.1	0.190	n.a.
	Goat 2	GPS_G(2)	412	n.a.	1.5 ± 1.3	45.9 ± 150.5		
31 October	Goat 1	GPS_G(1)	398	4.3 ± 1.3	1.6 ± 1.1	40.2 ± 218.8	n.a.	n.a.

Data show means ± one standard deviation. n.a.: not applicable.

[a] For GPS_G, two rovers were used simultaneously on day 2, while on day 1 and day 3 only one device was tested.

[b] PDOP = position dilution of precision; for explanation refer to the respective footnote in the text.

[c] Vertical error of position determination, a parameter that can be recorded by GPS_G.

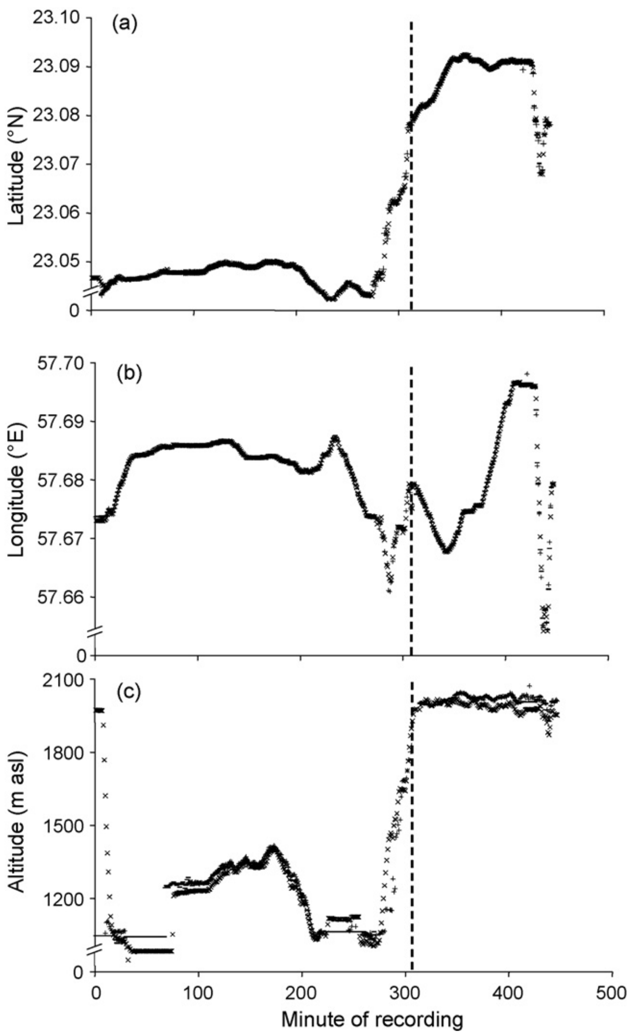

Fig. 3 – Latitude (a), longitude (b) and altitude (c) recorded by three different GPS collars (−GPS_G, +GPS_H, ×GPS_S) in the Jabal al Akhdar Mountains, northern Oman. Total recording time was 447 min, of which 311 min (left of dotted line) were spent in 'obstructed terrain' with reception of GPS satellite signals hampered by partial cliff cover, and 136 min in 'open terrain' (right of dotted line).

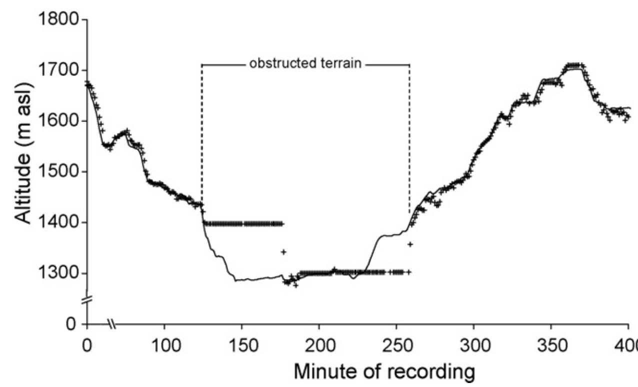

Fig. 4 – Comparison of the altitude recorded by GPS_G (+) and a barometric altimeter (solid line) mounted on a goat's neck in the Jabal al Akhdar Mountains, northern Oman (experiment 3). The faulty GPS signals during minutes 126–259 of recording (solid lines) were due to obstruction of satellite signals by steep mountain slopes and subsequent use of the last recorded altitude for the next 2D positions until the signals from a fourth satellite were received.

logger type and terrain quality did not significantly affect the divergences. However, there was no linear relationship ($r^2 < 0.1$) between the number of satellites used for position fixes and the magnitude of divergence of the latitudinal, longitudinal and altitudinal data.

