MARINE MAMMAL SCIENCE, 18(1):156-166 (January 2002)

ASSESSMENT OF ARGOS LOCATION ACCURACY FROM SATELLITE TAGS DEPLOYED ON CAPTIVE GREY SEALS

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ABSTRACT

The Argos satellite system is commonly used to track and relay behavioural data from marine mammals, but their underwater habit results in a high proportion of locations of non-guaranteed accuracy (location classes (LC) 0, A and B). The accuracy of these locations is poorly documented in marine mammals. We assessed the accuracy of all LCs on four juvenile grey seals fitted with Argos satellite relay data loggers held in captivity in an outdoor tank for a total of 61 seal-days. 426 locations were obtained from seals in captivity and their latitude and longitude error was assessed, before and after filtering following McConnell *et al*. (1992). There was significantly more error in longitude than

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latitude in all LCs except LC A. The ratio of the standard deviations of longitude:latitude ranged from 1.77 (LC 3) to 2.58 (LC 1). Filtering had very little effect on errors in LCs 3 to 1, but in the remaining LCs filtering resulted in error reductions ranging from 8% to 63%. In LCs 0, A and B, error reduction was greater in the 95th percentile errors, especially in longitude. The averages of the latitude and longitude 68th percentile errors and those predicted by Argos (in brackets) were 226 (150), 372 (350) and 757 (1000) m for LCs 3, 2 and 1 respectively. Both latitude and longitude errors of LCs > 0 were normally distributed. Both filtered and unfiltered LC A locations were of a similar accuracy to LC 1 locations, and considerably better than LC 0 locations. The documentation of location errors presented here will allow an informed decision to be made about which LCs provide useful information in a particular marine mammal tracking study.

Key words: Argos, satellite telemetry, location estimate accuracy, gray seal, *Halichoerus grypus*, marine mammals; animal tracking.

Argos satellite telemetry is commonly used to track marine animals at sea and relay behavioural data (McConnell 1986, Martin *et al.* 1993, Hammond & Fedak 1994, McConnell *et. al* 1999, LeBoeuf *et al.* 2000). In 1999, more than 450 marine animals were fitted with Argos transmitters, representing 30% of all animals tracked by Argos[2]. Nonetheless, the aquatic environment presents particular difficulties for satellite telemetry. Because marine animals spend most of their time underwater, from where reception of uplinks is precluded, the uplink success rate is lower than in terrestrial or aerial applications.

At least four successive uplinks during a satellite pass are necessary for a location to be assigned to location classes (LC) 0, 1, 2 or 3 (Service Argos 1996). However, in 1994 Service Argos set up a new service providing a location from only two (LC B) or three (LC A) successive uplinks. LCs 0, A and B predominate in marine mammal tracking due to the low uplink rate (e.g. McConnell & Fedak 1996, where 90% of location fixes were LC < 1, and references in Goulet *et al.* 1999); but their accuracy is 'not guaranteed' by Argos. The aim of this study was to estimate the accuracy of Argos fixes of all LCs, with a particular emphasis on LCs A and B, from satellite tags mounted on animals.

Materials and Methods

Data collection

The study was conducted on four yearling female grey seals (*Halichoerus grypus*) temporarily kept in captivity. These were young of the year and weighed approximately 12-18 kg at capture. We hoped to simulate the range of behaviours used by seals in the wild by allowing them to swim, make shallow dives and haulout. Rapidly varying

[2] Personal communication from Service Clientèle, CLS Argos, 8-10 rue Hermes, 31 526 Ramonville St Agne, France, May 2000.

degrees of SRDL submergence would truncate or postpone transmissions as would occur at sea.

Satellite relay data loggers (SRDLs) were glued to the nape of the neck, just behind the back edge of the skull, using a quick-setting epoxy resin (Fedak *et al*. 1983). The seals were then kept in an outdoor tank for between 11 and 22 days. Following release, they were tracked for between 13 and 80 days.

