Empirical analysis and modeling of Argos Doppler location errors in Romania (#31068)

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Empirical analysis and modeling of Argos Doppler location errors in Romania

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Background. Advancements in tracking technology allow researchers to understand the spatial ecology of many terrestrial and aquatic animal species. Argos Doppler is a widely used technology for wildlife tracking due to the small size and weight of the units, which fit small-bodied species and the longer lifespan, compared to miniaturized GPS. In practice, large Argos location errors often occur due to communication conditions such as transmitter settings, local environment, area of reception, behavior of the tracked individual.

Methods. Considering the geographic specificity of errors and the lack of benchmark studies in Eastern Europe, our research objectives are (1) to evaluate the accuracy of locations produced by Argos Doppler technology under various environmental conditions, (2) investigate the effectiveness of straightforward destructive filters for improving Argos Doppler data quality, and (3) to provide guidelines for for processing Argos Doppler wildlife monitoring data. We assessed the errors associated to Argos locations in 4 geographic locations from Romania in static, low speed and high-speed tests, and then we evaluated the effectiveness of Douglas Argos distance angle filter algorithm to minimize location errors.

Results. Argos locations received in our tests had larger horizontal errors than those indicated by the operator of the Argos system, including under ideal reception conditions. The errors were anisotropic, with larger longitudinal errors for the vast majority of the data. Errors were mostly related to speed of Argos transmitter at the time of reception, but other factors such as topographic conditions and position of the device relative to the sky at the time of the transmission contributed to receiving low-quality data. The Douglas-Argos filter successfully excluded largest errors while retained a large amount of data when the threshold was properly defined for the local scale (2 km).

Discussion. Filter selection requires previous knowledge about the movement patterns and behavior of the species of interest, and parametrization of the selected filter must follow a trial and error approach.

EMPIRICAL ANALYSIS AND MODELING OF ARGOS DOPPLER LOCATION ERRORS IN ROMANIA

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ABSTRACT

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INTRODUCTION

Advancements in wildlife tracking technology allow researchers to track the movement of many terrestrial and aquatic species (Thomas et al. 2012). Movement analysis evolved from short-term local studies on a few individuals to long-term global studies on hundreds of individuals, allowing researchers to answer complex questions about animal movement and space use. These data can be included into statistical models and used to understand movement patterns, population redistribution, habitat use, habitat selection, and conservation needs (Bridge et al. 2011; Doherty et al. 2017; Hooten et al. 2017; Pop et al. 2018a; Pop et al. 2018b; Rozylowicz & Popescu 2013).

Collecting quality movement data remains a challenging task mainly due to technological constraints (Bridge et al. 2011; Thomas et al. 2012). Well-known tracking technologies such as radio telemetry (VHF telemetry), satellite-based telemetry (GPS, Argos), and light-level geolocation have certain limitations (Bridge et al. 2011). The main challenge is the device physical size, in particular, mass, which must not exceed 5% of the animal's body weight (Silvy 2012). Furthermore, transmitters have to be protected from the environmental hazards and damage and include a long-lasting battery or alternative power source for consistent one-way or two-way communication (Bridge et al. 2011). As such, devices meeting these parameters may be cumbersome and heavy (Silvy 2012), and not suited for many small-bodied animals.

The most accurate tracking technology is GNSS-GPS, producing under 10 meters horizontal accuracy locations (Madry 2015), however, present-day GPS receivers weight from a minimum of 4 grams (lifespan limited to a few transmission days) to systems exceeding one kilogram (typically a lifespan averaging 2 years and remote data download), making this device suitable only for individuals weighing over 80 grams. An alternative option for long-term studies is the Argos satellite Doppler-based system, which allows producing transmitters under 5 grams with extended lifespan and an unlimited number of locations delivered in near real-time to researchers (Bridge et al. 2011; Hooten et al. 2017; Thomas et al. 2012). However, the small size comes at a cost in terms of lower accuracy of locations when compared to GPS, and thus, data interpretation may pose challenges for inexperienced users (Rozylowicz et al. 2018). Regardless of the device size, Argos transmitters (Platform Transmitter Terminal - PTT) provide locations with the same error rate, and the data has to be subjected to complex control processes such as filtering and modeling (Thomas et al. 2012). If the PTT's are equipped with GPS receivers, the location precision can be increased by retaining only ground validated locations (Lopez et al. 2015). However, the trade-off results in increasing the minimum device weight to approximately 22 grams per unit.

Because radio frequencies of transmission and the satellite orbits are known, the location produced by PTT's may be determined to within one to a few hundred meters (CLS 2016). Collecte Localisation Satellites (CLS), the operator of Argos system, provide several metrics for data quality, including a location class (LC) based on the number of messages constituting the location. The estimated upper bound errors are 250 m for LC 3 (best accuracy class), 500 m for LC 2, 1500 m for LC 1 and over 1500 m for LC 0. For locations derived from 3 or less errors, Argos produce data with LC A, LC B. Invalid locations are labeled as LC Z and GPS locations as LC G (CLS 2016). CLS pre-processes these locations by using one of Argos nominal filters Least Square algorithm or Kalman Filter (Lopez et al. 2015). However, in practice, location errors of 10 to 100 kilometers often occur due to communication conditions driven by the environment or animal behavior (e.g., animal speed, terrain fragmentation, rain, cloud cover, temperature) (Christin et al. 2015; Costa et al. 2010; Douglas et al. 2012; Dubinin et al. 2010; Sauder et al. 2012; Witt et al. 2010). Thus, filtering the data to exclude implausible Argos locations before employing movement analyses has become a standard approach for researchers (Hooten et al. 2017). Furthermore, the quality of data seems to be highly dependent on the area of reception, with Argos systems in Eastern Europe having lower power, and their signals are hidden by radio noise across the Argos frequency (Gros et al. 2006).

Location errors can be filtered using destructive (i.e., removing implausible locations) and reconstructive filters (i.e., evaluation of uncertainty in the estimation of locations) (Douglas et al. 2012). Destructive filters remove duplicates (e.g., timestamp, coordinates with the same values), locations outside of a defined range (e.g., for geometric dilution of precision, latitude, longitude, location class), or locations exceeding a fixed movement rate or a turning angle (Douglas et al. 2012; Kranstauber et al. 2011). One such advanced destructive filter is Douglas Argos filter algorithm (DAF), available on Movebank database of animal tracking data (Kranstauber et al. 2011). DAF uses a threshold to mark the outliers as implausible locations, and is available in three settings: maximum redundant distance (MRD, retains near-consecutive locations within a distance threshold), distance angle filter (DAF, retains near-consecutive locations within a distance threshold and locations passing movement rate and turning angle tests), and hybrid filter

(HYB, for migratory species, combine MRD and DAF filters) (Douglas et al. 2012). In contrast, reconstructive filters employ advanced statistical methods to detect movement characteristics without removing locations (e.g., discrete-time movement model, correlated random walk state-space models, movement-based kernel density estimates, Bayesian State-Space Models, hidden Markov models), or model the data using the errors associated with movement (e.g., Argos error ellipse) (Hooten et al. 2017; Jonsen et al. 2005; Lopez et al. 2015; Silva et al. 2014).

