CSIRO PUBLISHING

Australian Mammalogy, 2013, **35**, 65–83
http://dx.doi.org/10.1071/AM12021

The success of GPS collar deployments on mammals in Australia

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Abstract. Global Positioning System (GPS) wildlife telemetry collars are being used increasingly to understand the movement patterns of wild mammals. However, there are few published studies on which to gauge their general utility and success. This paper highlights issues faced by some of the first researchers to use GPS technology for terrestrial mammal tracking in Australia. Our collated data cover 24 studies where GPS collars were used in 280 deployments on 13 species, including dingoes or other wild dogs (*Canis lupus dingo* and hybrids), cats (*Felis catus*), foxes (*Vulpes vulpes*), kangaroos (*Macropus giganteus*), koalas (*Phascolarctos cinereus*), livestock guardian dogs (*C. l. familiaris*), pademelons (*Thylogale billardierii*), possums (*Trichosurus cunninghami*), quolls (*Dasyurus geoffroii* and *D. maculatus*), wallabies (*Macropus rufogriseus* and *Petrogale lateralis*), and wombats (*Vombatus ursinus*). Common problems encountered were associated with collar design, the GPS, VHF and timed-release components, and unforseen costs in retrieving and refurbishing collars. We discuss the implications of collar failures for research programs and animal welfare, and suggest how these could be avoided or improved. Our intention is to provide constructive advice so that researchers and manufacturers can make informed decisions about using this technology, and maximise the many benefits of GPS while reducing the risks.

Additional keywords: field performance, fix success, location data, satellite, wildlife tracking.

Received 1 May 2012, accepted 4 July 2012, published online 4 February 2013

Introduction

Global Positioning System (GPS) collars are being used increasingly by researchers and wildlife managers to track medium-to-large-sized mammals. However, there are still very few studies published from Australia on which to gauge their success (but see Claridge *et al*. 2009; Moseby *et al*. 2009; Robley *et al*. 2010; Ellis *et al*. 2011; Ruykys *et al*. 2011; Matthews and Green 2012; Allen 2012). Many researchers have experienced difficulties with the technology, some of which have been overcome with time and experience. Several previous international studies have dealt with the issue of GPS performance. For example, the success of GPS data acquisition and the precision of locations in relation to collar position have been reported (Moen *et al*. 1996; D'Eon and Delparte 2005) and in some cases compared among habitats with different vegetation cover and terrain (Dussault *et al*. 1999; Di Orio *et al*. 2003; Cain *et al*. 2005; Recio *et al*. 2011). At this time, we are aware of only a small number of studies that have examined the long-term performance and reliability of GPS collars under field conditions, and these were undertaken in Africa (Hemson 2002), North America (Johnson *et al*. 2002; Gau *et al*. 2004), central Asia (Kaczensky *et al*. 2010) and New Zealand (Blackie 2010). Various studies on animal ecology (e.g. home range, resource selection) report individual issues, including release failures (e.g. Burdett *et al*. 2007; Kochanny *et al*. 2009), VHF transmitter failures (e.g. Kochanny *et al*. 2009) and erratic or premature GPS failures (e.g. Girard *et al*. 2002; Andersen *et al*. 2008; Zweifel-Schielly *et al*. 2009), but assessment of collar performance was not a focus of these papers. Furthermore, since unsuccessful studies, or collar failures, tend not to be published, information on the prevalence of total collar failure is not readily available. Such information is important when wildlife scientists are compelled to work within tight budgets, short timeframes and limited resources, and is needed for the uptake and ultimate success of GPS technology (Lizcano and Cavelier 2004).

The aim of this paper is to provide researchers who plan to use GPS telemetry with background knowledge of project logistics and information about the strengths and weaknesses of GPS telemetry, gained through our numerous field studies on 13 species of mammals in Australia. Manufacturers of GPS collars may also benefit from a greater understanding of the most common sources of failure, and the costs to researchers when the technology does not meet expectations. We restricted our synthesis to studies involving non-volant, terrestrial mammals, but note that GPS technology also has been used on marine mammals (e.g. Sheppard *et al*. 2006) and flying-foxes (e.g. Spencer and Miller 2006) in Australia. Specific objectives were to: (1) determine the success of collars, or, conversely, the types and rates of failures; (2) investigate issues in relation to collar design, and the GPS, VHF and timed-release components; and (3) identify problems relating to unforeseen costs of collar retrieval, refurbishment and reconfiguration, and possible impacts on the welfare of animals after collar deployment. Our intention is to provide this information in a constructive manner so that researchers and manufacturers can be fully informed when making decisions to use this technology.

