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Measuring accuracy and precision for CLS:Argos satellite telemetry locations

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Abstract The CLS:Argos location and data collection system is used widely by researchers tracking the movements of animals. The accuracy of the Argos location classes is undefined for most Argos locations for studies involving tracking animals. Published empirical data on the accuracy of animal-mounted transmitters are limited to stationary units. The accuracy of the positions is defined by Argos, except for location classes (LC) = 0, A, B, and Z. The distinction between 'accuracy' and 'precision' is discussed using field measurements from 24,466 Argos records collected throughout the world, but mostly in the Southern Hemisphere, between 1992 and 2001. Factors affecting the defined 'accuracy' and 'precision' are identified from this analysis. Neither the transmitter's age, nor its attachment to a bird degraded its performance. However, the performance of transmitters in terms of the locations they provided was affected when the objects they were attached to moved rapidly, and, with 1 platform transmitter terminal (PTT), by altering of the proportion of location classes within the experiment, but not the 'precision' of the classes (LC = 3, 2, 1, and A). The 'precision' (rounded, measured as 1 SD of the mean of the distance of the location from the actual position occupied by the transmitter, for "Location Classes" 3, 2, and 1 was <2.5 km; that for LC = A, 15 km; LC = 0, 25 km, and for LC =B, 56 (latitude) and 94 km (longitude). The 'accuracy' (mean distance between the Argos location and the actual position of the transmitter, was 0.1-5.0 km for LC = 3 to B, which covers almost all the locations used by animal telemetry studies. The variation in 'accuracy' was, therefore, negligible compared to the variation in 'precision'.

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INTRODUCTION

CLS:Argos satellite telemetry is used extensively to track animals and to report on environmental and behavioural data (Jouventin & Weimerskirch 1990; Weimerskirch *et al*. 1993, 1994; Freeman *et al.* 1997; Murray *et al.* 2002; Nicholls *et al*. 2002; Vincent *et al.* 2002; BirdLife International 2004). Because of this successful use, it has become increasingly important to understand the accuracy of the Argos locations for establishing relationships between animals, their distribution patterns and the environment (weather, oceanic features, including currents and bathymetry). Distance and speed calculations require an understanding of the accuracy of the Argos locational data.

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Fast-flying Procellariiformes (albatrosses, petrels, shearwaters), which can forage in an ever-changing pattern and may dive beneath the surface, provide a challenge to good satellite reception, and their habits often result in degraded location accuracy.

The CLS:Argos satellite telemetry system (Argos) grades its calculated locations using details from the quality of satellite reception. The system specifies the accuracy of its locations for three grades, Location Class (LC) = 3, 2, 1 (Anon. 1994, 1999).

A further 4 location classes are also provided (LC = 0, A, B, Z, and records without a location, hereafter Z???). The accuracy for these classes is >1 km for LC = 0, or is unspecified (LC = A, B, Z) by Argos. These latter LCs are the commonest records obtained from most animal studies.

Argos specifies the accuracy as ±1 standard deviation (68% of the locations are likely to be within ± 1 SD), at 100 m, 300 m, and 1000m of the Argos location for LC = 3, 2, 1 respectively). Researchers using the system often misunderstand these measures of positional accuracy, and we suggest adopting the following definitions, used both in statistics and in GPS studies (Keating 1994; Hulbert 2001): '*Accuracy*', mean distance error from a known true position; '*Precision*', the area (corresponding to ranges of values of latitude and longitude) within which 95% (± 2SD) of locations are likely to be found (fig. 1, Hulbert 2001). 'Precision' is a measure of the tightness of the grouping, (cf. target-shooting), being the clustering of points about the mean of those points, whereas 'accuracy' is the offset, or bias, of that mean relative to the true location point.

We report on various factors inherent in deployments on animals of small, low-powered satellite tags (platform transmitter terminals, PTTs) available from the mid- to late-1990s, which may affect their performance. Our data are from PTTs deployed at fixed locations, as well as on stationary and fast-moving seabirds, a fur seal (*Arctocephalus* sp.), small ships, cars, and trains. The proportions of the LCs obtained and the 'accuracy' and 'precision' of the Argos locations under these varied field conditions are reported and discussed.

METHODS

Source of data

Argos provides a diagnostic file (DIAG) containing all records of contact with the PTT. Simpler versions are available in a variety of formats known as PRV files. The DIAG files include the PTT identification number, date and time, LC, a quality index, 2 locations (1 on each side of the satellite orbit), together with other information on the quality of reception and data from sensors. The PRV records provide no diagnostic data, and only a single location record^{-1}, but they report which satellite receivd the messages and, in some formats, the data from the sensors at each message (unlike the DIAG, which provides only a single set of sensor data for the pass).

We used the CLS:Argos Location Service Plus in the archived version of the DIAG file for this paper, except for data obtained in 2001 (see below). The Argos locations were given in latitude and longitude, using the WGS84 geodetic system (Anon 1999). The Argos DIAG files also included records without a location (a message was received, but no location could be determined – denoted here as Z???). We use the term 'locations' for all Argos-determined positions, differentiating them from the GPS- or map-determined co-ordinates for a known true position (TP).

Between 1992 and 1999 we received 24,466 records (including Z??? category) under various conditions from a wide geographic area in both the northern and southern hemispheres. In 2001 there were an additional 570 records (PRV file only) obtained from a calibration test in Australia. Included in the full dataset are Argos records collected before the PTTs left the manufacturer, during the calibration of sensors and epoxy packaging, a variety of stationary deployments, and when they were deployed on albatrosses (5-10 kg), a petrel (Westland petrel, *Procellaria westlandica*), and shearwaters (short-tailed, *Puffinus tenuirostris*; sooty, *P. griseus)* (0.5-1.2 kg), a fur seal (*Arctocephalus* sp.), ships, cars, and trains.

PTTs

PTTs from 3 manufacturers (Microwave Telemetry, models 100, Nano, Pica; Telonics, ST6, ST10; Toyocom, 21803C) were used, All except the ST6s were low- or very low-power miniature PTTs. The repetition rates used (interval between sending messages to the satellite) were 60-90 s. The duty cycles (on-off periods of transmissions programmed to achieve fewer locations day^{-1}, but over more days) were: continuous; 3h on 3h off; 25h on 23h off; and combinations selected from 6-9 h on then 33-135 h off. The transmitters were designed to transmit for periods of 1 month to >2 years (Nicholls & Robertson 2000; Nicholls *et al*. 2002; BirdLife International 2004; Nicholls & Robertson 2007b).

Stationary deployments

The PTTs transmitted from positions with very variable visibility to the satellites: in and near laboratories, homes, field stations or camps, during testing and calibration both before and after being deployed on animals or transport vehicles. The true position (TP) of known test sites was obtained, where possible from a GPS determination using the WGS84 geodetic system, or the most recent maps or charts. An audited set of records was available from PTTs deployed on albatrosses, known to be present at their nest site, from the observations of a resident field team.

Mobile deployments

PTTs deployed on albatrosses were taped, or glued to back feathers (Nicholls *et al*. 1995) or held on the back with a harness. Glued transmitters were preened into the back feathers, while those PTTs with harnesses were preened into the feathers while the bird was at the nest and partially covered by the folded wings. In flight however, the harnessed PTTs were observed sitting above the back feathers. Deployments on the Westland petrel, and on the short-tailed and sooty shearwaters involved the PTT being glued to the back feathers (Freeman *et al.* 1997; Nicholls *et al*. 1998; Söhle *et al*. 2007). The fur seal PTT was deployed off Tasmania glued to the fur between the seal's shoulders (R. Gales, *pers. comm.*).

For the deployments on ships (generally travelling at 9-10 knots), the PTT was placed high on the superstructure at *c.*3-7 m above the sea (not on the mast), where there was a clear view of the horizon. An hourly GPS log was available for ships' voyages between Bluff and Antipodes I, New Zealand. From the GPS log, a linear interpolation of an estimated true position (TP) at the time of each 'location' was calculated, and this 'TP' was used to estimate the 'accuracy' of the 'location'.

PTTs were taped to the roof of a sedan car. The car was driven around a car manufacturer's proving circuit at representative Australian country road driving speeds, generally 50-100 km h^{-1}, with additional stopping and restarting. It was driven 24 h day^{-1} during weekdays, but was parked at weekends. The irregular track was entirely within an area of 2 km × 2 km, (*c*.80 km east of Melbourne, Australia) during Nov to Dec 1999. The location of the centre of the track was estimated from the 1:100 000 map to obtain the TP.

The PTTs (1 in 1999, 2 in 2001) deployed on trains were cushioned, using a rubber mat and Silastic® glue, and bolted to an aluminium plate. This plate was then bolted to the roof (4 m above ground) of a stainless steel railway carriage used in a trans-continental train travelling across southern Australia between Sydney (New South Wales) and Perth (Western Australia) via Port Augusta and Adelaide in South Australia. The train travelled on a regular 3-day timetable at *c*.100-110 km h^{-1} when on open track (including the longest section of straight railway line in the world). It remained stationary at railway stations and marshalling yards. Unlike the 1999 data, the 2001 record data were not DIAG archival files, because only a real-time downloaded PRV format was available. We had sought a GPS-PTT to deploy with our PTTs, but none was available at the time of the test. The positions relating to the rail line was coarsely estimated from the positions of selected railway stations along the route.

Data preparation

Each of the 2 'locations' provided in the Argos DIAG file was inspected. The 1st 'location' was accepted unless, after considering the distances between the 4 adjacent 'locations', the 2nd 'location' provided a shorter distance travelled. This change in the selection was uncommon, but occurred more frequently for fast-moving PTTs, and for records received immediately after long "off"-periods with no transmissions.

This was the only pre-processing done before any of the following analyses. However, the 2001 train records (PRV files) provided the 1st listed location only, and did not report 'locations' where the number of Argos plausibility tests passed was <2. This is unlike the DIAG file, where all calculated locations (including implausible locations) were reported. Some real time (PRV) records are recalculated by Argos before being archived, thus occasionally altering the location of the record (G. Oon, Argos, *pers. comm.)*. These variations make this PRV dataset significantly different from the rest of the data reported here.