Considering the behavioural, environmental and geographic specificity of Argos errors and the lack of benchmark studies in Eastern Europe, our research objectives are (1) to provide empirical evidences of the accuracy of Argos Doppler locations in Romania, (2) investigate the effectiveness of straightforward destructive filters for improving Argos data quality, and (3) to provide guidance for processing Argos wildlife monitoring data in Eastern Europe. We assessed the errors associated to Argos locations in 4 geographic locations from Romania in static, low speed and high-speed tests and then we evaluated the effectiveness of Douglas Argos distance angle filter (DAF) algorithm to minimize location errors.

MATERIALS & METHODS

We used five Argos Platform Transmitter Terminals (PTT), model GeoTrack 23g Solar PTT (GeoTrack Ink., Apex, NC), with a repetition period of 60 seconds. The PTTs were initially programmed for 8 hours ON/43 hours OFF transmission cycle, then manually activated at the start of the working day and restarted if the transmission day was longer than 8 hours. Daily activation occurred 10 minutes before the first Argos satellite was scheduled to be visible according to satellite pass prediction (CLS 2016). The PTTs were glued on stake 20 cm each other, with the antenna pointing towards the sky, in the same direction. Argos messages were processed by CLS using the standard Kalman filter location algorithm (CLS 2016), with a predefined average speed of 16 m/s. To estimate the accuracy of Argos locations, we matched each Doppler location with a GPS location (Garmin Oregon 650, Garmin Ltd.) obtained within maximum 5 minutes. Garmin GPS receivers have a precision <10 m in low-rise residential areas, and thus, GPS locations can be considered as accurate locations.

The accuracy of Argos locations was tested in four areas in Romania, across potentially different topographic, and reception conditions: (1) Bucharest city, two urban parks within residential area

(Tineretului Park for static test, 44°24'N 26°06'E; and shoreline of Vacaresti Lake for mobile tests, 44°24'N, 26°07'E); (2) Saveni, Ialomita county (44°35', 27°37'"E) as representative for unobstructed flat lowland; (3) Iron Gates Natural Park, Mehedinti County (44°41'N 22°21'E), along Danube River, as representative for a narrow valley, and (4) Sighisoara (Breite for static tests, 46°12'N 24°45'E; Sighisoara-Apold for mobile tests, 46°09'N 24°46'E) as representative for moderately fragmented upland). In each area, we carried out three tests: a static, a low-speed, and a high-speed test (Figure 1, Data S1).

Each motion-controlled test lasted 6 transmission days, with minimum 6 transmission hours per day. For static tests, the five PTTs were positioned 30 cm above ground in unobstructed transmission conditions. For low-speed tests, we walked at normal speed (4-5 km/h) with the PTTs glued on the stake and attached on a backpack. For high-speed test, we biked with maximum 15 km/h with the PTTs glued on the stake and positioned on the bike. In each test, the GPS receiver was set to record a location to every 30 seconds.

Argos messages were downloaded daily. Each Argos message was assigned to the corresponding area and motion-controlled test. Prior to statistical analyses, the dataset was cleaned to eliminate messages without coordinates, timestamp, and duplicate messages (i.e., keeping only a message per location per PTT).

The magnitude of spatial errors was estimated using several error metrics. Distances between Argos locations and the corresponding "true" GPS locations were calculated as the geodesic distance on WGS 1984 reference ellipsoid (i.e., *location error*, meters). The direction of error was calculated as bearing along a rhumb line between the Argos and GPS locations (i.e., *error bearing*, 0-360°) (Hijmans et al. 2017). Latitudinal and longitudinal errors were calculated as the difference between the UTM coordinates of Argos latitude/Argos longitude and the corresponding GPS ~~longitude~~/GPS longitude (i.e., *Latitudinal and Longitudinal errors*, km). Furthermore, Argos locations were classified as *"in"* or *"out"* of ellipse error by plotting GPS locations with the ellipse error components provided by Argos for each location.

Variability of log-transformed location errors was evaluated using linear-mixed effects models with *Motion* (static, low-speed, high-speed), *Place* (Saveni, Bucharest, Sighisoara, Iron Gates), and terrain ruggedness index, *TRI*, (Riley 1999) as fixed effects and the receiving points (locations generated simultaneously by all transmitting PTTs at a satellite pass) nested in the satellite generating the Argos locations as random terms (a total of 6 satellites generated data).

Several linear-mixed effects models were fitted using different combinations of fixed effects, but with the same nested random effects using function *lmer* with restricted maximum likelihood (REML) in package *lme4* (Bates et al. 2014) in program R (R Core Team 2011). We used Akaike's Information Criterion corrected for small sample size (AICc) to select the best model predicting the variance of log-transformed location errors. We evaluated the variance explained by fixed effects (marginal R-squared) and collectively by fixed and random effects (conditional R-squared) (Nakagawa & Schielzeth 2013).

To evaluate the effectiveness of data filters to minimize the location errors, we partitioned the data by area of reception and then ~~run~~ a Douglas-Argos filter (DAF) on Movebank tracking platform (www.movebank.org) (Douglas et al. 2012; Kranstauber et al. 2011). Data were partitioned by area of reception to understand the capacity of filters to eliminate the errors when the tracked species move locally with different speed (static, low-speed, high-speed movement). Movebank offers three versions of the Douglas-Argos filter: (1) maximum redundant distance filter (MRD), (2) distance, angle, and rate filter (DAR), and (3) hybrid filter (HYB). We ~~run~~ distance, angle, and rate filter (DAR) filter, which retains spatially redundant locations passing movement rates and turning angle tests. We uploaded data for each area of reception, and applied DAF two times, with the threshold radius in km within which 2 points are considered self-confirming (MAXREDUN) at 2 km (DAF 2) and at 15 km. MAXREDUN is the most influential parameter of the DAR filter and marks as valid two consecutive locations within the threshold distance. Smaller values, such as 2 km are suitable for local scale movement while larger values (e.g., 15 km) for macro scale movements (Douglas et al. 2012). It is recommended to retain locations above LC 1 (locations with higher accuracy class), however, because we were interested in the effectiveness of DAR filter in eliminating location errors from the whole dataset, we did not provide a location class threshold. MINRATE (maximum sustained rate of movement over a period of several hours) was 15 km/h (maximum velocity achieved during the test) and RATECOEF as 10 (specific for movements in a very circuitous pattern) (Douglas et al. 2012). The results of two user-specific filters (DAF 2 and DAF 15) were compared to unfiltered data.

For statistical analyses and graphics, we used packages *dplyr* (Wickham et al. 2018), *dunn.test* (Dinno 2017), *ggpubr* (Kassambara 2018), *lme4* (Bates et al. 2014), *MuMIn* (Barton 2018), *merTools* (Knowles et al. 2018), *ggeffects* (Lüdecke 2018), *openair* (Carslaw & Ropkins 2012) and *geosphere* (Hijmans et al. 2017) for R 3.5.1 (R Core Team 2011).

RESULTS

Between June 2017 and September 2017, the five Geotrack 22g Solar PTTs received 3705 valid Argos locations. Each PTT generated a similar number of locations (min = 717, max = 760, χ^2 (df = 4, n = 3705) = 1.86, p = 0.76). For each location, Argos PTTs transmitted between 1 and 14 messages to one of the six polar-orbiting satellites flying Argos instruments. Argos satellites generated a dissimilar number of locations (min = 310, NOAA-N'; max = 890, NOAA-18, χ^2 (df = 5, n = 3705) = 399.87, p < 0.001).