Methods

We compiled data from 24 studies across Australia (Fig. 1) in which GPS collars were used in 280 deployments on terrestrial mammals weighing 1–74 kg, including dingoes or other wild dogs (*Canis lupus dingo* and *C. l. familiaris* and their hybrids), feral cats (*Felis catus*), foxes (*Vulpes vulpes*), kangaroos (*Macropus giganteus*), koalas (*Phascolarctos cinereus*),

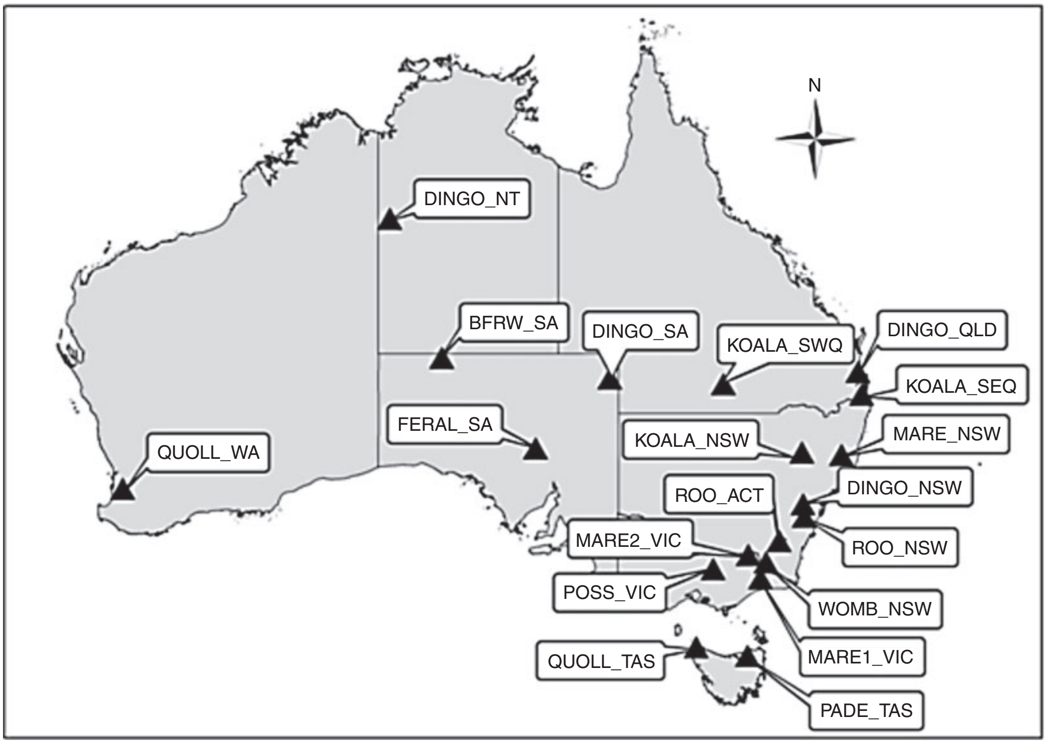

Fig. 1. The locations of GPS collar deployments for each study in Australia. Refer to Table 1 for species and location descriptions.

livestock guardian dogs (*C. l. familiaris*), pademelons (*Thylogale billardierii*), possums (*Trichosurus cunninghami*), quolls (*Dasyurus geoffroii* and *D. maculatus*), wallabies (*Macropus rufogriseus rufogriseus* and *Petrogale lateralis*), and wombats (*Vombatus ursinus*). The collars used in these studies were manufactured by Blue Sky Telemetry (Aberfeldy, Scotland), Followit Wildlife (Lindesberg, Sweden), Precision Agriculture Research Group (Armidale, Australia), Sirtrack (Havelock North, New Zealand), Sigma Delta Technologies (Floreat, Australia), Telemetry Solutions (Concord, California, USA), and Titley Electronics (Lawnton, Australia). Where different collars, programmed settings (such as scheduled fix interval), or locations were used within a research program, these were separated into different studies for analysis. Collars were deployed for up to 12 months, with most studies being shorter than six months (Fig. 2).