Locations were mapped in Arc View 3.2© (ESRI Inc., Redlands, California, U.S.A.). Except for Fig. 1 (geographic projection), all other maps presented here use an equidistant azimuthal projection centred at 135°E and 30°S. All distances calculated (Nicholls *et al.* 2002) were the great circle distances between 'locations' or between a 'location' and the TP. One great circle degree was taken to be 111.12 km. Differences in longitude, were converted to great circle degrees as the cosine of the mean latitude. An Excel® spreadsheet was used for calculating the distances, and JMP 4.0.2® for statistical analysis.

Measurement of 'precision' or 'accuracy' or both

Three methods were used to measure the error distance between the known true position (TP) and the 'locations' for stationary-sited PTTs,. The 'locations' for the different sites and their 'precision' and 'accuracy' (as appropriate) were measured for each LC using the following methods.

Method 1 The mean ± 1SD of the great circle distances between the TP (see above) and each 'location'. This method takes a single distance from the TP to each 'location' for each record (cf. the other 2 methods, which differentiate between the offset errors in latitude and longitude), and is the measure of 'accuracy', often used (incorrectly) by tracking practitioners (Keating 1994). It is not the same measurement of accuracy as that specified by Argos (Anon. 1999).

Method 2 Using only the 'locations', the 'precision' was measured as ± 1SD of the means for both the latitude and longitude of the 'locations' (expressed as km). The position corresponding to the mean of these values is the 'estimated true position' and its displacement from the TP is defined as the 'accuracy'.

Method 3 The 'accuracy' and 'precision' of 'locations' given as the mean ± 1SD of the differences between the TP and each 'location'. These are calculated separately for both latitude and longitude (expressed as km), because the direction as well as the distance from the TP to the 'location' is important. Perfect 'accuracy' requires mean = 0 for both latitude and longitude.

To test whether movement of the PTT during its deployment degraded its performance, the 'accuracy' and 'precision' were measured using a modification of *Method 3*. The PTTs were deployed on ships, cars, and a transcontinental train. The TP at the time of each Argos 'location' was estimated. For the ship deployments, the TP was estimated for each 'location' by interpolation from the ship's log that reported hourly GPS positions. For the car

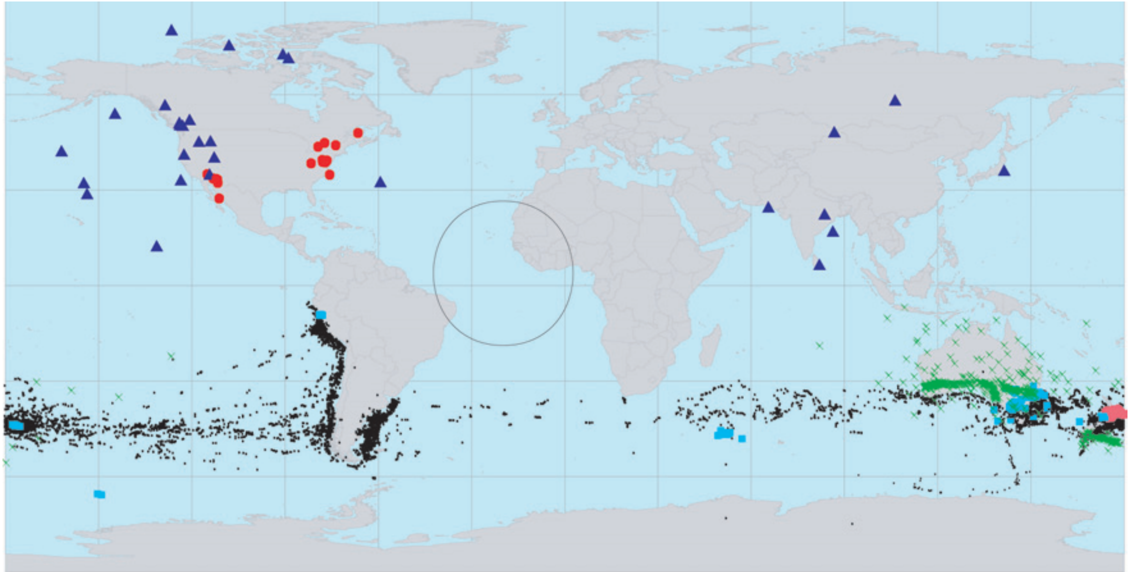

Fig. 1 Geographic distribution of Argos 'locations' used in this study. PPTs deployed on pelagic seabirds and a fur seal (*Arctocephalus* sp.)(•); boat, car and transcontinental train (×); USA manufacturer and packaging sites (●); stationary deployments (e.g., Crozet I., Indian Ocean) (■); unexplained and aberrant Northern Hemisphere locations within deployments (▲). Circle, 'foot print' area along satellite orbital path in which PTTs are visible to satellite from 5° above an ocean horizon.

deployment, the TP was assumed to be the centre of the proving circuit on which the car travelled. Without a GPS being fitted alongside the PTT on the train, it was not practical to calculate the PTT's true position, so only a qualitative analysis was attempted for this deployment.

RESULTS

Geographic coverage

We analysed 21,329 Argos 'location' records (Fig. 1, Table 1). Most data were for albatrosses in the Southern Hemisphere at 5°S to 60°S, but also included data from shearwaters that reached the edge of Antarctica at 65°S, a transcontinental train across Australia, and stationary deployments in the Australasian region. Some data were available from the Northern Hemisphere for 'locations' at the manufacturers' sites during final testing.

A few of deployments in the Southern Hemisphere resulted in unexplained records from the Northern Hemisphere: the accompanying data in the DIAG files make it clear that these transmissions originated from our PTTs.

Distribution of records

Within each sample, the proportion for each of the LCs varied according to different operating conditions. Some of the variables affecting the proportions could be identified (Table 1, Fig. 2).

An improved Argos location algorithm was introduced on 15 Jun 1994 (Anon. 1994), when

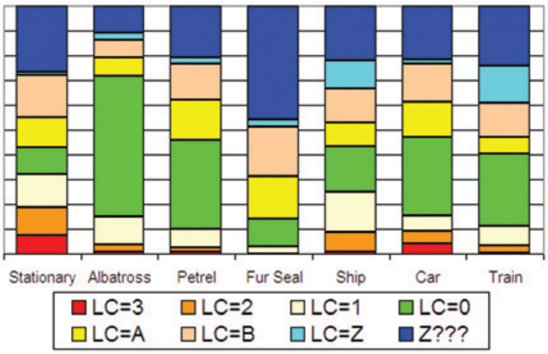

Fig. 2 Proportions of location classes (LC) in sets of Argos records received from different kinds of deployment. Note gradual reduction in proportion of LC = 3, 2, 1 and the increase in LC = 0 for albatrosses at sea. Proportion of poorer quality LC = A, B, Z, and no 'location' Z??? increases with increasing target speed, erratic movement, or reduced visibility to the satellite.

3 new LCs were added (LC = A, B, Z) and LC =0 was redefined. There were also LC =Z DIAG records which had no location (our LC =Z???), but these records did include data from sensors. Our data are shown as separate sets of samples to reflect this change and to bring together sets with similar operating parameters (Table 1). The sets are as follows: (a) Stationary PTTs while they were still at the manufacturer, or while being packaged; (b) Stationary PTTs before and after

Table 1 The number and percentages of 24,466 Argos records for each Location Class (LC) obtained from stationary and mobile PTTs (pre- and post-mid 1994). All data except for the 2001 PRV records are from DIAG records.

1992 to 14 June 1994			Percent of location classes (LC)							
Deployment	Location	*n*	3	2	1	0	A	B	Z	Z???
Final test at manufacturer's laboratory										
	MT, Massachusetts	49	6	12	16	65	n/a	n/a	n/a	n/a
Stationary, bench testing at packaging manufacturer										
	Sirtrack	22	0	0	32	68	n/a	n/a	n/a	n/a
Stationary site transmissions, pre- and post-deployment										
	Bellambi	77	4	3	39	55	n/a	n/a	n/a	n/a
	Melbourne	72	10	4	36	50	n/a	n/a	n/a	n/a
	Crozet I	101	1	11	53	35	n/a	n/a	n/a	n/a
Mobile platform transmissions										
	Ship	26	0	19	35	46	n/a	n/a	n/a	n/a
	Diomedea sanfordi, Taiaroa Head	260	1	8	30	61	n/a	n/a	n/a	n/a
	Diomedea exulans, Australia	1155	0	4	24	72	n/a	n/a	n/a	n/a
Total pre-mid 1994		1762	19	91	493	1159	n/a	n/a	n/a	n/a
Percentage pre-mid 1994		1762	1	5	28	66	n/a	n/a	n/a	n/a
15 June 1994 - 1999										
Stationary										
Final test at manufacturer's laboratory										
	MT, Massachusetts	46	4	24	15	15	13	9	2	17
	Telonics, Texas	117	6	10	21	14	11	6	3	29
Stationary, bench testing at packaging manufacturer										
	Sirtrack	600	3	4	9	7	16	23	1	38
Stationary site transmissions, pre- and post-deployment on bird										
	Nelson	129	9	8	9	13	14	14	1	33
	Nelson Airport	37	3	19	27	32	5	5	0	8
	Te One, Chatham I	68	9	7	6	7	7	18	0	46
	Southlight Lab.	233	9	9	15	13	12	19	1	21
	Pymble	233	7	9	8	5	16	28	0	27

Table 1 Continued

Deployment	Location	*n*	3	2	1	0	A	B	Z	Z???
	Sisters I, on rock	63	24	13	14	3	11	11	0	24
Stationary site transmissions on albatrosses										
	Sisters I audited sitting *Diomedea sanfordi* ([a] see note)	333	11	18	24	16	8	12	1	11
Moving very locally, not on bird										
	Bellambi	502	9	11	13	15	11	15	1	26
	Melbourne	456	8	17	13	9	10	15	2	27
	Peru, fishing village	68	6	1	0	0	10	22	0	60
Subtotal and percentages		2817	8	11	13	11	12	17	1	27
Deployed on nesting birds, mobile animals & vehicles										
Albatrosses										
	Diomedea exulans, Bellambi	1391	1	7	21	41	8	8	1	13
	Diomedea gibsoni, Bellambi	608	0	0	2	60	8	10	4	15
	Thalassarche eremita, The Pyramid	7888	1	3	11	57	8	8	2	10
	Diomedea sanfordi, Sisters I. ([b] see note)	4575	1	3	9	62	7	7	2	10
	Diomedea sanfordi, Taiaroa Head	2493	1	4	12	52	6	5	8	12
Subtotal and percentages		16955	1	3	11	57	8	7	3	11
Petrel, shearwaters										
	Westland petrel, Punakaiki	587	1	2	8	39	15	13	4	18
	Sooty shearwater, Taiaroa Head	643	1	1	8	31	18	19	1	21
	Short-tailed shearwater, French I.	143	0	1	7	43	14	5	1	28
Subtotal and percentages		1373	1	2	8	36	16	15	3	21
Fur seal										
	Tasmania	35	0	0	3	11	17	20	3	46
Mobile platforms										
	Various ships after mid-1994	159	1	8	16	18	9	14	11	22
	Cars, Melbourne proving track	371	4	5	6	32	15	15	2	22
Deployment	Location	*n*	3	2	1	0	A	B	Z	Z???