The tank was 2 m deep, 4 m wide, and 6 m long with a small beach that allowed the seals to haul out. The location of the tank was 48.3889° N, 4.4347° W as determined by differentially-corrected GPS using the WGS 84 geodetic system, with an accuracy of 4 m. From the water surface the sky was visible from an angle of 26° above the horizon northwards, 24° eastwards, 18° southwards and 14° westwards. At this latitude Argos predicts on average 3.4 and 5.9 passes per satellite per day visible above 20° and 5° elevations, respectively.[3]

The SRDLs (Sea Mammal Research Unit, University of St Andrews, Scotland) weighed 370g and consisted of a data logger interfaced to an Argos RF transmitter unit. The RF units were type PTT100 (Microwave Telemetry, MA, US) and their transmitted power was 500mW. A brief description of the SRDLs is provided by (Fedak *et al.*, 1996). The seal activity was assigned to one of three activity classes: 'diving' if below 6m for more than 6 seconds, 'hauled out' if continuously dry for more than 10 minutes, or otherwise 'at surface'. The proportion of time that consisted of haulout activity within each completed six-hour interval was calculated and transmitted. Other detailed dive data were collected and transmitted but they are not considered in this analysis.

The default transmission interval was 40 s, but if the wet/dry sensor indicated the SRDL was underwater a transmission was delayed until the seal surfaced. Furthermore, in order to prolong tag life, transmissions were prevented when the wet/dry sensor was continuously dry for more than 3 hours. Thereafter the SRDL transmitted for one hour in every six hours until it became wet and the haulout period ended.

Data processing and analysis

Locations were filtered by an algorithm described by McConnell *et al.* (1992). This iterative forward/backward averaging filter identifies fixes that would require an unrealistic rate of travel. The 'maximum speed parameter' in the filter was set to 2.0 $m.s^{-1}$. Grey seals seldom travel faster than this value over prolonged intervals (Thompson *et al.* 1991, McConnell *et al.* 1999).

The latitudinal and longitudinal errors were calculated from locations obtained while the seals were captive, grouped by LC and both pre- and post-filtering. The frequency distributions of these errors were summarized and smoothed using gaussian kernel density estimation (function *density* in R, Ihaka & Gentleman 1996; Venables & Ripley 1999). 68^{th} and 95^{th} percentiles were calculated from the ranked, absolute errors. Argos express accuracy for LCs 1-3 in terms of 68^{th} percentiles.

We calculated the probability (*P(norm)*) that each error distribution was drawn from a normally distributed population, with variance = sample variance and mean = sample mean, using a Kolmogorov-Smirnov test (function *ks.test*). We then tested for bias by calculating the probability (*P(mean!=0)*) that the error distributions were each

[3] Personal communication from Roland Liaubet, CLS Argos, 8-10 rue Hermes, 31 526 Ramonville St Agne, France, March 2001.

drawn from a population with mean = 0. Where the error distribution was assumed to be normal (*P(norm)* > 0.05), we used Welch Two Sample t-test (function *t.test*), otherwise we used a Wilcoxon non-parametric test (function *wilcoxon.test).* We also tested for significant differences in the variances of longitude and latitude errors. Where both error distributions were assumed to be normal (*P(norm)* > 0.05) we used an F-test (function *var.test*), otherwise we used a Fligner-Killeen median test (Conover *et al.* 1981, function *fligner.test*). We report significant differences (*P(var(lon):var(lat) = 1)* < 0.05)) as the ratio of longitude:latitude standard deviations. The analyses were conducted using R version 1.2.2.

RESULTS

A total of 426 location fixes were obtained during captivity over 61 seal-days, of which 59 were identified as unreliable by the filtering algorithm. The remaining 367 filtered fixes represented a mean of 6.0 locations per seal-day. The distributions of latitudinal and longitudinal errors are shown in Figure 1 and error statistics are shown in Tables 1 and 2.