The dataset is dominated by low quality data, with over 29% of locations labeled as LC B (generated from 1 or 2 messages). Forty six percent of the locations were classified by CLS as error bounded (Argos LC 3, 2, and 1), from which 14.25% were of high estimated quality (LC 3, < 250 m estimated accuracy).

Empirical mean location error of the five PTTs was 3583.66 m (stdev = 8225.97 m). Location errors differed significantly by Argos location classes (Kruskal-Wallis chi-squared = 1170.95, df = 5, p-value < 0.001), except for LC 1 and LC A which show identical ranking. All the error bounded location classes (Argos LC 3, 2, and 1) had measured errors significantly larger than the location class specific 68th percentile estimated by CLS. Argos LC 1, LC A, and LC B had smaller errors than LC 0, a location class which is considered a more accurate class by CLS (Figure 2, Table 1).

As expected, longitudinal errors dominated the dataset. 67.19% of locations had larger longitudinal errors when compared to latitudinal errors of the same point, and in average longitudinal errors were larger (mean = 2872 m, stdev = 7678) than latitudinal errors (mean = 1604.4 m, stdev = 3272.3), a consistent pattern in all location classes (Table 1). The largest proportion of longitudinal errors were in LC 0 (73.96% of locations) and LC 1 (73.44%), while the largest proportion of latitudinal errors were in LC B (39.29%) and LC A (38.42%) classes. Geographically, most errors were to East and West, followed by North-East and South-West errors, while oriented toward North and South are less present in the dataset (Figure 3, Figure 4).

The best linear mixed model shows that fixed factors *Motion* and *Place* had a significant impact on errors (Table 2). Motion and Place explained 17.45% of variance in the error data (marginal

R-squared), while the random part of the model explained 56.79% of variance (conditional R-squared). The proportion of variance in errors accounted for by the reception points nested in the satellite (Intra Class Correlation Coefficient, ICC) was 41.91%, while the satellites themselves accounted only for 5.73%, suggesting that while satellites may show a consistent pattern of error, reception conditions at the transmission are highly variable influence the quality of data (Table 3).

Comparison of confidence intervals of fixed factors showed that the locations from motion-controlled differed significantly, with error from high speed tests larger than in low speed, and errors in low speed tests larger than in static (mean error static tests = 2708.84 m, mean error for low speed tests = 3779.73 m, mean error for high speed test = 4550 m, Figure 5, Table 4). The area of reception (Place) contributed to the error variance, with locations from Iron Gates (narrow valley) generating larger errors when compared to locations from the other sampling areas (e.g., mean error Iron Gates = 4698.35 m vs. mean error Saveni = 3122.01 m, Figure 5, Table 5). Interestingly, we found substantial errors in static tests from Iron Gates, as large as locations in low-speed tests from Saveni, Bucharest, and Sighisoara. (Figure 5).

Douglas-Argos DAR filter applied to raw data successfully excluded largest errors when MAXREDUN was defined for local (2 km, DAF 2) and continental (15 km, DAF 15) scales of study. However, DAF 2 filter was more effective in excluding large errors, by retaining only 84.35% of the initial locations compared to 94.82% excluded by DAF 15 filter (Figure 6, Table S1, Table S2). The mean error of DAF 2 filters was 2313.51 meters (stdev =3134.67), an improvement comparing to 3584 meters (stdev = 8226) of initial data. DAF 15 filter retained almost all the locations in LC 3, LC 2 and LC 1 classes, while DAF 2 only slightly changed the number of LC 2 and LC 1 locations. The most impacted location class was LC 0 - the class with largest errors in our data - with only 68.35% of location retained by DAF 2 and 90.42% by DAF 15 (Table S1, Table S2). Longitudinal and latitudinal errors were equality filtered by Douglas-Argos filters, thus, the errors are geographically distributed as in the unfiltered dataset (Figure 7).

DISCUSSION

The accuracy of Argos Doppler locations received from Romania was negatively influenced by the movement speed and topographic fragmentation of the reception area. Furthermore, our empirical data showed that Argos locations yielded a low accuracy in stationary tests performed in unobstructed areas, which suggests that Argos Doppler telemetry data must undergo a comprehensive filtering process before using in movement analyses.

In our motion-controlled trials in four areas of Romania with different levels of topographic fragmentation, only 14% of locations were considered as category LC 3, the most accurate Argos location class (CLS 2016). However, the 68th percentile of locations error metric was twice as large as the 68th percentile provided by CLS as upper bound error for LC 3 (520.85 m vs. 250 m). All error-bounded Argos locations classes (LC 2, LC 1, and LC 0) included larger horizontal errors than those indicated by CLS (CLS 2016), which is in line with the results attained in other controlled and real-life studies. For example, a stationary and mobile test in Southern Russia (Dubinin et al. 2010) and tests on animals at sea (Costa et al. 2010) yielded errors similar to ours for LC 3 data. Data from these studies and ours indicate higher errors than those indicated by CLS for all location classes. In our test, LC 0 was the most inaccurate location class (68th percentile = 5877.38 m), which corroborates other studies (Douglas et al. 2012; Lowther et al. 2015). This suggests that LC 0 locations must be filtered together with LC A and LC B, and should not be considered as an accurate location class (CLS 2016). Argos errors are not isotropic, and longitudinal errors were larger than latitudinal errors (CLS 2016; Douglas et al. 2012), as already reported by all benchmarking studies (Lowther et al. 2015; Sauder et al. 2012; Witt et al. 2010). For example, in our study, the mean latitudinal errors for LC 3, LC 2, and LC 1 were only slightly larger than CLS 68th percentile for the respective location class. However, these data are not likely useful for movement studies, such as home-range analyses (Hooten et al. 2017) since longitudinal errors are significant even in perfect reception environment (i.e., flat areas, unobstructed by vegetation).

The accuracy of Argos Doppler locations is influenced by a plethora of factors such as PTTs repetition rate, topography, vegetation, terrain ruggedness, electromagnetic noise, geographic area, etc (Christin et al. 2015; Douglas et al. 2012; Dujon et al. 2014; Freitas et al. 2008; Lowther et al. 2015; Nicholls et al. 2007; Sauder et al. 2012; Soutullo et al. 2007; Witt et al. 2010). South-Eastern Europe is considered as an area with poor reception quality due to the broadband noise covering Argos 401.650 MHz ± 30 kHz frequency (Gros et al. 2006), which might have a negative impact on quantity and quality of data. Our linear mixed effect model showed that the movement speed of PTT had the most considerable influence on Argos locations error, while the area of reception contributed only marginally to the explained variance of errors. As expected motion-controlled tests generated significantly different errors, with static tests generating smaller errors than low-speed tests, and high-speed tests larger errors than low-speed tests. However, sky obstruction from topography influenced data acquisition, since data obtained from highly fragmented Iron-Gates test area comprise larger errors than in the other three test areas, including from Bucharest city, potentially affected by electromagnetic interferences (Gros et al. 2006). In the Iron Gates area the static test generated positional errors as large as in low-motion tests in the other three areas, which suggests that locations from fragmented areas are highly imprecise and can lead to biased conclusions about animal movement and locations if ~~are~~ not adequately filtered (Lopez et al. 2015). Since our errors were similar to those obtained in other studies outside Europe, the broadband noise affecting Southeastern Europe seems to have minimal influence on the accuracy of Argos locations. However, the variance explained by the random part of our linear mixed effects model suggests that the satellite taking the location of the PTT ~~have~~ minimal impact on accuracy (yet, satellites carrying 3rd generation ~~of~~ Argos instruments produce slightly more accurate locations) while the position of the PTT toward the satellite is a dominant source of positional errors. These errors are probably due to the low angle of in-view satellite as a result of local topography, the existence of obstructing vegetation or ~~just due to~~ the relative position of the respective PTT toward the sky (Christin et al. 2015; Doherty et al. 2017; Dubinin et al. 2010; Soutullo et al. 2007).