Data were collated on the species and locations of collar deployments, habitat types, collar types and manufacturers, the reliability of GPS components, VHF components and timed-release devices, statistics on GPS performance, costs, and animal welfare. While these data provide descriptive statistics on GPS collar utility and success, they do not permit a comparative evaluation of one collar brand with another, because collars were deployed on different species in widely different habitats and locations.

Appendix 1 provides descriptions of each study, the collars used, and dates of deployment. Appendix 2 contains a description of the components of GPS collars and how they operate, as well as a glossary of terms associated with the technology.

Results

Of the 280 deployments of GPS collars, 249 were retrieved and/or downloaded remotely. However, retrieval rates ranged from 0 to 100% among studies (Table 1). Reasons for loss of collars (or non-retrieval) included loss of VHF signal due to presumed battery failure or damage to the antenna, animals moving out of range, and the release of collars in burrows where they could not be retrieved. While we cannot accurately account for each lost collar, we were able to discern the reasons for losses from some collars that were considered lost and later found through extensive ground and aerial searches. Of the 249 collars that were retrieved and/or downloaded, 96% had recorded some data. However, due to shortened operating life, intermittent failure and/or disruptions to the fix schedules and duty cycles, the number of recorded locations often was less than expected.

The average operating life (i.e. real lifespan) of the GPS collars was 101.7 days and amounted to 67.7% of the expected mean. Only 53% of collars operated for their full deployment or expected life (Table 2) and operating success was higher for studies of shorter duration (Fig. 3). In only five studies was the GPS receiver on all collars still functioning at the end of the deployment period, which, in these cases, was less than 92 days. The longest time a GPS operated successfully was 403 days on a dingo collar programmed to record eight fixes per day. Eight studies (40%) reported at least one collar failing to collect GPS locations within 10 days of deployment, and a further six studies (30%) reported a collar failing within 40 days. Suggested reasons for premature GPS failure included wear and tear (e.g. breakdown of the GPS aerial and/or aerial cables), poor battery quality, and exhaustion of the battery from sample rate malfunctions (see below).

Unintended shifts in duty cycle or sample rate occurred in 18% of deployments, but in any one study this problem affected 0–70% of collars deployed (excluding the study in which only one collar with data was retrieved). On average, shifts from programmed sample rates occurred after 59 days from those deployments. Intermittent collar failures, in which a collar did not log a location for one or several days, occurred in 31% of deployments (Table 2). Loss of data was often considerable. For example, one koala collar logged erratically over 159 days, and provided only 11 days of useable data.

Fix (i.e. GPS location) acquisition over the deployment period was generally lower than programmed rates, even for studies in open (e.g. desert) environments where there was an unimpeded view of the sky. However, two studies reported a higher than expected number of fixes per collar (Table 3). While, on average, only 66% of expected fixes per collar were collected, the total number of fixes for each study generally was high (mean = 16 698; range = 233–58 575). Mean horizontal dilution of precision (HDOP) was 3.0 (range = 1.5–5.0) (Table 4). Locations with lower HDOP values are considered to be more precise (D’Eon and Delparte 2005) and the percentage of fixes with HDOP <5 ranged from 67 to 99% among studies.

VHF transmitter failure was reported in 9 of 24 studies (Table 5). In two cases, the VHF transmitter was programmed to activate on a set date but did not initialise. In the other seven studies, the VHF transmitter stopped operating, sometimes within a few days of deployment (average = 2.9 months). In some collars, VHF transmitter failure was caused by water ingression. Other possible causes included faulty batteries or circuitry and chewed/damaged antennas, which reduced transmission strength below that which could be detected.

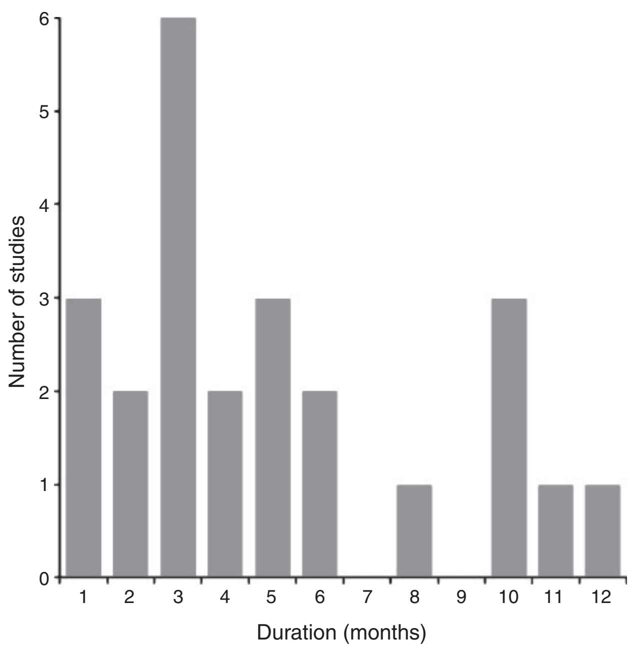

Fig. 2. Duration of GPS collar deployments among compiled studies of mammals in Australia.