Table 1 Continued

Trans-continental train, southern Australia	728	0	3	8	29	7	14	15	24
Subtotal and percentages	1258	2	4	9	28	9	14	11	23
Unexplained Northern Hemisphere records within Southern Hemisphere deployments									
Northern Hemisphere	29	0	7	0	48	7	17	21	0
Total post mid 1994-1999 (See note)	22134	338	850	2393	10719	1947	2071	679	3137
Percentage post-mid-1994 to 1999		2	4	11	48	9	9	3	14
Jun- Jul 2001, PRV files only which include only locations with 2 or more plausibility tests passed									
Mobile platforms									
Trans-continental train, southern Australia	570	5	11	18	43	11	12	n/a	n/a

Note. Sisters I. audited sitting *Diomedea sanfordi* subset [a] included in analysis of *Diomedea sanfordi* deployments [b], but not double-counted in total.

field deployments where we knew the site; (c) Stationary PTTs audited by field observation on birds observed at the nest; (d) Stationary PTTs at known fixed sites intended to measure 'accuracy'; (e) Moving PTTs deliberately transported over a known route, or within a specified small area; (f) PTTs deployed on several species of albatross, petrel, and shearwaters, where the birds were tagged at breeding sites, and include records of the birds flying at sea. In addition, some deployments were made at sea, and the bird remained at sea throughout the deployment; (g) One PTT (at Crozet I, southern Indian Ocean) fell off the bird near its nest, and another (in Peru) was apparently taken from an albatross at sea and subsequently recovered ashore from a fisherman: these circumstances provided stationary records.

'Location' data available for our study included information from PTTs when new, during sensor calibration, packaging, refurbishment, and deployment on animals under various conditions, or on mobile vehicles.

Overall, there were fewer "best quality" (LC = 3, 2, 1) records (Table 1, Fig. 2). Together, they made up 32% of records for a range of stationary PTTs, but only 11-15% for fast-moving vehicles, 15% for albatross, and 11% for the petrel and shearwaters. Argos calculated a location for a few LC = Z records: 0-3% for stationary and bird-deployed PTTs, but 9-13% for the ship, car, and train deployments. The proportion of no-location records (LC =Z???) varied for stationary PTTs (8-60%, perhaps depending on the PTTs' visibility to the satellites), 10-15% for albatrosses but higher for a petrel and shearwaters (18-28%), vehicles (22-24%), and highest for a seal at sea (46%).

Variables

We identified the following factors potentially affecting the distribution of 'locations' between each LC:

MANUFACTURER PTTs from 2 manufacturers performed similarly before their dispatch. This was not a definitive test, for it did not allow for improvements made during the manufacturers' final tuning, and the conditions (model of PTT; radio noise; and to satellite) were not controlled. However, the results suggest that the various models of lower-powered units manufactured by Microwave Telemetry were not disadvantaged in comparison to the higher-powered Telonics ST10 transmitters.

PTT MODEL Comparison of the results from combinations of Microwave Telemetry models versus the Telonics ST10 for the large albatrosses did not indicate substantial differences in the performance of PTT models, except for the single MT pica PTT (#899) tested (see below).

Individual PTTs Keating *et al*. (1991) reported that they, and others, had found that individual PTTs varied in performance, yielding 68% errors of 593-1816 m. We observed variation between PTTs, but did not quantify the differences.

Packager Batteries, antenna, epoxy, and fibre casing reinforcing, and waterproofing of all our PTTs were added by Sirtrack Ltd. Most PTTs transmitted from inside the assembly laboratory. Only rarely were the units tested outside, which may account for the low proportion of LC = 3, 2, 1 locations. The performance of the same PTTs was often better when deployed at sea.

Packaging The addition of the packaging was not observed to degrade the transmission performance.

Local movement of PTTs At Melbourne, the PTTs were transported short distances while being carried to a laboratory. At Bellambi, the units were variously exposed to satellite view, stored in containers (in a boat ashore, and at sea), in anticipation of the later deployment on birds caught at sea. Thus, the visibility of the transmitter to the satellites was often restricted and there were undefined local movements, which together may account for the high proportions of both very good (LC = 3) and very poor (A, B, Z???) 'locations', for those data. For the "Peru" PTT, contact was 1st lost at sea, and transmissions were not received until a month later, when 'locations' were received from the neighbourhood of a fishing port in Peru. The unit was recovered from a fisherman, but was possibly not held at a fixed site while transmitting ashore.

PTT fallen to the ground The Crozet I sample was from an ST6 PTT that had been deployed on an albatross which had been caught off Australia. The temperature regime and motion sensor data transmitted by the PTT indicated that it was motionless and no longer on a live bird. It was subsequently found lying on wet ground in a trench (Nicholls *et al.* 1995) beside the nest. This position may have caused the reduced number of LC = 3 records, but LC = 2 and 1 records dominated.

Satellite visibility The UHF signal requires a clear line of sight between the PTT and the satellite's receiver. Buildings, vegetation, and high terrain block or reflect transmission and there was some evidence that this affected locations in the data available to us. At Nelson, high terrain blocked the horizon to the south, which may account for the differences between 'locations' at that site and those in the Nelson airport sample, where there was a much clearer horizon. Similarly at The Pyramid (Chatham Is), the nest sites of the Chatham albatrosses *(Thalassarche eremita)* used have a high cliff partially blocking visibility of the horizon to the north.

Radio noise A group of ST10 PTTs at an isolated island (Little Sister I, Chatham Is, 850 km east of New Zealand) with an unobstructed view to the sea horizon in all directions provided a sample with the highest proportion of LC = 3 (24%), and a majority (51%) of LC = 3, 2, 1 'locations'. The very low background radio noise in this isolated area and the optimal visibility to satellites probably account for the good reception and high proportion of higher class records.

Effect of the bird A similar sample, also from Little Sister I, demonstrated the effects of PTTs deployed on the northern royal albatross *(Diomedea sanfordi)*, which were alternately incubating ashore and foraging at sea. The nest sites were monitored regularly and we selected individual Argos records when the bird was audited every 3-4 h daily between 0600 h and 2000 h, either on or beside the nest. In this sample, 52% were LC = 3, 2, or 1 'locations', the highest proportion of any sample, and with the 2nd highest (10%) proportion of LC = 3. These data suggest that the presence of the bird did not degrade the transmission performance of the PTT. It had been thought that the folded wings partially enveloping the antenna might detune it, reducing the transmission, but the bird may also provide a stable temperature environment and a ground plane giving improved radiation.

Poor radio propagation A sample from Te One, Chatham I, was from the batch of ST10 PTTs later used on Little Sister I. The proportion (46%) for LC = Z??? was high, and may have resulted from a diminished satellite visibility from its position in the swale between consolidated sand dunes. The site is known to have poor HF radio transmission and reception.

Albatrosses at nest versus flying The proportions of the LCs for stationary northern royal albatross audite**d** at the nest differed (Pearson $\chi^2_{df=5} = 848.5$, $n = 4574$, $P<0.0001$) from unaudited records collected from the same birds that included foraging time away from the island.

Flying and diving behaviour There were more LC = A or B and fewer LC= 0 records for the smaller birds. The albatross and petrel/shearwater samples differed probably because of the smaller birds faster, more erratic, flight, and because they dive beneath the surface (which reduces visibility to the satellite and which may expose the PTT to temperature shock). The Westland petrel differed from the 2 shearwaters (Pearson $\chi^2_{df=10} = 33.5$, $n = 1553$, $P = 0.0002$). The 2 shearwaters may have differed (Pearson $\chi^2_{df=5} = 13.0$, $n = 966$, $P = 0.02$) because the sooty shearwaters were recorded both at sea and in their nesting burrows, whereas the short-tailed shearwater was entirely at sea. The fur seal data extended the trend of lower numbers of LCs = 3, 2, 1 and increased numbers of LC = A, B, Z, Z??? records, arising from the seal's maritime behaviour.

Stability Patterns of location class representations associated with the known erratic flight of shearwaters, and from the ship at sea, showed a higher proportion of the poorer LCs, which suggests that roll and pitch of the platform may influence results.

Frequency drift Normally the transmission frequency of a PTT is very stable, but it is possible for the transmitted frequency to drift slowly over months of deployment. If the frequency continues to drift and eventually exceeds Argos specifications, contact will be lost, but the cause will only be apparent if the frequency data are followed. To our knowledge, loss through frequency drift has occurred once, with an MT pica PTT (J. Nelson, *pers. comm.*).

Speed The fast car and train both yielded low proportions of LC = 3, 2, 1 'locations' and a high proportion of LC = B, Z, Z??? records. Both platforms were otherwise stable, with negligible roll and pitch components as compared to a flying seabird.

Ground plane coupling Once the PTTs were deployed on birds, away from radio noise and clear of obstructing hills and vegetation, our experience suggested that the signal reception improved. The ground plane of the PTT's antenna may couple to the mass of the bird, and possibly also to the sea, resulting in improved transmission performance (P. Howey, *pers. comm.*).