There was significantly more error in longitude than latitude in all LCs except LC A. The ratio of the standard deviations of longitude:latitude ranged from 1.77 (LC 3) to 2.58 (LC1). This ellipsoid nature of the distribution of errors was not affected by filtering, with one exception. After filtering, LC B variance ratios were no longer significantly different from unity (P = 0.069).

The effect of filtering on reducing the 68th and 95th percentile of errors is shown in Table 2. Filtering had very little effect on errors in LCs 3 to 1, but in the remaining LCs filtering resulted in error reductions ranging from 8% to 63%. Error reduction was greater in the 95th percentile errors, and in longitude, in LCs 0, A and B. A total of 13.8% of all locations were rejected by filtering, most of these belonging to LCs 0, A and B.

The averages of the latitude and longitude 68th percentile errors, and those predicted by Argos (in brackets), were 226 (150), 372 (350) and 757 (1000) m for LCs 3, 2 and 1 respectively. For these LCs, all latitude errors were less than Argos predictions and all longitude errors were greater than Argos predictions.

Both filtered and unfiltered LC A locations were of a similar accuracy to LC 1 locations, and considerably better than LC 0 locations. LC B locations (filtered or not filtered) had by far the largest errors.

Both latitude and longitude errors of LCs > 0 were normally distributed. Of the remaining LCs, only filtered LC 0 had normally distributed errors for both latitude and longitude. The non-normality of the other distributions was primarily due to the disproportionately high occurrence of extreme errors.

Significant bias was only observed in the latitude errors of LCs 2 and B. However the magnitude of the bias was only 88 and 993 m respectively.

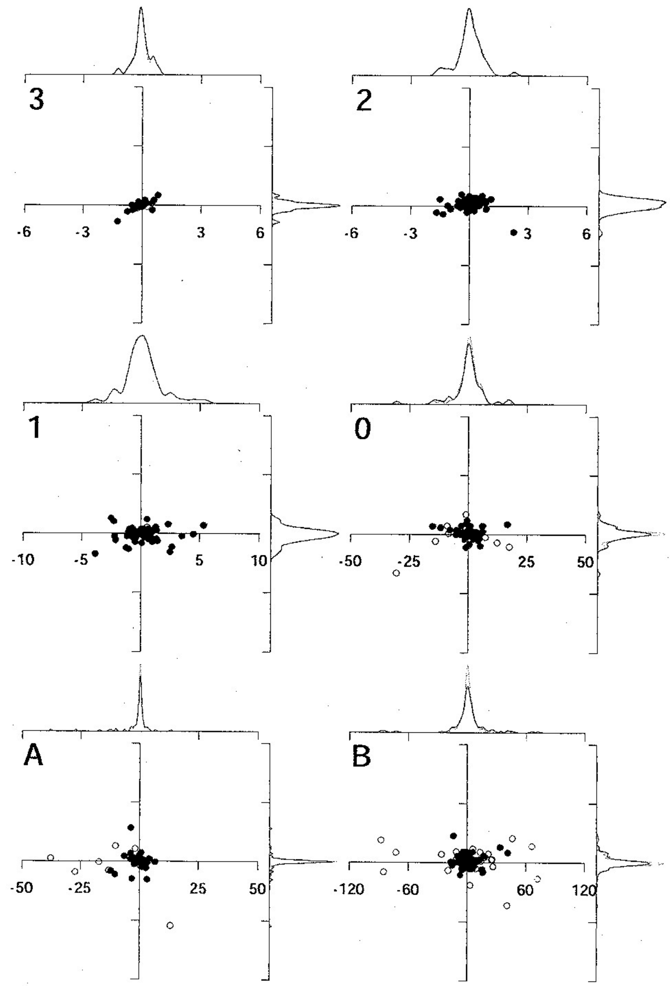

Figure 1. Distribution of location errors. The plots are grouped by Location Class (LC) and the open circles represent locations, which failed to pass the location filter. The x and y axes are scaled the same, in units of kilometers. The frequency distribution of x and y errors are shown as gaussian kernel density estimates (see Methods), grouped by all locations (solid line) and filtered locations (dashed line).