Because of the large positional errors, Argos Doppler location have to be filtered or modeled considering the uncertainty of locations (McClintock et al. 2014). Data filtering is a challenging task, as the aim is to reduce as much as possible the low-quality data while retaining the necessary amount of data for analyses (Hooten et al. 2017). In our filtering exercise, we tested the effect of Douglas-Argos distance, angle, and rate ~~filter~~ (DAR) filter, which retains spatially redundant locations passing movement rates and turning angle tests (Douglas et al. 2012). The results indicate that selecting a proper self-validating distance threshold significantly reduce the errors while retaining a large amount of data. In our case, a larger threshold, MAXREDUN 15 km, reduced the efficacy of the filter considerably by retaining 10% more locations than the filter with MAXREDUN threshold at 2 km. The differences between the two approaches suggest that previous knowledge of movement behavior are important to obtaining processed good quality data. For example, if the species is known to perform frequent long-distance movements, then a lager MAXREDUN is required. We tested the DAR filter by targeting all the location classes, however, LC 3, LC 2, and LC 1 were only slightly impacted, and thus, we recommend running the filter using the LC 1 as threshold location class as suggested by Douglas et al. (2012).

Even if selecting the optimal threshold, the post-processed data may include large positional errors, therefore, we recommend incorporating Argos error metrics such as error ellipse into the final model (McClintock et al. 2014) or use state-space modeling approaches instead of classical movement analyses (Hooten et al. 2017). While we provide results based on the Douglas-Argos distance, angle, and rate (DAR) filter, other available filtering approaches might be more effective (e.g., speed filters, Douglas-Argos MRD, Douglas-Argos HYB, etc.), and should be explored before implementing movement analyses using Argos data.

CONCLUSIONS

Argos locations received from motion-controlled tests performed in four geographic areas with distinct reception conditions had larger horizontal errors than those indicated by the operator of the Argos satellite system (CLS 2016), including when reception conditions ~~are~~ ideal. The magnitude of errors ~~is~~ variable; however, LC 0 locations were constantly prone to large errors. The errors were anisotropic, predominantly oriented East and West, a pattern ~~confirmed by the~~ larger longitudinal errors ~~in the vast majority of data~~. Errors were mostly related to speed of Argos PTT at the time of reception, but other factors such as topographic conditions and position of the PTT toward the sky at the time of the transmission contribute ~~at~~ receiving low-quality data. Thus, Argos data must be filtered before any movement analyses, and caution should be used before using Argos data for studies of habitat selection, especially for species with small home ranges, such as songbirds, reptiles or small mammals. Filter selection for data processing requires knowledge about the movement patterns and behaviors of the species of interest, and parametrization of the selected filter must follow a trial and error approach.

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Figure 1

Areas of reception for the three motion-controlled tests within Romania (static, low-speed, high-speed).

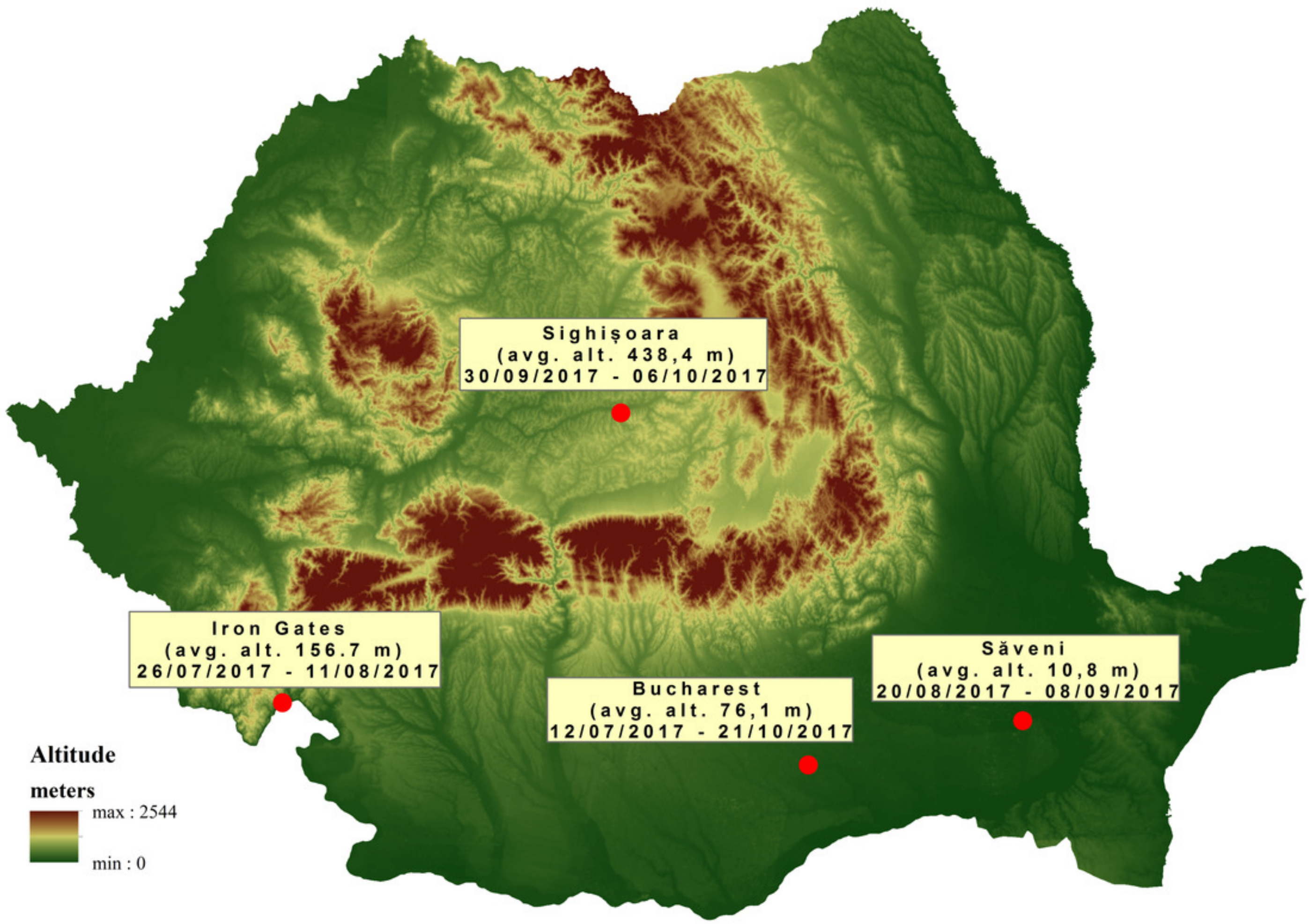


Figure 2 (on next page)