Repetition rate and duty cycle Repetition rate directly influenced the number of messages available to the satellite for the 'location' calculation, and the LC is determined, in part, on this component (e.g., LC = 3, 2, 1, and 0 require a minimum of 4 messages). After a long time interval with no transmission (long duty cycle), the 1st LC and the LC for the next few 'locations' was often of the poorer classes.

Temperature A stable transmitter radio frequency is essential for the accurate determination of the Doppler shift between transmissions, and therefore the accuracy of the 'location'. As the frequency stability depends on temperature, rapid changes in temperature should cause deterioration in LC. We observed this in the shearwaters, and attribute the high LC performance of the audited nesting albatrosses to, in part, the thermo-regulation provided by the bird.

Battery deterioration Stored lithium cells pacify, which reduces the available current. On starting a PTT with new batteries, it may take 1-2 days to reverse this process before the battery reaches optimal performance. Turning off a PTT and leaving the battery partially discharged will cause it to pacify: when used again this process may reverse only partially and thus not provide optimal performance (P. Howey, K. Lay, *pers. comm.*). Where it was possible to measure battery life from the length of our deployments, the batteries we used appeared to run according to the battery specification, contrary to the experience of Britten *et al*. (1999).

Altitude Argos requires that the maximum operating altitude be set by the user, although the effect may be small in many applications (Keating *et al*. 1991; Britten *et al*. 1999). All our data (except for a portion of the train journey, at the few terrestrial sites, and for nesting albatrosses) were collected at or near sea level. No correction was asked of Argos.

Case history of MT pica PTT #899

PTT #899 was deployed successfully on a variety of platforms (ship, car, car, train and stationary) to measure 'accuracy' and 'precision'. The PTT throughout its working life was exposed to variable mechanical shocks, and rapid variations in temperature (cold-hot-cold). This was the only PTT that produced, sporadically throughout its life of >6 years, anomalous location results. An analysis of these aberrant results clarifies aspects of the Argos system and PTT properties. Fig. 3 (also Fig.1) shows the uncharacteristically wide spread of positions that were attributed initially to the fast movement of the train along a fixed route. However, when no other deployments with other transmitters demonstrated a similar dispersal characteristic, the DIAG file data for #899 was examined more closely. The data showed that on several occasions the frequency of the transmitter was either stepped or random for periods, before returning to a stable pattern. These were the occasions when the 'locations' became more widely scattered. The LC = 0, B, and Z 'locations', in that order, were the most affected. This experience demonstrated the importance of the DIAG file data categories for the exploration of behaviour, diagnostics, and anomalies that are not included in the PRV files.

In summary, the data in Table 1 and Fig. 2 demonstrate that the stationary PTTs typically yielded roughly equal proportions for each LC (except LC = Z). Where there was good satellite visibility, more than half the records were LC = 3, 2, or 1. That this performance could be achieved on a stationary large albatross indicated that deployment on the bird did not degrade the PTT performance. With reduced satellite visibility, the performance was greatly degraded, with the proportion of records without a 'location' (LC =Z???) rising to high levels (46-60%). PTTs on free-ranging seabirds showed a rise in the proportion of LC = 0 records, and a reduction in both the best and poorer (LC = 3, 2, and A, B) records. The rapid and frequently changing flight of the petrel and shearwaters further degraded the performance, with few LC = 0 records and a further increase in the proportions of LC = A, B, and Z??? records. The same effect was seen in the fur seal. The PTTs on the ships, cars and

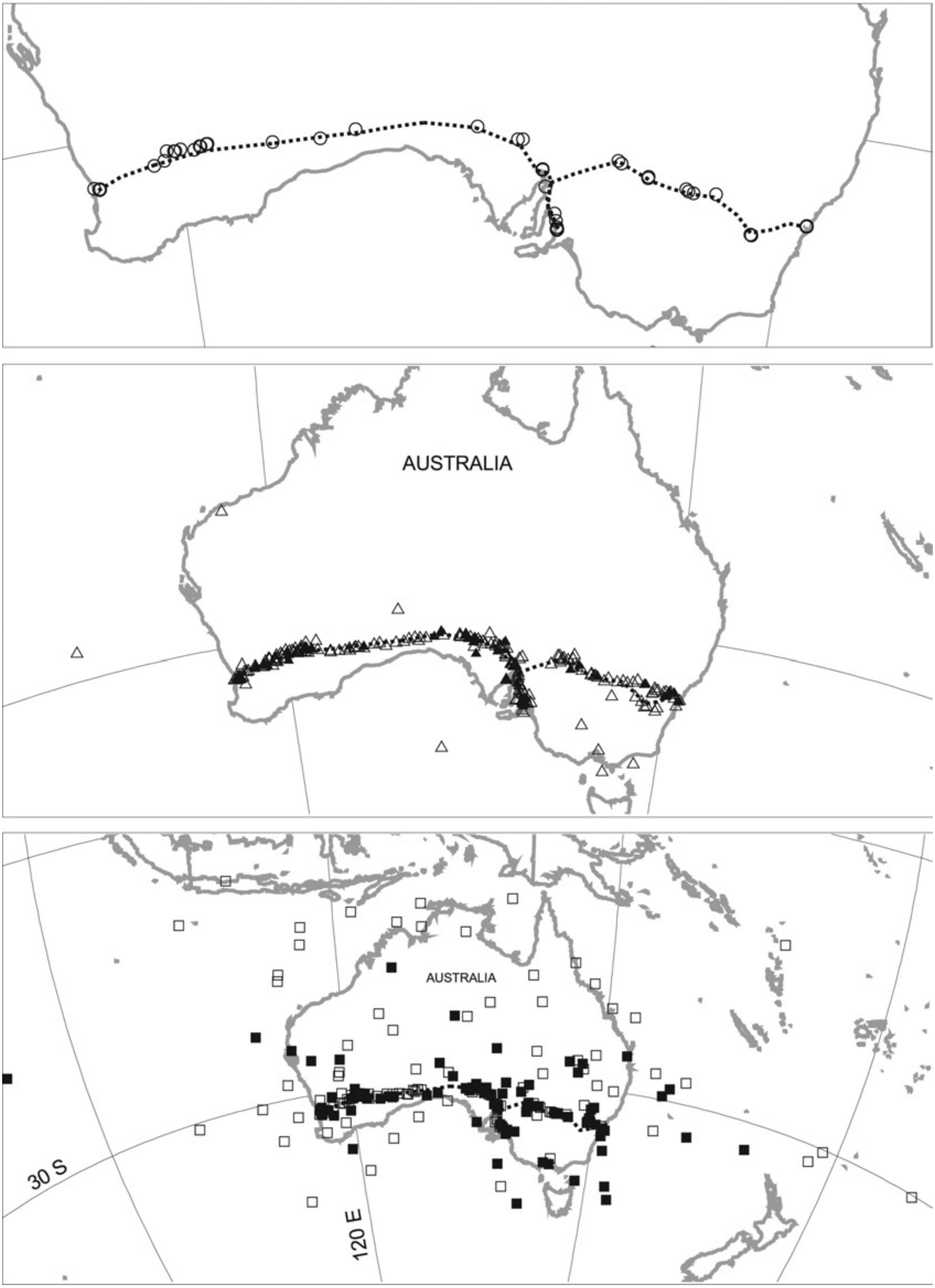

Fig. 3 Comparative 'location' distributions for PTT #899 when carried by a transcontinental train on multiple trips across southern Australia between 12 Aug and 9 Dec 1999. ○, LC =3, 2, 1; △, LC =0 ; ▲, LC =A ; ■, LC =B ;□, LC =Z. Broken line represents actual route train.

Table 2 The 'accuracy' (mean distance between 'location' and true position, km) and 'precision' (SD, km) of Argos Location Classes (LC) from 1269 'locations' (see text, Method 1) for stationary PTTs deployed at fixed true positions (TP) shown as the mean ±1 SD of the radial distance (km) between the TP and the 'locations'. Note: researchers sometimes use this measure incorrectly; they are not the measurements used by Argos.

			Location classes (LC)						
		n	3	2	1	0	A	B	Z
Number of location records		1269	122	164	237	173	222	327	24
All samples			0.5 ± 0.3	0.7 ± 1.6	1.7 ± 3.1	16 ± 31	5 ± 19	38 ± 102	178 ± 216
Final test at manufacturer's laboratory									
Various PTTs, stationary	Telonics Texas	83	0.7 ± 0.3	0.8 ± 0.7	1.5 ± 1.2	1 ± 26	2 ± 2	24 ± 39	257 ± 305
Stationary, bench testing at packing manufacturer									
Various PTTs, stationary	Sirtrack	372	0.5 ± 0.5	0.6 ± 0.4	1.8 ± 3.2	7 ± 9	7 ± 28	33 ± 47	60 ± 93
Stationary site transmissions									
Single PPT, stationary	Melbourne 1999, #899	41	0.3 ± 0.3	0.9 ± 0.8	0. 7 ± 0.1	73 ± 97	2 ± 1	5 ± 366	346 ± 272
Single PPT, stationary	Nelson Airport	34	0.2 ± -	0.9 ± 0.6	2.0 ± 0.9	5 ± 2	11 ± 9	33 ± 1	60 ± -
Single PPT, stationary	Southlight Lab., #899	184	0.4 ± 0.2	0.5 ± 0.3	0.8 ± 0.7	21 ± 26	4 ± 6	23 ± 39	161 ± 36
Various PPTs, stationary	Te One, Chatham I	37	0.6 ± 0.3	0.8 ± 0.1	1.0 ± 0.3	6 ± 7	6 ± 12	19 ± 43	52 ± -
Various PTTs, stationary	Pymble	170	0.4 ± 0.2	1.3 ± 4.4	5.5 ± 8.4	18 ± 43	2 ± 4	14 ± 43	±
Various PTTs, stationary	Sisters I, on rocks	48	0.5 ± 0.2	0.6 ± 0.2	0.6 ± 0.4	1 ± 1	2 ± 4	24 ± 27	257 ± -
Various PTTs, stationary, on nesting birds	Sisters I, at nest	300	0.5 ± 0.2	0.7 ± 0.4	1.3 ± 1.1	25 ± 41	4 ± 6	19 ± 37	214 ± 68

Notes: 1, samples chosen to ensure that PTT remained stationary in single, accurately-known site; 2. Only post-15 Jun 1994 data are included; 3, *n* = number of locations used to calculate standard deviation (does not include Z??? reports with no location; see Table 1).