Table 1. Summary of GPS collar deployments and retrieval success for each study (or research case) of mammals in Australia

Study	Species	Location	Collar type	No. of deployments	% retrieved[A]	% with data
BFRW_SA	Black-footed rock-wallaby	Anangu Pitjantjatjara Yankunytjatjara Lands, north-west South Australia	Sigma Delta Technologies	10	80	13
DINGO1_NSW	Dingo	Blue Mountains, New South Wales	Sirtrack	12	58	100
DINGO2_NSW	Dingo	Blue Mountains, New South Wales	Sirtrack	5	100	100
DINGO1_NT	Dingo	Tanami Desert, Northern Territory	Sirtrack	15	87	100
DINGO2_NT	Dingo	Tanami Desert, Northern Territory	Blue Sky Telemetry	7	29	0
DINGO_Qld	Dingo	Maroochy Shire, south-east Queensland	Sirtrack	9	100	100
DINGO_SA	Dingo	North-east South Australia	Sirtrack	16	81	100
FERAL_SA	Red fox and Cat	Arid Recovery, northern South Australia	Sirtrack	18	94	100
KOALA_NSW	Koala	Gunnedah, New South Wales	Sirtrack	31	100	100
KOALA1_SEQ	Koala	Coomera, south-east Queensland	Sirtrack	9	89	100
KOALA2_SEQ	Koala	Coomera, south-east Queensland	Sirtrack	6	100	100
KOALA_SWQ	Koala	Mulga Lands, south-west Queensland	Titley Scientific	7	57	100
MARE_NSW	Livestock guardian dog (Maremma)	Yarrowitch, New South Wales	UNETracker	3	100	67
MARE1_Vic.	Livestock guardian dog (Maremma)	Buchan, Victoria	Telemetry Solutions	3	100	100
MARE2_Vic.	Livestock guardian dog (Maremma)	Tallangatta, Victoria	Telemetry Solutions	4	100	100
PADE_Tas.	Tasmanian pademelon and Bennett's wallaby	Scottsdale, Tasmania	Followit Wildlife	30	100	100
POSS1_Vic.	Mountain brushtail possum	Strathbogie Ranges, Victoria	Sirtrack	3	100	100
POSS2_Vic.	Mountain brushtail possum	Strathbogie Ranges, Victoria	Sirtrack	6	100	100
POSS3_Vic.	Mountain brushtail possum	Strathbogie Ranges, Victoria	Sirtrack	20	100	100
QUOLL_Tas.	Spotted-tailed quoll	Cape Grim, north-west Tasmania	Telemetry Solutions	9	100	100
QUOLL_WA	Western quoll	Northern jarrah forest, Western Australia	Sigma Delta Technologies	6	0	–
ROO_ACT	Eastern grey kangaroo	Canberra, Australian Capital Territory	Sirtrack	26	96	100
ROO_NSW	Eastern grey kangaroo	Jooriland, New South Wales	Sirtrack	12	100	100
WOMB_NSW	Common wombat	Snowy Mountains, New South Wales	Sirtrack	13	85	100
Total				280	89	96

[A]Collar retrieved or GPS data downloaded remotely.

Timed-release devices were fitted to collars in nine studies, but two studies retrieved collars before the programmed release dates, and in one study all the collars were lost when the VHF transmitter failed. Thus, only six studies were available to assess the performance of the timed-release mechanism. Of the 83 collars involved in these studies, 5% released before or after the programmed time/date, and a further 19% failed to release at all (Table 5).