Cumulative distribution of Argos locations errors (log meters) partitioned by Argos location classes (LC). The 68th percentile of measured error is larger than the 68th percentile provided by Argos CLS for error bounded LCs (upper erro

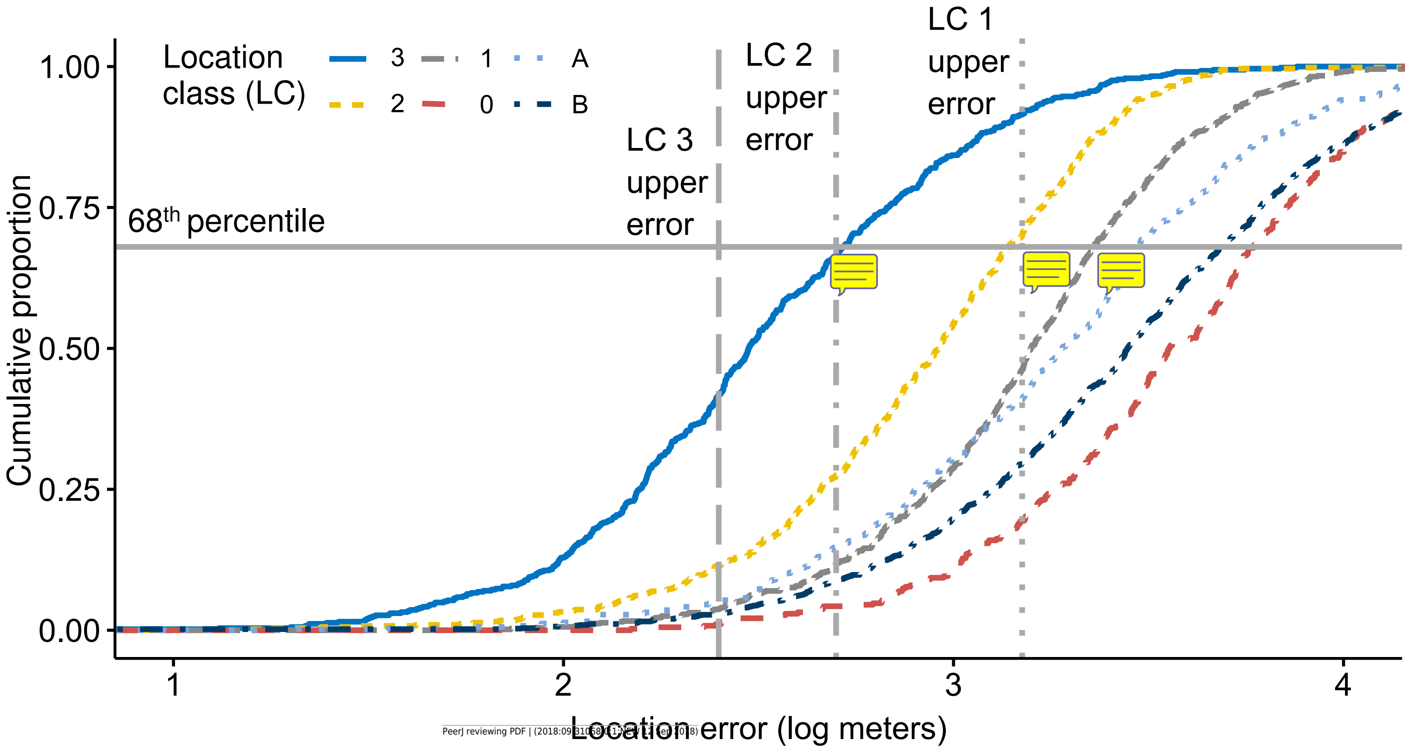

Location class (LC)
3
2
1
0
A
B
LC 3 upper error
LC 2 upper error
LC 1 upper error
68th percentile
Cumulative proportion
1.00
0.75
0.50
0.25
0.00
1
2
3
4
Location error (log meters)

Figure 3 (on next page)

Latitudinal and longitudinal locations errors (km from "true" GPS locations) for a) all data and b) Argos locations with errors under 20 km from "true" GPS locations.

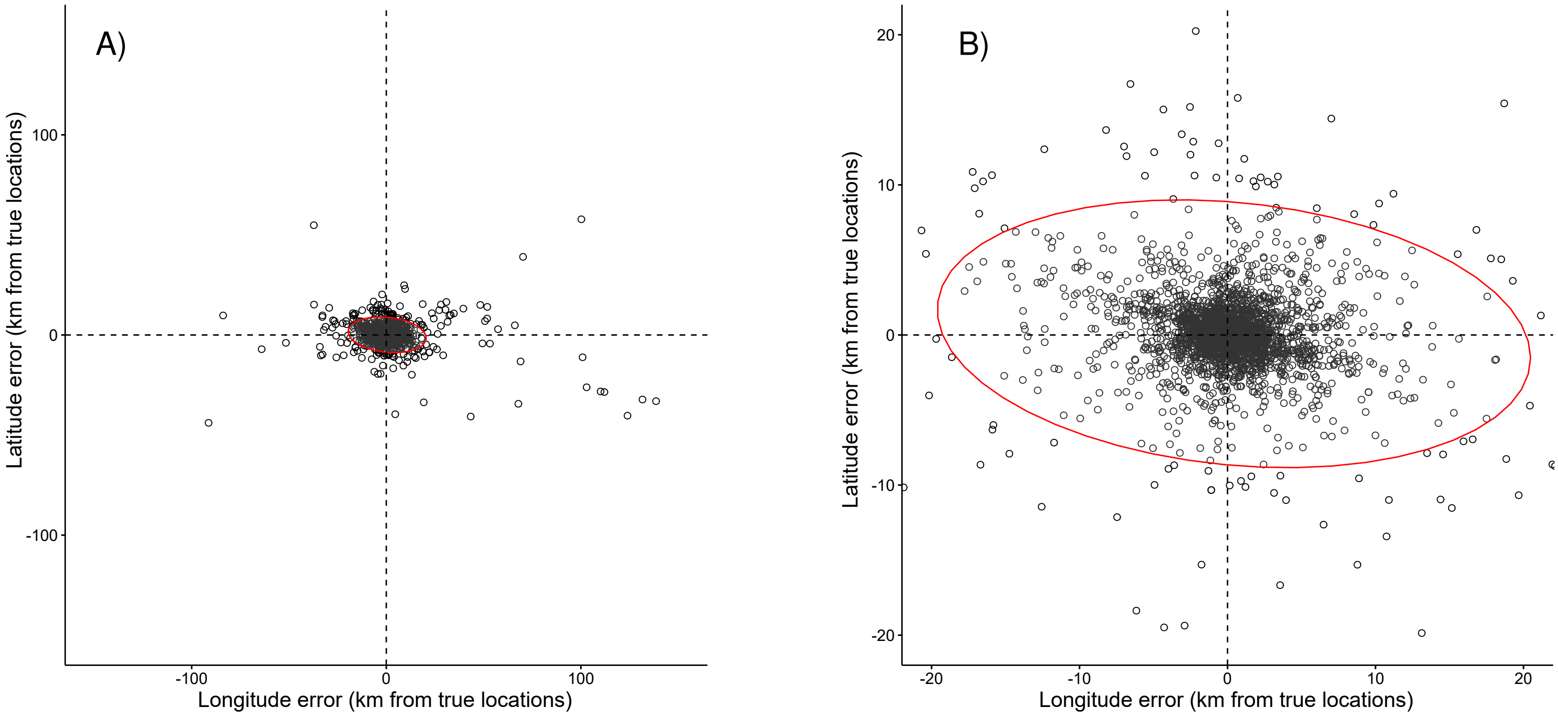

A)
B)
Latitude error (km from true locations)
Longitude error (km from true locations)
100
0
-100
20
10
-10
-20

Figure 4 (on next page)

Magnitude and frequency of Argos errors relative to “true” GPS locations. The first three intervals of error magnitude resemble upper bound errors for LC 3, LC 2 and LC 1.