Table 3 The 'accuracy' (mean distance between 'location' and true position, km) and 'precision' (SD, km) of 1269 'locations' as calculated using Method 2 (see text) of Argos Location Classes (LC) taken from Argos 'location' data from stationary PTTs deployed at fixed true positions (TP), in both latitude and longitude.

			Location classes (LC)													
			3		2		1		0		A		B		Z	
Deployment	Location		Lat	Long	Lat	Long	Lat	Long	Lat	Long	Lat	Long	Lat	Long	Lat	Long
'Accuracy' (Mean)		*n*	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean
Final test at manufacturer's laboratory.																
Various PTTs, stationary	Telonics Texas	83	-0.04	-0.07	0.13	-0.24	-0.06	-0.03	-5.53	2.07	-0.15	-1.08	9	-19	-122	-45
Stationary, bench testing at packing manufacturer																
Various PTTs, stationary	Sirtrack	372	0.08	0.22	0.00	-0.11	-0.41	-0.37	-0.06	-0.84	-0.77	-2.27	-2	-2	-7	-47
Stationary site transmissions																
Single PPT, stationary	Melbourne 1999	41	-0.08	0.09	-0.02	0.18	-0.24	0.25	21.19	-69.21	0.50	0.25	-7	123	188	-31
Single PPT, stationary	Nelson Airport	34	-0.11	-0.22	0.30	-0.04	-0.10	1.07	-0.51	1.26	-6.16	-1.93	4	3	0	0
Single PPT, stationary	Southlight Lab	184	-0.12	0.21	-0.16	0.15	-0.01	0.11	-2.11	-6.75	-1.54	-1.44	1	-10	28	-157
Various PPTs, stationary	Te One, Chatham I	37	-0.50	-0.31	-0.71	-0.35	-0.47	-0.30	-1.80	-3.82	-1.86	-5.66	2	-6	0	0
Various PTTs, stationary	Pymble	170	0.20	0.18	-0.68	-0.51	-3.38	0.22	-10.39	-11.60	-0.83	0.26	-2	9	-45	209
Various PTTs, stationary	Sisters I, on rocks	48	-0.46	0.09	-0.43	0.16	-0.14	-0.13	-0.99	0.15	-0.31	-1.63	-7	6	0	0
Various PTTs, stationary, on nesting birds																
.	Sisters I, at nest	300	-0.43	0.06	-0.43	0.03	-0.30	0.23	13.23	-5.94	0.67	1.17	2	-6	22	35
'Precision' (1 SD)																
Final test at manufacturer's laboratory																
Various PTTs, stationary	Telonics Texas	83	0.31	0.93	0.30	0.90	0.89	1.74	25.7	8.0	0.9	3	14	39	365	162
Stationary, bench testing at packing manufacturer																
Various PTTs, stationary	Sirtrack	372	0.53	0.49	0.37	0.61	2.67	2.46	8.1	7.7	19.7	22	27	51	23	99
Stationary site transmissions																
Single PPT, stationary	Melbourne 1999	41	0.06	0.35	0.26	1.08	0.29	0.91	30.8	92.1	0.7	2	257	395	414	59
Single PPT, stationary	Nelson Airport	34	-	-	0.96	0.50	1.22	1.54	4.4	3.8	14.1	8	1	3		
Single PPT, stationary	Southlight Lab	184	0.21	0.34	0.30	0.44	0.51	0.85	16.4	28.9	3.6	6	12	42	25	32
Various PPTs, stationary	Te One, Chatham I	37	0.32	0.26	0.12	0.30	0.11	0.93	3.1	8.3	2.9	11	19	48	-	-
Various PTTs, stationary	Pymble	170	0.13	0.40	3.34	3.08	6.81	6.69	32.1	30.4	3.1	4	16	43	-	-
Various PTTs, stationary	Sisters I, on rocks	48	0.12	0.19	0.17	0.39	0.44	0.59	0.9	0.3	0.5	4	20	21	-	-
Various PTTs, stationary, on nesting birds																

Table 4 The 'accuracy' (mean distance between 'location' and true position, km) and 'precision' (SD, km) for the 1269 Argos 'locations' from stationary PTTs at known true points (TP) as calculated using Method 3 (see text)). Negative values, southward differences for latitude and westward for longitude.

		Error (km)			
		Latitude		Longitude	
LC	*n*	Mean ± SD	Min, Max	Mean ± SD	Min, Max
3	122	0.07 ± 0.32	-1.00, 1.12	-0.04 ± 0.46	-1.30, 1.63
2	164	-0.03 ± 1.23	-14.86, 1.67	-0.19 ± 1.19	-13.48, 2.60
1	237	-0.26 ± 2.53	-17.53, 4.34	-0.02 ± 2.44	-14.52, 14.76
0	173	2.84 ± 25	-107, 111	-4.68 ± 24	-135, 51
A	222	-0.58 ± 13	-178, 56	-1.29 ± 15	-180, 68
B	327	-1.08 ± 56	-524, 628	3.59 ± 94	-494, 906
Z	24	27.45 ± 257	-650, 595	-30.87 ± 111	-281, 209

Negative latitudes indicate that the distance is southwards of the true point.
Negative longitudes indicate that the distance is westwards of the true point.

Table 5 Comparison of the 'accuracy' (mean distance between 'location' and true position, km) and 'precision' (SD, km) of stationary PTTs at a known true point (TP), with *mobile* PTTs deployed at estimated TPs. Stationary PTT data from Table 4 except for removal of small number of locations of LC =Z (and similarly small number of LC =Z locations removed from the mobile PTT data set). 'Accuracy' and 'precision' of mobile PTT locations calculated using Method 3, except that the TP was interpolated from GPS determinations for the ship, or the TP was the centre of the car proving circuit (see text). "Accuracy', range, in km.

		'Accuracy'	'Precision' (SD, km)											
	LC	3,2,1	3		2		1		0		A		B	
Deployment	*n*	Min - Max	Lat	Long	Lat	Long	Lat	Long	Lat	Long	Lat	Long	Lat	Long
Stationary PTTs	1245	0.1 - 0.3	0.3	0.5	1.2	1.2	2.5	2.4	24	24	13	14	55	94
Ship at 0-10 knots	106	-1.2 - 1.96	1.5	1.9	1.4	1.9	3.5	2.3	20	9	10	29	394	602
Car in 1 km radius	284	-0.16 - 0.7	0.2	0.5	0.6	1.4	1.9	3.5	15	46	20	25	357	596

trains showed a much higher proportion of LC = A, B, or Z records (57% of 'location's) compared to albatrosses (29%). This higher proportion matched the lower representation of LC = 0 'locations'. Most (85% for albatrosses; 89% for the petrel and shearwaters) of our Argos records from seabirds (Table 1) were of Argos's unspecified 'accuracy' and 'precision' (LC = 0, A, B, Z) categories, and 11% and 21%, respectively, of the received records lacked a location (LC =Z???).

Good satellite visibility, lack of oscillation of the transmitting plane, and a stable temperature appeared to increase the proportion of higher-quality LCs. In the data for these small, wildlife-tracking PTTs (ST10, PTT-100, Nano), transmitter type and power, the presence of the bird, and the transmitting regime seem to have been relatively unimportant influences on the proportional distribution of the LCs in our deployments. The lower-powered Pica PTT #899 on the fast-moving train provided many poor LCs, yet when deployed on the shearwaters its LCs were equally poor, but not markedly poorer than those of the higher-powered PTTs (Klomp & Schultz 1998; Nicholls *et al.* 1998).

'Precision' and 'Accuracy' of stationary PTTs

The 'precision' and the 'accuracy' were measured for 8 samples where the transmitting conditions and the true position (TP) of the fixed sites were known.

Precision

'Precision' of the LCs as measured by Method 1 decreased progressively for records from LC = 3 to Z, except for LC = A, which generally had higher precision than the LC =0 records (Table 2). The LC = 3, 2, 1 categories were each 2-3 times poorer than the Argos specification of accuracy for these classes (Anon 1999). Additionally, the precisions for the Argos unspecified accuracy (LC = 0 and B records, especially) were very variable.

The single measurement of Method 1 combines the latitudinal and longitudinal components, which vary independently (Keating 1994; Brothers *et al.* 1998), and it was sensitive to any difference in the placement of the TP. Exceptional — and unexplained — data were the high standard deviations of LC = 2 and 1 records at Pymble and LC = 0 and B at Melbourne in 1999 (but see notes on PTT #899 above). Both sites were in "radio-noisy" cities: the

Table 6 Comparison of various published field measurements of 'accuracy' and 'precision' for the location classes (LC) of Argos 'locations' with both the Argos specifications and with our data for both stationary and mobile PTTs.

Source	'Precision' (km)													
	Location classes (LC)												*n*	Unit
	3		2		1		0		A		B			
	Lat	Long	Lat	Long	Lat	Long	Lat	Long	Lat	Long	Lat	Long		
Argos specification (Anon 1999)	0.10	0.10	0.30	0.30	1.00	1.00	>1	>1	Indeterminate				n/a	1 SD
Brothers *et al.* (1998) stationary, on rock	0.30	0.20	0.70	1.00	2.00	1.40	4.1	13.1	8.6	6.2	10.7	14.9	227	1 SD
Britten *et al.* (1999) fixed location, on caged birds							5.1		2.7		63		36	1 SD
Anderson *et al.* (1998)	0.23										17.8		229	1 SD
Vincent *et al.* (2003)	0.16	0.29	0.26	0.48	0.49	1.00	2.3	3.3	0.76	1.2	4.6	7.2	426	68%-ile
This paper: Stationary PTTs	0.30	0.50	1.20	1.20	2.50	2.40	25	24	13	15	55	94	1245	1 SD
This paper: Sisters I, Marine environment: Audited sitting albatross	0.21	0.34	0.32	0.49	0.80	1.40	35	29	3	6	22	35	297	1 SD
This paper: Ships tracked by GPS @ 10 knots	1.47	1.95	1.42	1.95	3.49	2.27	19.9	9.5	10	29	394	602	104	1 SD
This paper: Car on proving ground	0.2	0.5	0.6	1.4	1.9	3.5	15	46	20	25	357	596	284	1 SD

former was inside a residence; the latter was on the ground, with reduced visibility, and the PTT was a low power unit (which had, however, performed better at the isolated, Southlight, field laboratory 5 months earlier).