To demonstrate the applicability of the location errors obtained from this captive study to studies on free-ranging animals, we compared the number of uplinks per location at each LC before and after the seals were released (Table 3). The number of uplinks per LC before and after release were very similar for each LC ≥ 0 and, by definition, were identical for LCs A and B. The percentage contribution of LCs before and after release is also shown in Table 3. A greater percentage of LCs > 0 were obtained before release (29.8%) than after (20.2%). The study seals spent a greater amount of time hauled out (using our definition above) while captive (20.2%) compared with post-release (16.3%) and may have spent more time near the surface while captive.

Table 1. Details of latitudinal and longitudinal error, grouped by Location Quality (LQ) and whether the locations were filtered (+ yes or – no) (McConnell & Fedak 1996). 68th and 95th percentiles of ranked absolute errors are shown, as well as the Argos predicted 68th percentile (expressed as metres from true location). The column *P(norm)* indicates the probability that the location errors were drawn from a normally distributed population (Kolmogorov-Smirnov test). The column *P(mean!=0) i*ndicates the probability that the location errors were drawn from a population with mean = 0 (Welch Two Sample t-test if *P(norm)* < 0.05, otherwise Wilcoxon non-parametric test). The mean of the errors (the bias) is shown where *P(mean!=0)* < 0.05. We also tested whether there was a significant difference in the variance of longitude and latitude errors (F test if *P(norm)* > 0.05, otherwise a Fligner-Killeen median test (Conover *et al.* 1981)). Where there was a significant difference (*P(var(lon):var(lat)=1)*<0.05) we show the ratio of the standard deviations of longitude and latitude error. Probabilities < 0.05 are shown in bold, and those < 0.001 are shown as 0.000.

			latitude					longitude							
LC	filtered	*n*			P(norm)	P(mean!=0)	mean (m)	68 %-ile	95 %-ile	P(norm)	P(mean!=0)	mean (m)	P(var(lon):var(lat)=1)	sd(lon): sd(lat)	Argos predicted 68 %-ile
3	-	25	157	326	0.231	0.709	-	295	742	0.641	0.556	-	**0.007**	1.77	150
	+	23	157	326	0.364	0.750	-	295	742	0.762	0.490	-	**0.011**	1.75	
2	-	51	259	511	0.419	**0.048**	88	485	1355	0.912	0.913	-	**0.000**	2.13	350
	+	50	259	511	0.576	**0.040**	95	485	1355	0.336	0.891	-	**0.000**	2.14	
1	-	55	494	1265	0.407	0.214	-	1021	3498	0.215	0.453	-	**0.000**	2.58	1000
	+	54	427	1265	0.400	0.173	-	1021	3498	0.260	0.481	-	**0.000**	2.60	
0	-	60	2271	5517	0.208	0.784	-	3308	15361	**0.016**	0.944	-	**0.024**	2.01	
	+	48	1851	4618	0.577	0.122	-	3029	10551	0.176	0.899	-	**0.000**	2.07	
A	-	103	762	5373	**0.000**	0.347	-	1244	10393	**0.000**	0.618	-	0.257		
	+	91	678	3612	**0.000**	0.241	-	909	3866	**0.000**	0.750	-	0.439		
B	-	132	4596	15535	**0.009**	**0.048**	993	7214	41219	**0.000**	0.274	-	**0.004**	2.41	
	+	101	3193	10116	**0.019**	0.337	-	4815	15417	**0.019**	0.613	-	0.069		

Table 2. Percentage of locations rejected by the location filtering algorithm of McConnell *et al*. (1992) and the percentage reduction in 68th and 95th percentile errors by filtering ((before-after)x100/before). The data are taken from Table 1.