In total, we spent AU$684 832 on collars and equipment from manufacturers. An additional 25% of initial costs was spent post-deployment on unexpected costs associated with refurbishment or retrieval of failed collars, labour, extra searches (e.g. aerial searches, purchase of additional equipment such as burrow cameras), travel (fuel, accommodation) and animal capture (e.g. darting). The costs associated with locating and retrieving 'lost' collars were up to $50 000 (mean = $6040) and 1760 person-

Table 2. Operational success of GPS collars deployed on mammals in Australia
See Table 1 for Study details. DINGO2_NT and QUOLL_WA: no data; n.a., not available

Study	Mean no. of days operating (range)	% of expected days	% collars operated over full deployment	% collars with intermittent failure
BFRW_SA	7 (0–28)	6	0	100
DINGO1_NSW	269 (130–403)	74	43	86
DINGO2_NSW	53 (52–54)	152	100	0
DINGO1_NT	198 (33–300)	66	47	8
DINGO_Qld	23 (5–43)	66	100	0
DINGO_SA	180 (7–320)	56	62	0
FERAL_SA	61 (8–126)	66	23	88
KOALA_NSW	100 (4–179)	61	61	39
KOALA1_SEQ	109 (17–154)	115	80	13
KOALA2_SEQ	95 (81–163)	91	83	17
KOALA_SWQ	114 (64–160)	95	50	50
MARE_NSW	44	100	67	0
MARE1_Vic.	57 (19–78)	37	0	100
MARE2_Vic.	118 (9–160)	76	50	25
PADE_Tas.	220 (30–240)	92	27	0
POSS1_Vic.	129 (87–155)	140	100	33
POSS2_Vic.	74 (36–115)	86	67	100
POSS3_Vic.	77 (4–120)	46	40	20
QUOLL_Tas.	31 (7–35)	112	100	0
ROO_ACT	42 (3–103)	22	44	n.a.
ROO_NSW	62 (35–70)	100	100	0
WOMB_NSW	157 (26–346)	47	18	91
Total	98.8	65.4	52.4	30.5

Fig. 3. Relationship between the expected GPS life (or time in the field) and the percentage of collars operating at the end of the deployment period in each study ($n = 22$). The trend line is significantly negative ($r = -0.59$, $P = 0.004$).

hours (average = 180) (Table 6) over and above the investment that had already been allocated towards retrieving collars. Indeed, project running costs that included travel, labour and outlays associated with capture and data analyses, would add a substantial amount to these figures. Using just the initial cost of collars and any additional expenses associated with tracking and retrieval, we calculated a cost per fix, and found that it varied considerably among studies (mean = \$2.23; range = \$0.02 to \$129), with higher amounts for studies that experienced catastrophic collar failures such that no locations were recorded (Table 6).

Across all studies, 168 (60%) collared individuals were recaptured, allowing potential animal welfare issues to be assessed. The most frequently reported problem was loss of fur around the neck (12% of recaptured animals). Three pademelons died as a consequence of animal handling related to GPS collar deployment (McMahon *et al.* in press), while four individuals (one quoll, one fox, and two kangaroos in captive trials) sustained minor injuries (e.g. skin lacerations) that prompted the researcher to change the collar design. Most researchers contributing to this review were the first to use GPS collars on their study species. Consequently, 48% of studies involved changing the original collar design, often by returning the collars to the manufacturer.

Discussion

GPS telemetry has become an important tool in wildlife research to investigate animal movements (D'Eon and Delparte 2005; Thomas *et al.* 2011) with the expectation that it offers several salient advantages over traditional techniques. Chief among these is the ability to collect higher numbers of locations automatically, remotely, and more precisely than with VHF and satellite-based methods (Hulbert and French 2001; Johnson *et al.* 2002; Graves and Waller 2006; Bandeira de Melo *et al.* 2007; Mattisson *et al.* 2010; Thomas *et al.* 2011). With a greater number of fixes, which can be taken independently of season, weather, time of day or year, and without the disturbance of a researcher tracking the animal, GPS telemetry is potentially less susceptible to bias than VHF radio-tracking (Johnson *et al.* 2002; Mattisson *et al.* 2010; Robley *et al.* 2010). Thus, GPS collars can gather more data at a significant cost saving per location, and with greater researcher safety (Johnson *et al.* 2002). Such data often facilitate the

Table 3. Fix success of GPS collars deployed on mammals in Australia
See Table 1 for Study details. DINGO2_NT and QUOLL_WA: no data. n.a., not available