In situations where the exact position of the TP was not known, it was possible to measure 'precision' (assuming that the records were normally distributed), but not 'accuracy'. The 'precision' (as ± 1SD of the mean of both latitude and longitude, km) of the 'locations' are given in Table 3. These values in comparison to the results of the alternate procedure of measuring the mean ± 1SD of the distances between the TP and the 'locations' for both latitude and longitude are given in Table 4. The SDs from these 2 methods were the same (within the 'accuracy' presented here) (Table 4). Note that the means of the 'locations' (latitude and longitude) were very close to the position co-ordinates of the TP. The distributions were close to normal and, for most of the LCs, the latitude and longitude were not correlated, i.e. the covariance was very small (Fig. 4).

The standard deviations of the latitudes and longitudes (as km) LC^{-1} for all 'locations' were similar for LC = 3, 2, 1, 0, and A (Table 4). The standard deviation of longitude was larger for LC = B and was the reverse for the small sample of variable LC = Z records. Conservatively rounding the standard deviation gave the 'precision' for LC = 3, 2, and 1 as 2.5 km, for LC = A as 15 km, for LC = 0 as 25 km, for LC = B as ~75 km (55-95 km), and for LC =Z as >100 km (see also Tables 2-4, Fig. 4). The latitude and longitude components of the 'precision' were nearly equal for all LC except LC = B & Z (Table 4, Fig. 4).

The 'precisions' for the measurements from the ship and the train were very similar to those obtained from the stationary PTTs. There were small differences in LC = 3 for the ship-born PTT, which were attributed to inaccuracies in determining the TP of the ship. For the fast car, there was a loss of 'precision' for LC = 0 and A, and especially for LC = B on both ship and car the 'precision' was significantly lower (Table 5).

'Accuracy'

The mean of the radial distances between the true position (TP) and 'locations' for LC = 3, 2, and 1 was 0.5-16 km (Table 2). For LC = 3, 2, 1, the mean of the differences in latitude and longitude (expressed as km), was similar for both, and was -0.5-1.1 km (except for 3.4 km at 1 site) from the TP for 9 different stationary samples (Table 3). For all the distances (latitude and longitude) between the TP and each 'location', the means were -0.3-0.1 km for LC = 3, 2, and 1, and -4.7-3.6 km for LC 0, A, and B (Table 4).

'Precision' and 'Accuracy' of mobile PTTs

We attempted to measure these factors with mobile PTTs, to try and simulate with various duty cycles the effects of instability and speed under controlled

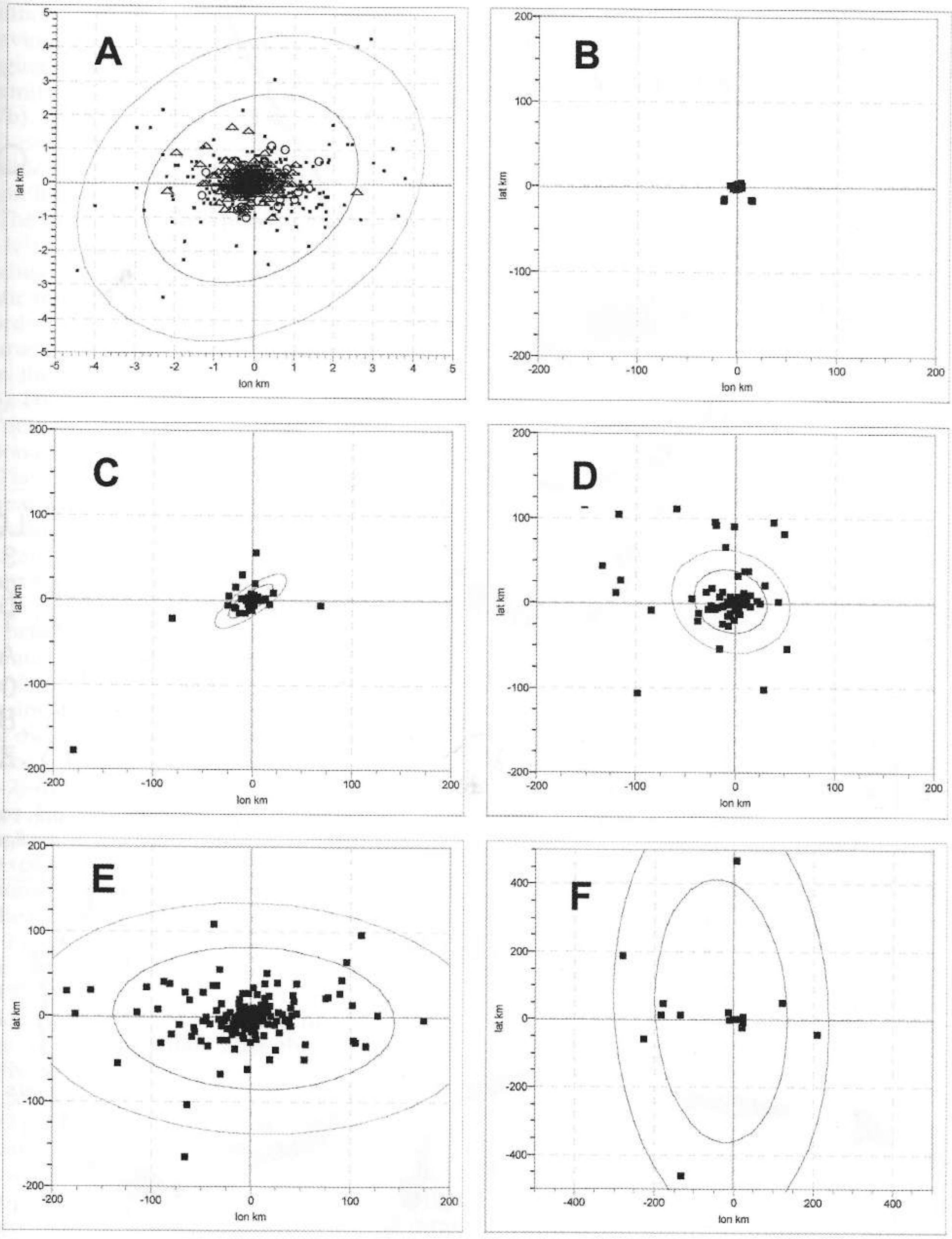

Fig. 4 Bivariate fit of Argos 'locations' from stationary PTTs, for Location Classes (**A, B**) LC =3, 2, 1, n = 523; LC = 3 ○, LC = 2 △, LC = 1 ■. (**C**) LC = A, n = 222; (**D**) LC = 0, n = 173; (**E**) LC = B, n = 327; (**F**) LC = Z, n = 24. Distances (km) in latitude and longitude from a known true position (TP), when compared to Argos 'locations' were measured for each of the LC groups. The TP is at 0,0 on the x- & y-axes. Note the change of scales for (**A**) compared with (**B**) to (**E**) and again with (**F**). The 'precision' is illustrated as normal density ellipses for 68% and 95% confidence limits. The correlation between latitude and longitude is only significant for LC=2 (0.821, n = 164, P = 0.000) and LC =A (0.791, n = 222, P = 0.000). Generally the latitudinal and longitudinal errors were equal except for LC = B where the longitudinal error was nearly twice that of the latitude error and vice versa for LC = Z. The 'accuracy' is illustrated by the very slight offset towards the upper left in (**A**), but at the smaller scales, the 'accuracy' is too small to be visible.