LC	Percentage of locations rejected	latitude		longitude	
		68 %-ile	95 %-ile	68 %-ile	95 %-ile
3	8.0	0.0	0.0	2.1	0.0
2	2.0	0.0	0.0	0.0	0.1
1	1.8	0.0	0.0	0.0	0.0
0	20	11.6	19.4	8.5	48.0
A	11.7	11.2	33.3	27.3	62.9
B	23.5	37.5	27.4	37.7	62.7

The effect of the number of uplinks on location error was also examined. Absolute latitude and longitude errors *(ab_error*) were separately regressed onto the number of uplinks (*n_uplink*), grouped by LC. The regression was not carried out for LCs A and B since each, by definition, was composed of just three and two uplinks respectively. The only regression in which the slope was significantly different from zero was that for the latitude error of LC 0:

$ab\_error = 4759 - 482 \times n\_uplink$, $F_{1,58} = 4.2$, P(slope=0) = 0.044, $r^2 = 0.051$

DISCUSSION

We have shown that Argos location classes (LC) 0, A and B can provide useful information for tracking marine mammals, even though Argos does not guarantee their accuracy to be within specific limits. We have also provided quantitative information on the distributions of errors within each LC from SRDLs attached to seals and we compared these to the specifications provided by Service Argos. We show that, in practice, LC A's are nearly as accurate as LC 1's. With appropriate filtering, even LC B locations provide useful information in studies where high spatial accuracy is not required.

Table 3. Comparison of the percentage of locations and the number of uplinks per location, grouped by LC, before and after release.

	% of total		mean number of uplinks per location	
LC	captive	released	captive	released
3	5.9	2.5	5.28	5.71
2	11.9	5.2	5.73	5.03
1	12.9	12.5	5.07	5.51
0	14.2	20.8	5.33	5.46
A	24.2	23.6	3	3
B	30.9	35.4	2	2

Error distributions

The location errors shown in this study are in general agreement with the predictions provided by Argos. However the error was generally greater in longitude than in latitude, resulting in an elliptical distribution of locations with the major axis aligned along east-west, across the satellite track. Keating *et al.* (1991) and Brothers *et al.* (1998) also demonstrated greater longitudinal error (for LCs > 0), but their locations were generally less accurate than those reported here. It is, however, worth reiterating Keating *et al.*'s reminder that Argos 68th percentile predictions refer to latitude and longitude errors separately. Some previous studies have interpreted Argos predictions as referring to the actual distance from the truth. We avoid reporting errors here as actual distances since doing so both tends to perpetuate the misinterpretation of Argos predictions and also obscures the fact that location error is in fact greater in longitude than latitude. It is also important to note that the longitudinal (cross-track) error is particularly affected by ionospheric propagation disturbances caused by solar activity[3]. Thus longitudinal errors reported here and from other studies will be influenced by the 11-year solar activity cycle.

There was no statistically significant (at the $P<0.05$ level) bias in errors, except for latitude in LCs 2 and B. However, we suggest that the magnitude of the bias (88 and 993 m north respectively) is of little practical consequence in interpreting LCs 2 and B.

An important finding is that LC A has errors similar to LC 1 and far smaller than LC 0. Britten *et al.* (1999) also found that that LC A errors (68% of locations < 6.8 km from truth) were less than LC 0 errors (11.5km) which in turn were less than LC B errors (98.5 km). Even allowing for the fact that their measures of error were distances from the truth, their errors are significantly greater than those we report here. Brothers *et al.* (1998) report the standard deviations of latitude and longitude error to be 4.1 km and 13.3 km for LC 0 and 8.6 km and 6.2 km for LC A. Again their errors are greater than we report here. These latter two studies were carried out on miniature bird tags. We suggest that their greater errors may be due in part to frequency instability, possibly caused by greater variability in tag temperature. The tags in this study were probably less affected by temperature since they were much larger and thus had much higher thermal inertia, and they were frequently immersed in a large volume of seawater. Goulet *et al.* (1999) reported LC 1 errors (68% within 1335 m of truth) from seal tags that were similar to our results and LC 0 errors (68% within 44 km of truth) that were considerably greater than our results. Mate *et al.* (1997) reported LC 0 errors (68% within 7.5 km of truth) from whale tags that were greater than our results. We conclude from the variety of error estimates mentioned above that many factors affect error and that users should carry out their own accuracy test in conditions that most closely resemble those encountered the study species.