Study	No. of programmed fixes per day	Mean fixes per day[A] (range)	% operating days with 0 fixes (range)	Mean no. of fixes per collar (range)	% of expected fixes per collar[B]	Total fixes
BFRW_SA	16	8.3 (6–11)	77	233	12	233
DINGO1_NSW	6–8	5.7 (1–8)	33.8 (0–66.3)	1537 (802–2302)	87	10 762
DINGO2_NSW	144	137.5 (62–145)	0	7317 (6978–7534)	96	36 585
DINGO1_NT	24	20.8 (2–24)	0.1 (0–1.7)	4109 (713–6752)	57	53 424
DINGO_Qld	200	138 (12–196)	0	3522 (920–6870)	50	31 702
DINGO_SA	48	39 (6–48)	0	5432 (749–11043)	35	58 575
FERAL_SA	6	4 (3–6)	32 (2–93)	258 (23–622)	47	4383
KOALA_NSW	4	4.3 (1–1296)	1.9 (0–20.9)	429 (13–2074)	65	13 303
KOALA1_SEQ	12	10.6 (1–65)	0.1 (0–93)	1280 (222–1812)	110	8839
KOALA2_SEQ	5	4.6 (1–5)	0.02 (0–13)	746	68	2601
KOALA_SWQ	6	5 (1–6)	9.3 (1.8–23.8)	550 (318–694)	77	2200
MARE_NSW	144	117.9	0	4440	61	16 952
MARE1_Vic.	48	46 (1–48)	21.9 (6.4–52.6)	2280 (371–3338)	30	6839
MARE2_Vic.	48	47.6 (26–48)	9.2 (0–36.8)	5600 (354–7639)	75	21 808
PADE_Tas.	9	8.9 (6–9)	0	1744	95	54 859
POSS1_Vic.	9	10 (1–154)	3 (0–10)	1233	107	3698
POSS2_Vic.	10	12 (1–972)	7 (1–17)	755	94	4530
POSS3_Vic.	14	13 (4–40)	10 (0–97)	902	65	18 036
QUOLL_Tas.	12[C]	7.4 (1–12)	0	241 (182–280)	64	5150
QUOLL_WA	3	n.a.	n.a.	n.a.	n.a.	0
ROO_ACT	24	23.2 (3–36)	n.a.	1448 (70–3944)	32	n.a.
ROO_NSW	32	32	0	1779 (1006–2028)	93	21 351
WOMB_NSW	8	5.3 (1–30)	22.6 (0–59.6)	748 (40–2235)	28	8227
Mean/Total			12.2 (0–97)	(13–11043)	65.8	384 057

[A]For those days when at least one fix was recorded.
[B]For expected life of collar. This differs from fix success calculated over actual operating life.
[C]12 fixes for 5 days of the week, and 72 or 96 fixes per day for the remaining 2 days. Data presented for mean fixes per day and mean fixes per collar for those days with 12 fixes per day.

Table 4. GPS data performance statistics for collars deployed on mammals in Australia
See Table 1 for Study details. DINGO2_NT, MARE_NSW, PADE_Tas. and QUOLL_WA: no data

Study	% fixes with 3 satellites	% fixes with 4 satellites	% fixes with 5 satellites	% fixes with 6 satellites	% fixes with 7+ satellites	HDOP (mean ± s.d.)	% fixes with HDOP <5
BFRW_SA						5.0 ± 3.9	67
DINGO1_NSW	47.1	29.4	14.3	5.7	3.5	3.2 ± 2.2	77
DINGO2_NSW	44.5	31.6	15.5	5.7	2.6	3.4 ± 2.5	82
DINGO1_NT	3.4	9.3	23.4	29.0	3.4	1.8 ± 1.3	98
DINGO_Qld	54	30	12	3	1	3.5	88
DINGO_SA	0	5	21	32	42	2	98
FERAL_SA	20	18	25	18	21	2.7	94
KOALA_NSW	32.4	22.7	17.3	11.8	15.7	3.0 ± 2.6	86
KOALA1_SEQ	38.9	24.9	18.2	11	7	3.2 ± 2.6	86
KOALA2_SEQ	37.2	25.9	18.0	10.7	8.2	3.3 ± 2.7	84
KOALA_SWQ	0	14.6	18.7	17.6	49.1	1.7 ± 1.2	98
MARE1_Vic.	2	5	14	24	55	1.7 ± 0.9	99
MARE2_Vic.	1	4	9	16	69	1.5 ± 0.9	99
POSS1_Vic.	55.9	27.5	11.3	3.9	1.4	4.0 ± 3.0	77
POSS2_Vic.	41.2	17.0	16.4	15.8	9.6	3.2 ± 2.6	85
POSS3_Vic.	57.6	25.6	9.7	4.6	2.5	3.9 ± 2.9	78
QUOLL_Tas.	8.0	16.4	18.8	16.7	40.1	2.0 ± 1.4	94
ROO_ACT	35.6	21.6	15.4	13.1	14.3	3.1 ± 2.6[A]	86
ROO_NSW	44.0	29.7	16.8	6.8	2.8	3.5 ± 2.7	84
WOMB_NSW	46.6	25.8	12.6	7.6	7.4	3.5 ± 2.6	83
Total						3.0	