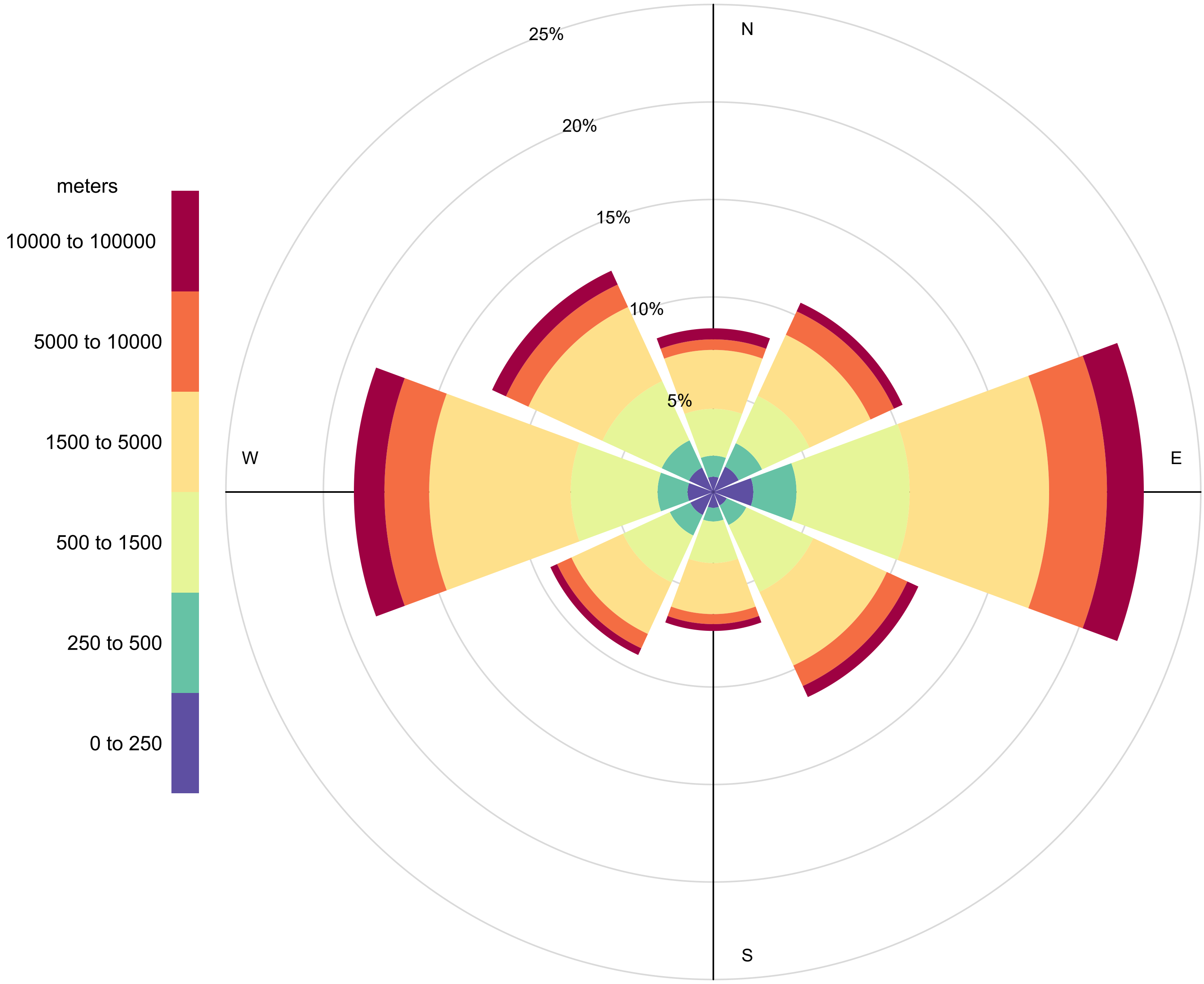

meters
10000 to 100000
5000 to 10000
1500 to 5000
500 to 1500
250 to 500
0 to 250
N
E
S
W
5%
10%
15%
20%
25%

Figure 5 (on next page)

Mean (±95% CI) fitted values for the optimal mixed-effects model predicting Argos location errors by *Motion* and *Place*.