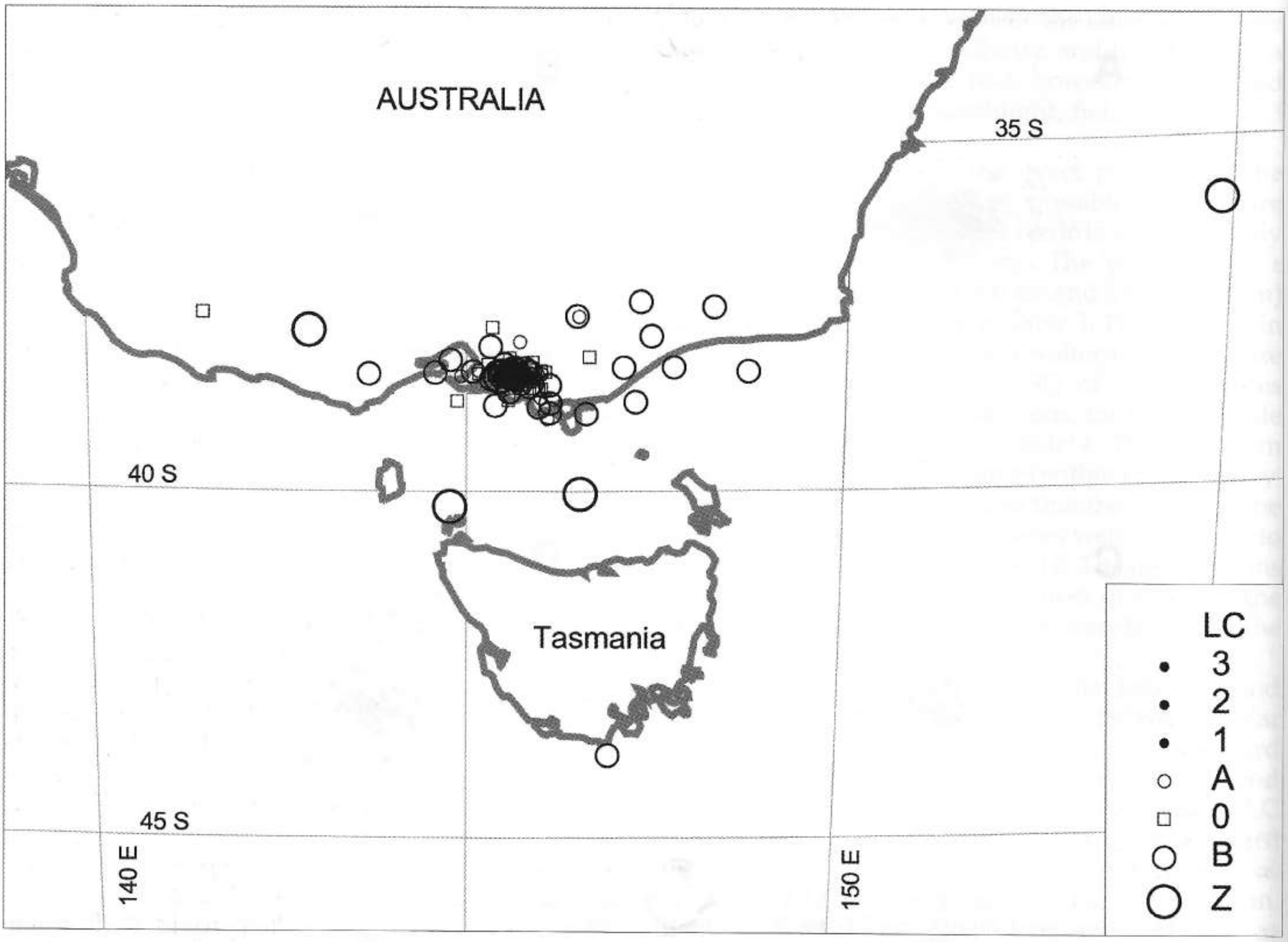

Fig. 5 Distribution of 'locations' from 2 PTTs on a car operated continuously at 0-120 km h^{-1} on weekdays within 1 km of a fixed point. Poor LCs dominated the more widely distributed 'locations'. Another 2 'locations' fell outside the figure.

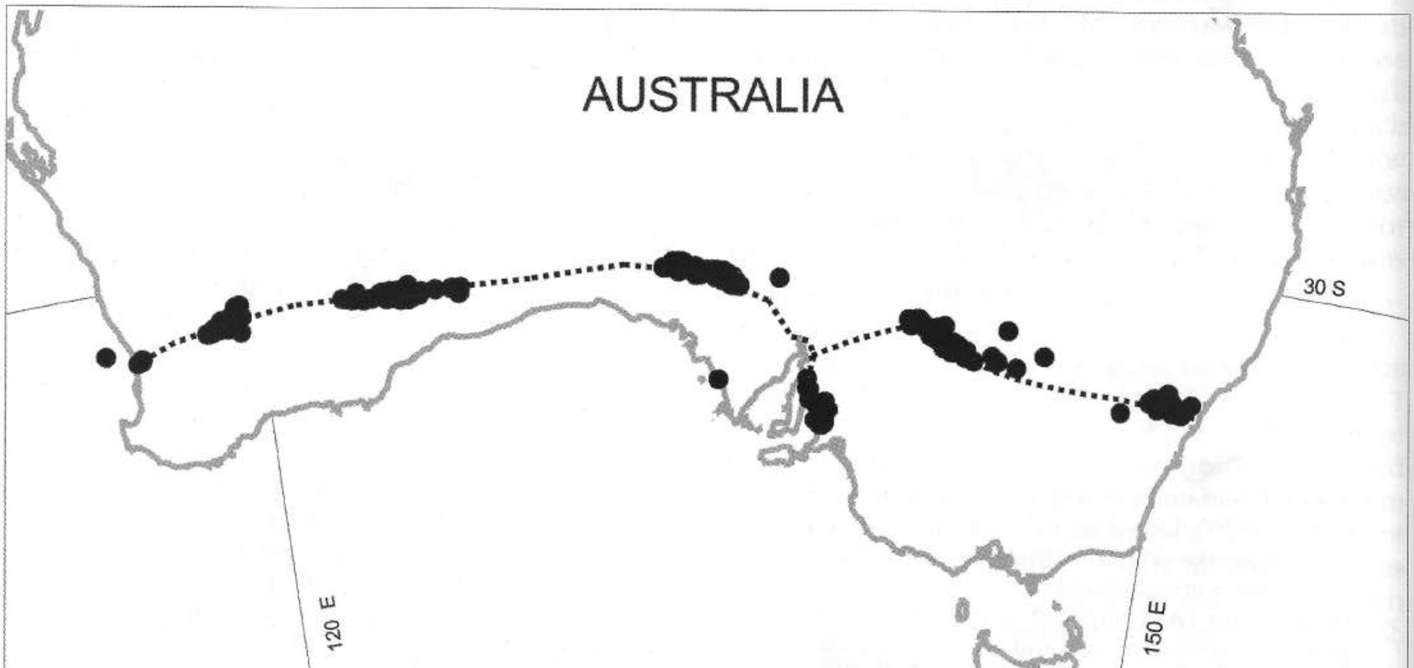

Fig. 6 Distribution of 'locations' (•) for PTT (#26593) in Jun–Jul 2001 when on a transcontinental train in southern Australia from real time PRV data, with the estimated position of the railway track (dotted line). Gaps in the mapped 'locations' result from the intermittent duty cycles of the PTT, orbits of the satellite, and the regular timetable of the train.

conditions for comparison with albatross flight behaviours: high speed within relatively small foraging areas and long migratory flights, and intermittent duty cycles (Nicholls & Robertson 2007b). We were not able to make direct GPS and PTT comparisons, and have relied on the best possible approximations of the relative TP to the Argos 'locations'.

The car-proving experiment (vehicle speed 0-100 km h^{-1}) operating on an irregular circuit within a radius of 1 km provided evidence that fast and erratic movements in small areas produced outlier records only among LCs = 0, B, and Z. Thus the accuracy and the precision did not differ markedly from the stationary experiments (Tables 1, 5; Fig. 2, 5). For the PTTs on the ship (speed 0-10 km h^{-1}), the 'accuracy' was similar to that obtained from the stationary PTTs (Tables 1, 5; Fig. 2).

The transcontinental train was used to test the comparable patterns received from fast- and direct-migrating albatrosses travelling to the south of Australia (1000 km south of the train route). The results from PTT #899 (8 h on: 17 h off duty cycle, which produced a "rolling" daily coverage over the period of the deployment and thus a more continuous track of 'locations') initially suggested a similar pattern of 'location' behaviour to the car experiment, until the problems already described were diagnosed (Fig. 3).

The other transmitter tested in 2001 (Table 1; Fig. 2, 6) produced only the PRV file (for which Argos had already selected the most plausible records) and the DIAG file was not available. With the exception of a very few records this deployment demonstrated that with a duty cycle of 3 h on and 9 h off the records closely approximated the train route. The 2 consecutive exceptional (LC = 2) records that were seriously displaced suggest that occasionally the PRV file calculations may err (Fig. 6). The most obvious discrepancies from the estimated TPs of the route were immediately after the transmitter was reactivated after an off period (CLS:Argos FAQ). This was presumably the explanation for the misplaced LC =2 positions, when the PRV file selection process probably wrongly selected the alternate position following a break in the transmission duty cycle. Though the PRV file did not report LC = Z or Z??? records, the remaining 'locations' demonstrated both 'accuracy and 'precision' in accordance with data from stationary PTTs (98% of records within 50 km of the estimated route of the train).

DISCUSSION

In the period 1992-2001 we accumulated 21,329 Argos 'locations' (from 24,466 records), mostly from tracking large seabirds, but including samples to calibrate the 'locations'. Our early analysis of these data suggested that the 'accuracy' and 'precision' of the 'locations' were poorer than the published CLS:Argos specifications (Anon 1999). Further, there were inadequate measurements of the errors for the Argos unspecified LC = 0, A, and B 'locations' (most of our data). It was uncertain that the empirical calibrations from other studies could be applied to our data. This confounded our early analysis of satellite tracks at different scales, and made it difficult to determine their relationship to oceanographic features. Further, when making our initial deployments, we were hindered by insufficient information on the extent to which PTT type, packaging, antenna, duty cycle-repetition rate, power supply, and satellite visibility at different locations affected their performance. We feel that this retrospective analysis, on one of the largest and most varied data sets presently available, provides guidance on the 'accuracy' and 'precision' of our Argos 'locations' and may help others with future deployment experiments.

Argos defines the kinds of 'locations', their properties and their accuracy, expressed in non-technical terms in the User Manual (Anon. 1999) and again in their Frequently Asked Questions (FAQ) service (CLS:Argos FAQ). The latter repeats earlier definitions, and adds that the error is 1σ equally for both axes, but then gives a single radial measure greater than these. This value appears to be a rounded value of the hypotenuse of the 2 ordinates measured for LC = 3, 2, and 1.

Argos Location Service Plus provides additional location classes, diagnostic information, and the 2nd (mirror) location on the other side of the satellite's orbit. Argos defines accuracy for LC = 3, 2, and 1 as $\leq$1 km for each axis and LC = 0 as >1.5 km error radius with no upper limit defined because the satellite collects insufficient information from which to estimate the error. The accuracy of other location classes (LC = A, B, and Z) is not specified by Argos. There is, however, the clear implication that: (a) a circle describes the 'accuracy' and 'precision', (b) the errors are normally distributed, and (c) the errors are the same for the 2 ordinates. The Argos FAQ (CLS:Argos FAQ) indicates that the combined latitude and longitude error, the radial distance for each of the LCs, is larger than that given in the User Manual (Anon. 1999), which is for the error on each ordinate.

We applied these concepts to our large and varied dataset, which includes newer and smaller PTTs than were used by others previously (Britten *et al.* 1999; Vincent *et al.* 2002). Our data include records from known-moving (as well as stationary) PTTs before and after improvements to the Argos location calculations introduced in Jun 1994 (Anon. 1994).

'Accuracy' (sometimes called bias or offset), is the difference between the known true position

(TP) and the mean of a set of Argos 'locations'. This 'accuracy' can be measured only when the transmitter is stationary and at a TP with both the 'location' and the TP measured with the same projection, specified geoid, and datum. We had such data for a few records (Tables 1-5; Fig. 3). The calculated means of the different LCs are not greatly different from the true positions.