[A]HDOP = 3.8 ± 2.8 excluding periods of collar failure.

Table 5. Success of VHF transmitter and timed-release components of GPS collars deployed on mammals in Australia
See Table 1 for Study details. MARE_NSW: no data. n.a., not available

Study	No. of collars with VHF transmitter failure [% of total deployed]	Mean no. of months to failure (range)	% expected months	% collars with timed-release failure	% collars released before or after time/date
BFRW_SA	10 [100]	1.7 (0–7)[A]		n.a.	n.a.
DINGO1_NSW	2 [17]	3 (2–4)	18	17	8
DINGO2_NSW	0	n.a.	n.a.	0	0
DINGO1_NT	0	n.a.	n.a.	13	0
DINGO2_NT	7 [100]	1	10	n.a.	29
DINGO_Qld	0	n.a.	n.a.	0	0
DINGO_SA	0	n.a.	n.a.	n.a.	n.a.
FERAL_SA	1 [6]	0	0	n.a.	n.a.
KOALA_NSW	0	n.a.	n.a.	n.a.	n.a.
KOALA1_SEQ	1 [11]	2	8	n.a.	n.a.
KOALA2_SEQ	0	n.a.	n.a.	n.a.	n.a.
KOALA_SWQ	5 [71]	3.2 (1–4)	27	n.a.	n.a.
MARE1_Vic.	0	n.a.	n.a.	n.a.	n.a.
MARE2_Vic.	0	n.a.	n.a.	n.a.	n.a.
PADE_Tas.	0	n.a.	n.a.	37	0
POSS1_Vic.	0	n.a.	n.a.	n.a.	n.a.
POSS2_Vic.	0	n.a.	n.a.	n.a.	n.a.
POSS3_Vic.	0	n.a.	n.a.	n.a.	n.a.
QUOLL_Tas.	0	n.a.	n.a.	n.a.	n.a.
QUOLL_WA	6 [100]	–[B]		n.a.	n.a.
ROO_ACT	4 [15]	2 (0.03–4)	6	n.a.	n.a.
ROO_NSW	0	n.a.	n.a.	n.a.	n.a.
WOMB_NSW	4 [31]	9 (5–14)	50	8	25
Total	14.3	2.9		19	5

[A]VHF transmitter was programmed to activate on a fixed date, but only 3 of 10 did. Of these, by the 7th month into the 10-month VHF collar deployment, none were working.
[B]VHF transmitter was programmed to activate on a fixed date but did not.

investigation of animal behaviour at much finer scales than those achievable with VHF technology, such as the actual speed an animal travels, the locations it visits, and the true time spent in a given habitat (e.g. Allen 2007). However, capital costs of collars and equipment, satellite signal reception, longevity under field conditions, and the potential for failure present possible counterbalances to these advantages (Johnson *et al*. 2002). Our evaluation of 23 studies using GPS collars on mammals in Australia revealed several common problems, including a shorter than expected GPS life, intermittent failures (i.e. days with no locations collected), fewer fixes per day than expected, changes to the fix schedule or duty cycle, early VHF transmitter and timed-release failures, and collar design issues (Table 7).

Lessons learnt

Collar returns

As with conventional radio-tracking studies, it is expected that a proportion of collars will be lost, such as from animals dispersing, moving out of range of the VHF, or from transmitter failure (Harris *et al*. 1990). Losses from GPS also can be experienced with catastrophic equipment failures, defined by Frair *et al*. (2010) as computer glitches or failed breakaway devices. We were unable to retrieve 31 collars from 280 deployments, and a further 10 collars that were retrieved did not collect any GPS locations. Thus, 15% of collar deployments did not return animal location information to the research programs, and we conclude that these losses are relatively common.