The two collars GPS_G and GPS_H registered the horizontal and vertical error together with every recorded position. Across the two types of terrain the average horizontal error of GPS_G was 1.8 m (S.D. 0.6, $n = 400$) compared to 14.8 m (S.D. 6.3, $n = 339$) for GPS_H ($P < 0.001$). Hereby the terrain ($P < 0.001$) and the co-variable 'number of position fixes per minute' ($P < 0.001$) significantly affected the horizontal error of position determination. In the obstructed terrain, the horizontal error was 2.0 m (S.D. 0.6, $n = 266$) for GPS_G and 15.7 m (S.D. 7.0, $n = 203$) for GPS_H. In the open terrain the respective values were 1.2 m (S.D. 0.2, $n = 134$) for GPS_G and 13.5 m (S.D. 4.8, $n = 136$) for GPS_H.

The average vertical error of position fix was 1.8 m (S.D. 1.2, $n = 400$) for GPS_G and 20.7 m (S.D. 9.4, $n = 339$) for GPS_H ($P < 0.001$). Thereby differences were influenced by the co-variable 'number of position fixes per minute' ($P < 0.001$), but not by the type of terrain ($P > 0.05$).

For both terrain types the vertical errors were numerically similar, although differences could be detected statistically ($P < 0.001$), but differences between receivers were large (GPS_G: 1.7 m, S.D. 1.4, $n = 266$, obstructed terrain *versus* 2.1 m, S.D. 0.5, $n = 134$, open terrain and GPS_H: 20.4 m, S.D. 10.3, $n = 203$, obstructed terrain *versus* 21.2 m, S.D. 7.9, $n = 136$, open terrain). In both collars the average number of position fixes per minute was higher in the open than in the obstructed terrain.

3.3. *Accuracy of altitude recordings*

In experiment 2 the average deviation between the altitude recordings of GPS_G and the barometric altimeter was >200 m (Fig. 4). Although average deviations were less than 70 m for GPS_G in experiment 3, the coefficient of variation for these averages was in the range of 330–540%, which was also reflected by large standard deviations (Table 3). GPS_G receivers have the capability to employ a self-consistency check for the recorded signals (GPS pseudo range measurements) if at least five useable satellites are received. The horizontal and vertical position errors calculated by the device thus represent the probabilistic radial errors for the estimated 3D coordinates of the receiver unit. The usefulness of such a self-consistency check and the value of the obtained information to assess the quality of the vertical GPS information (altitude record) is, however, doubtful given the large discrepancy between the vertical position error on the one hand and the deviation between barometrically and GPS determined altitude on the other hand (Table 3). The difference between the two modes of altitude determination (barometric *versus* satellite-based triangulation) was independent from the number of tracked satellites but positively correlated with the variation in PDOP ($r^2 = 0.75$, $P < 0.001$, $n = 939$). At PDOP values ≤ 6 the GPS-determined altitude deviated from the altimeter recordings by only 18.8 m (S.D. 21.9, $n = 121$; GPS_S), 22.4 m (S.D. 33.6, $n = 339$; GPS_G1) and 23.5 m (S.D. 140.4, $n = 420$; GPS_G2), with differences between loggers being insignificant. These findings are confirming observations from the open Sahelian drylands (Schlecht et al., 2004) that PDOP values can be used to evaluate the quality of position data – however, as the results of our first experiment show (Section 3.2), in topographically difficult terrain this should be checked with solid reference data for altitude – and most likely also for latitude and longitude.