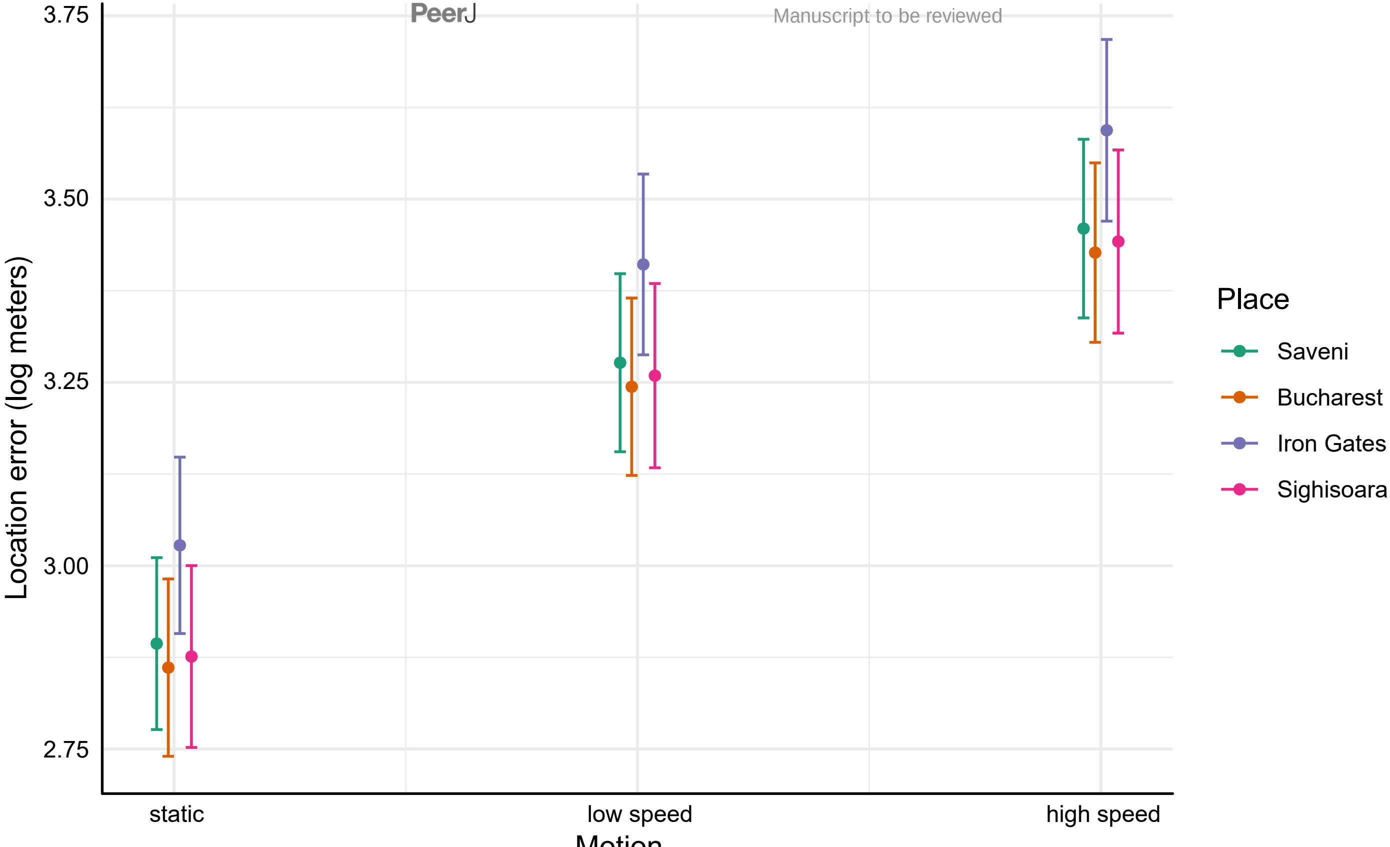

Location error (log meters)
3.75
3.50
3.25
3.00
2.75
static
low speed
high speed
Motion
Place
Saveni
Bucharest
Iron Gates
Sighisoara

Figure 6(on next page)

Effectiveness of Douglas-Argos DAR filter in moderating Argos location errors by location class.

NoF = unfiltered data, DAF 2 = Douglas-Argos DAR with MAXREDUN = 2 km, DAF 15 = Douglas-Argos DAR with MAXREDUN = 15 km.

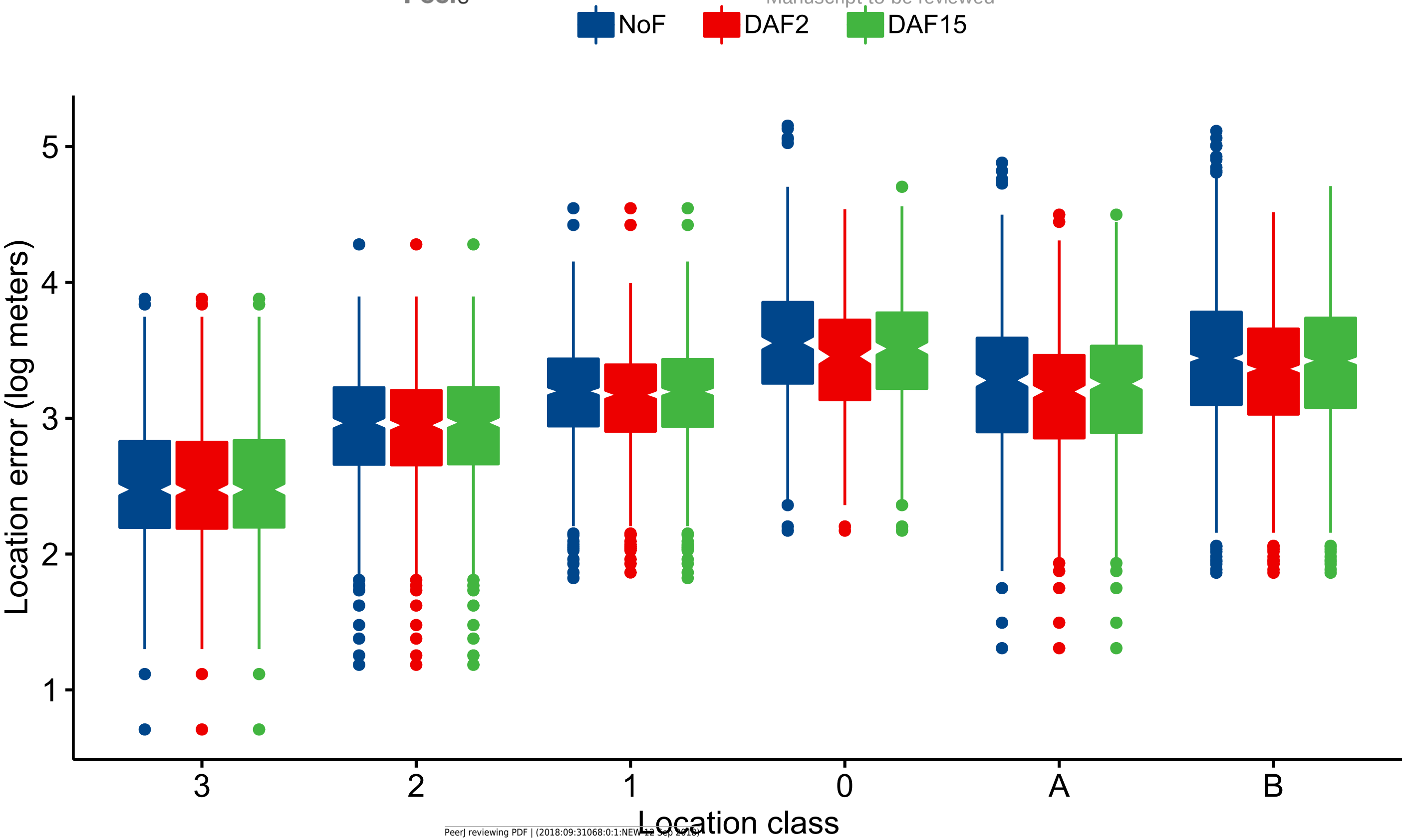
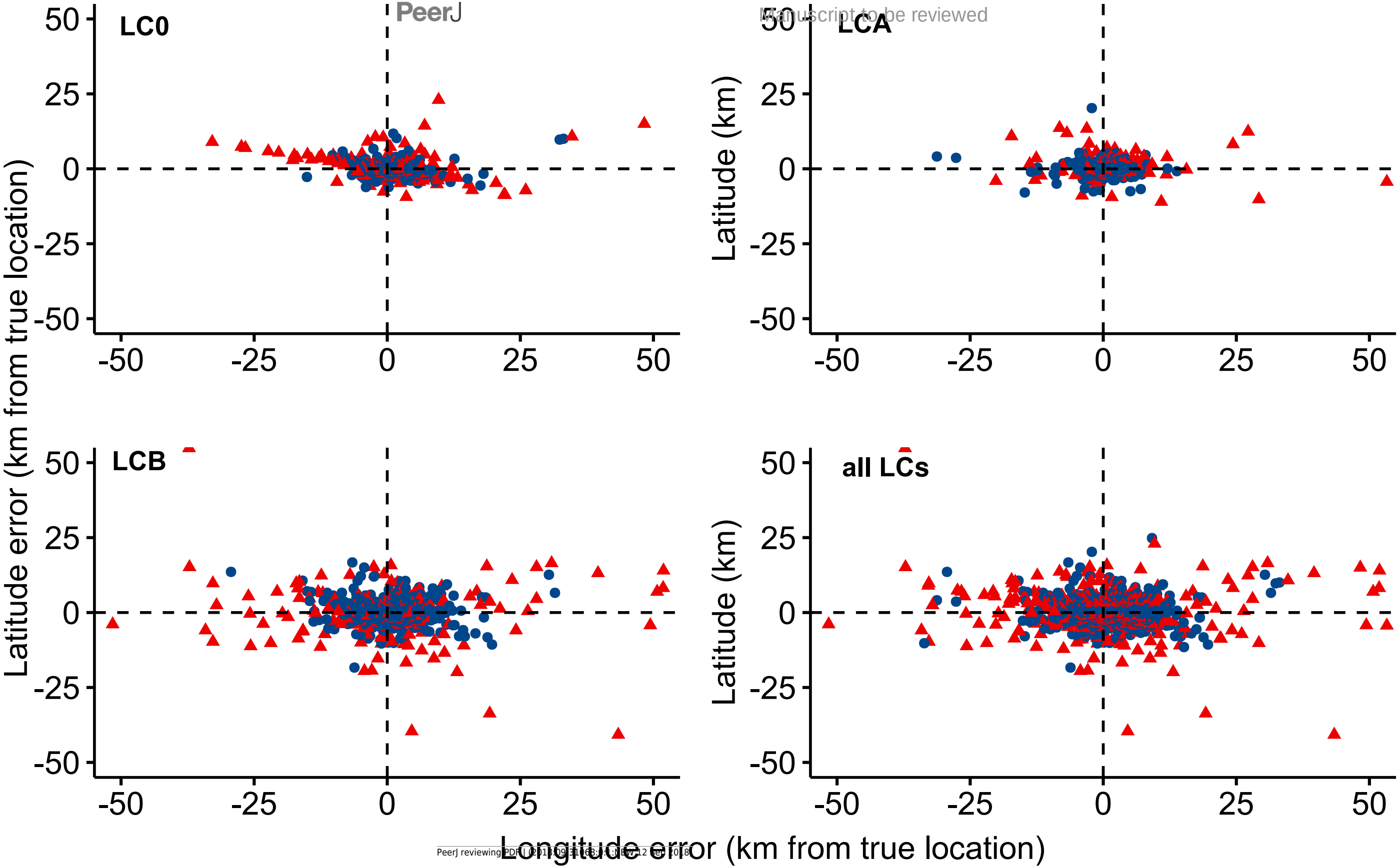