Users often dismiss LC A because Argos does not guarantee their accuracy. We suggest that LC A should be used because they provide a large amount of relatively accurate data. In this study, both captive and post-release, LC A comprised about a quarter of all the locations obtained while LC 1 locations, with a similar accuracy, comprised only 13%.

The usefulness of Argos location estimates is related to the range of movements displayed by the study animals. The estimates of location error given here can help in choosing the most appropriate location estimates to use. While location fixes of LC B were of poorer accuracy they nevertheless remain acceptable when the range of movement of the marine animals is large. Some marine mammals such as southern elephant seals (*Mirounga leonina*) have been tracked over thousands of kilometres, moving at an average rate of about 80 km/day (McConnell & Fedak 1996). Grey seals have also been tracked for more than 2000 km, with travel rates between 75 and 100 km/day (McConnell *et al*. 1999). In such cases, fixes of all LCs can be informative.

Filtering algorithm

The non-normal error distributions for LCs < 1 presented in this study suggest that techniques that identify extreme outliers are useful to improve estimates of location. We used an approach that was described by McConnell *et al.* (1992) that attempts to identify locations that would require unfeasibly high rates of travel to achieve. The filter reduced error in these LCs < 1, particularly in longitude and also particularly in locations with the greatest error (represented by the 95^{th} percentile).

The two LC 3s that were rejected followed rapidly after previous high quality locations. Since the time between locations was short any small error in location was transformed into a large apparent speed, and thus the locations were flagged as unfeasible. Conversely, when the inter-location interval is large (Goulet *et al*. 1999) a location with a large error may not be rejected since the animal could have swum to this erroneous location at a feasible speed.

The use of this filtering method resulted in a reduction in the number of remaining locations, primarily LCs < 1. As Keating (1994) points out, the balance between location accuracy and temporal resolution must be decided on a case by case basis.

Applicability to studies on free-ranging animals.

We argue that the results obtained in this study from captive animals can be applied to studies on free ranging animals. Our animals were allowed to swim and haulout while in captivity in the hope that they would perform a reasonable repertoire of the behaviours performed by free-ranging animals which might influence Argos location estimation. These behaviours included frequent submergence of the aerial and alteration its orientation. However the reduced satellite visibility due to the surrounding buildings while in captivity could potentially have resulted in fewer uplinks per LC and thus, potentially, reduced accuracy. Our results suggest that this was not the case. The number of uplinks per LC was similar before and after release, and identical for LCs A and B. Moreover, an effect of the number of uplinks on LC error was *only* observed in LC 0 latitudinal error. For this LC, each extra uplink reduced latitude error by an average of 482 m. The number of uplinks does, of course, influence which LC Argos assigns to a location fix. However, for a given LC (with the exception of LC 0 latitude) the number of uplinks does not affect location accuracy. In summary, we conclude that the reduced satellite visibility in this captive study, with any consequent reduction in uplink rate, does not impede the application of our results to studies of free-ranging animals.

ACKNOWLEDGEMENTS

We wish to thank Phil Lovell for his assistance in the analysis, Colin Hunter and Charlie Rob for SRDL construction and Simon Moss assistance in the field. We also thank Roland Liaubet, Cathy Picot and Anne-Marie Bréonce from Service Argos, and the seal curators and students who helped during the captivity and rehabilitation of the seals in Océanopolis. This study was funded by the Direction Régionale de l'Environement in Brittany (France), and the costs of satellite transmissions were funded by the Centre National d'Etudes Spatiales (Toulouse, France).

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