4. Conclusions

The extremely rugged terrain features of our study area with its steep gorges and hidden pastures poses extreme challenges to the signal reception capability of any GPS receiver. Unfortunately the collar with the easiest mode of operation given its sturdiness and ability to use standard AA size batteries (GPS_H) performed rather poorly in obstructed terrain. This made it unsuitable for high-resolution tracking of free ranging animals such as needed for detailed grazing or behavioural studies. Lacking correlation between PDOP and latitudinal, longitudinal and altitudinal differences in GPS recordings seem to make PDOP values a poor indicator of data quality in mountainous terrain. For applications requiring the accurate determination of altitudinal position in an animal's grazing track, such as for studies on energy expenditure, a properly calibrated barometric device whose records are unaffected by the geometry of satellite signals should be used in combination with a GPS receiver.

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REFERENCES

Agouridis, C.T., Stombaugh, T.S., Workman, S.R., Koostra, B.K., Edwards, D.R., Vanzant, E.S., 2004. Suitability of a GPS collar for grazing studies. Trans. ASAE 47 (4), 1321–1329.

Defremery, C., Sanguinetti, B.R., 1979. Voyages d'Ibn Battuta, vol. 4. Paris Imprimerie Imperiale 1853–58, Repr. Paris, Maspero, France.

Gebauer, J., Luedeling, E., Hammer, K., Nagieb, M., Buerkert, A., 2007. Mountain oases in northern Oman: an environment for evolution and in situ conservation of plant genetic resources. Gen. Res. Crop Evol. 54, 465–481.

Hulbert, I.A.R., French, J., 2001. The accuracy of GPS for wildlife telemetry and habitat mapping. J. Appl. Ecol. 38, 869–878.

Hurn, J., 1993. Differential GPS Explained. Trimble Navigation Ltd., Sunnyvale, CA, USA.

Lachica, M., Prieto, C., Aguilera, J.F., 1997. The energy costs of walking on the level and on negative and positive slopes in the Granadina goat (*Capra hircus*). Br. J. Nutr. 77, 73–81.

Mandaville, J.P., 1977. Plants. In: Harrison, D.L. (Ed.), The Scientific Results of the Oman Flora and Fauna Survey 1975. J. Oman Stud. Special Report 1, 229–267.

Moen, R., Pastor, J., Cohen, Y., Schwartz, C.C., 1996. Effects of moose movement and habitat use on GPS collar performance. J. Wildlife Manage. 60, 659–668.

Moen, R., Pastor, J., Cohen, Y., 1997. Accuracy of GPS telemetry collar locations with differential correction. J. Wildlife Manage. 61, 530–539.

Moen, R., Cohen, Y., Pastor, J., 1998. Linking moose population and plant growth models with a moose energetics model. Ecosystem 1, 52–63.

Nagieb, M., Siebert, S., Luedeling, E., Buerkert, A., Haeser, J., 2004. Settlement history of a mountain oasis in northern Oman—evidence from land-use and archaeological studies. Die Erde 135, 81–106.

Rempel, R.S., Rodgers, A.R., Abraham, K.F., 1995. Performance of a GPS animal location system under boreal forest canopy. J. Wildlife Manage. 59, 543–551.

Rodgers, A.R., Rempel, R.S., Abraham, K.F., 1996. A GPS-based telemetry system. Wildlife Soc. Bull. 24, 559–566.

SAS Institute, 2000. SAS System for Windows V8.1. SAS Institute, Cary, NC, USA.

Schlecht, E., Hülsebusch, C., Mahler, F., Becker, K., 2004. The use of differentially corrected global positioning system to monitor activities of cattle at pasture. Appl. Anim. Behav. Sci. 85, 185–202.

Schlecht, E., Hiernaux, P., Kadaouré, I., Hülsebusch, C., Mahler, F., 2006. A spatio-temporal analysis of forage availability, grazing and excretion behaviour of cattle, sheep and goats in Western Niger. Agric. Ecosyst. Environ. 113, 226–242.

Schlecht, E., Dickhoefer, U., Predotova, M., Buerkert, A., 2008. Grazing itineraries and feed intake of goats on communal pastures of the Jabal al Akhdar mountain range, Oman. In: Multifunctional grasslands in a changing world. Proceedings of the 2008 IGC/IRC Congress, Guangdong People's Publishing house, Guangzhou, China, vol. II, p. 77.

Zaibet, L., Dharmapala, P., Boughanmi, H., Mahgoub, O., Al-Marshudi, A., 2004. Social changes, economic performance and development: the case of goat production in Oman. Small Rum. Res. 54, 131–140.