Typically, while the 'accuracy' was high, there was a variable spread of 'locations' around the TP, - the 'precision', measured as the standard deviation (SD, σ) (expressed here as km). We measured 'precision' in 3 ways, each as a measure of the size of the cluster spread or group of 'locations', but only 2 indicated the shape (circle, ellipse or irregular polygon)of that group. Our results show that in most circumstances and for most LCs, the 'precision' was an ellipse.

There have been other reports where the latitude and longitude components of the 'precision' were also not equal (Brothers *et al.* 1998; Vincent *et al.* 2002). Our analyses showed that the *x-y* co-ordinates of the records were not independent (indicated by the skewed 'precision' ellipses): an error in either co-ordinate is related to an error in the other. Accordingly a single radial measure of error in these circumstances is inappropriate, as Keating (1994) and Vincent *et al.* (2002) explain, emphasising the care necessary in interpretation of 'accuracy' and 'precision' measurements. We support this advice, and our results provide additional information. We found that the 'precision' of 1 SD (68% of observations, assuming a normal distribution) for LC = 3, 2, 1 from deployed PTTs was <2.5 km not the <1 km specified by Argos (Anon. 1999). Further, we found that LC = A (15 km) was better than the Argos estimate of LC = 0 (25 km). The 'precisions' of LC = B were 75 km (55 km latitude; 95 km longitude components) and of LC = Z were >110 km (255, 110 km, latitude, longitude, respectively). Finally, the LC =Z??? records, while not providing a 'location', indicate at least that the PTT is still functioning. If fitted with appropriate sensors, such records can provide data, at least indicating whether or not the animal is still alive.

We believe the information on the 'accuracy' and 'precision' of records can be useful for interpreting 'locations' relative to an animal's environment and for deducing behaviour from the movements recorded. Their values are prerequisites, for accurate reporting of measurements for distance, direction, and speed travelled, and they are an essential part of the process of improvement of methods to objectively exclude outlier 'locations'. In addition, estimation of these parameters allows the weighting of 'locations' when curve-fitting to represent possible flight paths, and they may be of value in generating area use distributions (BirdLife International 2004). It is clear that the quality of all 'locations' was not equal.

Within our dataset, 'locations' of LC = A were more homogeneous and of higher 'precision' than records with LC = 0, thus confirming the advice from Argos (CLS:Argos FAQ) and the empirical measurements of others, summarised in Table 6 (Britten *et al.* 1999; Vincent *et al.* 2002). This finding should result in a change in the order of grading of LCs, which, of course, will have consequences for researchers when they are assessing and interpreting data.

Argos (CLS:Argos FAQ) advises that, in practice, there are 2 categories of LC = 0, those with errors of <10 km and those with errors >50 km, resulting from out-of-range instabilities of the frequency oscillator. Argos does not define the level of instability. Inspection of our data indicated that the instability could probably be identified with the Quality Index record (IQ, Anon. 1999) where either one or both the x or y components were <4, but we did not explore the matter further.

Keating *et al.* (1991) gave statistical definitions of accuracy, quoting Argos literature and personal communications from Argos. Their explanations of the Argos definitions make it explicit that: (a) Argos 'location' errors have a bivariate normal distribution; (b) the mean for each of the ordinates (latitude, longitude) is 0; (c) the errors are normally distributed; and (d) the standard deviations are equal and independent for the 2 ordinates. The radial error can thus be calculated as the hypotenuse of the errors of the 2 ordinates. Keating *et al.* (1991) indicated that a circle (not an ellipse or polygon because the ordinates are equal and independent) indicated the performance of the Argos locations. The position of the centre of the circle relative to the true position indicated 'accuracy' and the radius of the circle indicated the 'precision' (i.e. the circle contains a given proportion of the Argos locations for repeated locations of a fixed transmitter, and a radius of 1 and 2 SDs will probably contain 68% and 95%, respectively, of the Argos locations).

However, Keating *et al.* (1991) also emphasised that this definition reduces the 'accuracy' and the 'precision' relative to the simpler and incorrect interpretation used by many Argos users who have used the single radial measure. The other, more general, implications of our data on the performance of the PTTs suggest the need for further caution, because the results are variable, and the interactions complex, as illustrated by the following points.

(a) Strengthened and waterproofed packaging of the PTTs placed on an albatross back did not degrade the PTT performance.

(b) We did not observe any deterioration in the performance of the PTT within a deployment or deployments (except for PTT #899 as noted above), although the final 2-3 locations, coinciding with the presumed battery exhaustion, were generally of poor LCs .

(c) Variable duty-cycling of the PTTs to achieve a longer transmission life is a valuable procedure that does not degrade 'precision', but it does seem to increase the proportion of poorer LCs for the 1st location after a long period without transmissions, which is small price to pay for the benefits of a longer PTT deployment life.

(d) Of perhaps the greatest importance to biologists is the finding that, duty-cycle variables such as the persistent absence of locations in the same portions of the transcontinental train journey (Fig. 6) can produce non-biological patterns that may confound analyses of behaviour. These gaps resulted solely from a combination of the on-off periods of the PTT, the consistent train timetable, and missing- satellite orbits. Other artefacts of the duty-cycle variables included unequal sampling during the day, caused by changes in the time-of-day sampled as the animal (or train) moved between time zones, and the on-period's advancing through the day (Fig. 3), a situation which occurs when the duty cycles are not simple fractions or multiples of a 24-hour period (Georges *et al.* 1997; Murray *et al.* 2002; Nicholls & Robertson 2007b).

(e) The higher-powered Telonics ST10 and lower-powered Microwave Telemetry PTT-100 of various sizes performed similarly when over open ocean, in contrast to their performance in the radio-noisy land environments of the Northern Hemisphere.

(f) For a PTT subjected to temperature shocks such as when a shearwater submerged, we found that a higher proportion of poorer LCs (Fig. 2) indicated the poorer reception.

(g) A PTT on a bird with an erratic flight, such as an albatross foraging in a restricted area rather than migrating, yielded more records with the poorer LCs (Fig. 2) and this trend was confirmed by the car deployment (Fig. 5).

(h) The effect of movement of a PTT on its performance was an important new finding, which partly at least, because of a higher proportion of poorer quality LCs, supports the hypothesis that reception from a fast-moving PTT is degraded. The 'precision' of records from PTTs on the fast-moving car was similar to those for fixed PTTs, for all records but those with an LC = B or Z.

Given the variable quality grading of all 'location' data from satellite tracking, there are ranges of options for its use that include using only the best and accuracy-specified data (LC = 3, 2, 1). Such an approach has been used in calculating speeds (Weimerskirch *et al.* 1994). However, typically for animal tracking studies, such an approach may result in the arbitrary rejection of 50-75% of the available 'location' dataset.

A variety of filtering procedures allow the use of more 'locations' and may make for better economics when considering the capital and operating costs involved. Selecting data that is likely to be of poor 'accuracy' or 'precision' is still a matter for judgement, though objective criteria are available. Filtering, based on point-to-point speed of travel (McConnell *et al.* 1992) has been used for seals and penguins. Analyses of the tracks of fast-moving (115-135 km h^{-1}, measured s^{-1} by GPS, and >90 km h^{-1} for sustained, point-to-point ≥1 h intervals; Weimerskirch *et al.* 2002; BirdLife International 2004) albatrosses require additional filtering criteria.

The combined use of LC, quality index (IQ), and an examination of adjacent locations (Nicholls & Robertson 2007a) can be useful. With an improved understanding of the relative 'precision' of the LC, the proportional weighting of each 'location' provides an alternative approach (Freeman *et al.* 1997). Such procedures allow the use of a wider range of 'locations' than does the method of arbitrary exclusion based on LC quality alone. The upgrading of the LC = A that was indicated by our results and by Vincent *et al.* (2002) will require the adjustment of, or incorporation into, filtering algorithms. The separating of the 2 kinds of LC = 0 and refining their 'precision' might also be warranted (CLS:Argos FAQ).

Based on the experiences in this study, the use of the Argos criteria "Number of plausibility tests passed" (contained in the DIAG) is recommended, although it has not been used consistently before. To be effective, it is crucial that the user provides Argos with a realistic estimate of the maximum speed of the animal, so that this test is correctly applied, because only 2 tests are required for a valid record (CLS:Argos FAQ).

Mapping the distribution of a wide-ranging seabird may require variable selection of the LC criteria. Testing the flight patterns relative to wind data provided at a 100 km-grid scale, or to sea surface temperatures available at 10 km pixel resolution, or to bathymetric features at 1-10 km accuracy, or to fishing activity at <1 km precision, will require progressively more exacting selection criteria.

For short-term studies where the operator may not have the time for the development or understanding of some of the available selection processes, our study has demonstrated also that the use of the PRV file may be an economic and quick proposition (Fig. 6). However, while only a small percentage (Table 1) of 'location' records may be sacrificed (CLS:Argos FAQ), the greatest disadvantage of that approach in our view is the loss of the range of diagnostic data contained in the DIAG file.

Our analysis should assist in substantiating the empirical 'accuracy' and 'precision' of the Argos calculated 'locations'. It provides practical examples enabling the use of many more of the Argos 'locations' and demonstrates the confidence that can be given to them. Further examples related to this analysis are provided in Nicholls & Robertson 2007a, b; Nicholls *et al.* 2002).

The complex set of factors affecting PTT performance make it imperative to calibrate each PTT (stationary at or near the application site) for a period at the start of each deployment to detect 'accuracy' and measure the 'precision' of the 'locations' to allow for optimal resolution of the 'locations' during the later deployment. Not all Argos 'locations' can be used, but our procedures demonstrate that higher proportions of the total number of records can be retained, and that greater confidence can be attached to records that could indicate novel behaviour, that might otherwise be attributed to artefacts of the tracking system.

It is important to remember that these data are positional records of dynamic objects. Such records will vary according to individual animal's behaviour within their local environment. For many studies, the novel information on distributions will be a prime result from the satellite tracking, but we emphasise that a considerable body of other biological information may also be deduced.

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