NoF
DAF2
DAF15
Location error (log meters)
1
2
3
4
5
3
2
1
0
A
B
Location class

Figure 7(on next page)

Latitudinal and longitudinal errors (km from “true” GPS locations) in LC 0, LC A, LC B, and all LCs (red = rejected Argos locations; blue = accepted Argos locations).



LC0
LCA
LCB
all LCs
50
25
0
-25
-50
Latitude error (km from true location)
Latitude (km)
Longitude error (km from true location)

Table 1 (on next page)

Location error metrics for all Argos location class (3705 locations received on four reception areas within Romania, during three motion-controlled tests)

Location class	Sample size	Mean error (stdev) meters	68th percentile of errors meters	Mean error longitude (stdev) meters	Mean error latitude (stdev) meters	% locations in error ellipse	% locations out of error ellipse
LC 3	528	578.86 (802.5)	520.85	466.71 (744.47)	254.79 (375.95)	10.42	89.58
LC 2	520	1230.7 (1281.6)	1383.81	969.24 (1099.82)	580.09 (818.49)	4.62	95.38
LC 1	674	2222.8 (2466.2)	2280.64	1784.74 (2158.28)	1010.66 (1467.00)	5.64	94.36
LC 0	376	7127 (14870)	5877.38	6195.25 (14492.92)	2630.38 (4064.45)	11.17	88.23
LC A	505	3670 (6816)	2981.35	2894.15 (6484.07)	1622.35 (2617.89)	9.90	90.10
LC B	1102	5718 (10457)	4820.25	4444.84 (9611.44)	2739.37 (4725.23)	28.04	71.96
Total	3705	3584 (8226)	2758.73	2872.478 7677.608	1604.44 (3272.32)	13.98	86.02

1

Table 2(on next page)

Model selection for the mixed effect model of Argos locations errors.

Place = area of reception, motion = static, low speed, high speed, TRI = terrain ruggedness index, 1 = baseline model, AIC_c = Akaike's Information Criterion corrected for small sample size. The random part include reception point nested in satellite providing the respective location.

Model fixed parameters	df	AIC_c	AIC_cwt	weight
Place + Motion	9	4831.7	0.00	0.685
Motion	6	4834.1	2.44	0.202
Place + Motion + TRI	10	4835.3	3.61	0.113
Place × Motion	15	4846.9	15.19	< 0.001
Place × Motion + TRI	16	4850.5	18.83	< 0.001
1	4	5078.7	247.07	< 0.001
Place	7	5085.2	253.53	< 0.001

Table 3(on next page)

Summary of best mixed effect model (log errors ~ Motion -1+ Place + (1|Satellite/Reception point).

Parameter	β	SE	t-value	Lower CI	Upper CI
static	2.89	0.06	48.35	2.771	3.016
low speed	0.38	0.03	11.74	0.319	0.446
high speed	0.57	0.03	17.08	0.501	0.630
Bucharest	-0.03	0.04	-0.90	-0.103	0.038
Iron Gates	0.13	0.04	3.65	0.061	0.205
Sighisoara	-0.02	0.04	-0.45	-0.093	0.058

Table 4(on next page)

Location error metrics in the three motion-controlled tests carried out within Romania.

Motion	Sample size	Mean error (stdev) meters	Mean error longitude (stdev) meters	Mean error latitude (stdev) meters	% locations in error ellipse	% locations out of error ellipse
Static	1496	2708.84 (9588.76)	2315.32 (9215.04)	1042.22 (2810.01)	16.51	81.68
Low speed	1137	3779.73 (7779.31)	2879.02 (6871.40)	1851.93 (3977.74)	11.96	88.04
High speed	1099	4550.15 (6381.86)	3610.44 (5958.59)	2099.89 (2909.25)	12.28	87.72

Table 5(on next page)

Location error metrics in the four reception areas within Romania.

Place	Sample size	Mean error (stdev) meters	Mean error longitude (stdev) meters	Mean error latitude (stdev) meters	% locations in error ellipse	% locations out of error ellipse
Saveni	1106	3122.01 (5862.75)	2489.22 (5427.42)	1410.09 (2539.10)	13.29	86.71
Bucharest	969	3311.57 (7146.49)	2595.00 (6438.32)	1545.76 (3379.37)	16.10	83.90
Sighisoara	734	3277.75 (6439.44)	2615.05 (5982.89)	1529.57 (2690.64)	12.26	87.74
Iron Gates	896	4698.35 (12113.6)	3856.52 (11495.36)	1969.13 (4229.34)	13.95	86.05