Operating life

Manufacturers typically quote an expected operating life that is determined by fix schedule, duty cycle and battery capacity. In the field, however, maximum operational life is rarely attained. This is because operating life is influenced by environmental conditions (e.g. temperature and humidity), the time it takes for a position to be acquired (time to fix), and the batteries themselves. In locations with an obstructed view of the sky due to dense canopy cover, steep terrain, or the animal being underground or covered by rocks or logs, it may take longer for the GPS to acquire a fix – if at all – and, consequently, more battery power will be used (though fix acquisition 'time-outs' can help reduce this loss of battery capacity during periods of poor satellite reception). Our results showed that actual operating life was ~68% of the expected life, but there was high variability among individual collars and studies. A comparison of three collar brands by Blackie (2010) found similar percentages of operational life expectancy among brands, but also with high variability among individual collars (range 5.9–107.2%). Some manufacturers take into account a safety margin when calculating expected battery life – rather than publishing a best-case scenario – and it is certainly informative to enquire about this when planning the purchase of GPS devices.

Table 6. Costs of GPS tracking equipment and additional unexpected costs incurred by studies for the retrieval of failed collars

See Table 1 for Study details. Costs are those of the research project and do not include costs covered by manufacturers working to further develop or fix faulty products. The calculation of cost per fix incorporates both the initial costs of equipment and additional costs of retrieval, but does not include other project-related costs, such as capture, tracking and data analysis. n.a., not available

Study	Initial cost of collars and hardware/ software (AU$)	% additional costs of refurbishment or repair	% additional costs of retrieving failed collars[A]	Time retrieving failed collars[A] (person-hours)	Cost per fix (AU$)
BFRW_SA	29 975	0	0	0	129
DINGO1_NSW	37 640	0[D]	53	1760	5
DINGO2_NSW	5623	0	0	0	<1
DINGO1_NT	45 600	0[D]	9	300	<1
DINGO2_NT	15 400	0[E]	13	100	15 400[G]
DINGO_Qld	9000	11	11	40	<1
DINGO_SA	83 000	5	1	40	1
FERAL_SA	43 700	0[D]	57	160	15
KOALA_NSW	77 500[B]	40	0	0	8
KOALA1_SEQ	17 300	6[F]	17	15	2
KOALA2_SEQ	12 500	4[F]	0	0	5
KOALA_SWQ	11 880	0[D]	72	180	9
MARE_NSW	350	0	0	0	<1
MARE1_Vic.	17 500[C]	0[D]	0	0	3
MARE2_Vic.	17 500[C]	7	0	0	1
PADE_Tas.	70 000	0	14	60	1
POSS_Vic.	18 894	0[D]	0	0	<1
QUOLL_Tas.	28 370	0[D]	0	4	5
QUOLL_WA	15 000	0	7	14	16 000[G]
ROO_ACT	74 700	0[D]	67	552	n.a.
ROO_NSW	21 000	0	0	30	1
WOMB_NSW	32 400[C]	5	20	700	5
Total	684 832	6	19	3955	2.23

[A]Unanticipated additional costs and time beyond that allocated to the standard retrieval of data-logging collars.
[B]Cost is for 19 collars, deployed more than once.
[C]Approximate cost converted from US$ or NZ$.
[D]Fixed or replaced by manufacturer at no cost.
[E]Not fixed or replaced by manufacturer.
[F]Costs of refurbishment for additional deployments.
[G]Total cost with no fixes recorded.

The studies with shorter intended deployments had higher success, mainly because problems contributing to shortened operating life generally occurred only after some time in the field. Thus, while GPS collars appear to be suitable for collecting animal movement data over several seasons or throughout the year, only a small proportion of collars operated reliably for such extended periods. Our experience confirms the suggestion of Gau *et al*. (2004) that the reliability and performance of GPS collars decreases as time in the field increases.

Fix acquisition

Fix rates (i.e. the number of successful fixes divided by the number attempted) are frequently lower on GPS collars that are attached to free-ranging animals. This is mainly due to canopy cover, topography, collar orientation, fix interval and collar brand (Frair *et al*. 2010). However, obtaining intermittent fixes (days with no fixes) was a common problem in our studies and the reasons for its high incidence may differ from those mentioned above. Often, assessments of fix success of collars under different conditions are conducted over short periods (e.g. 24 h: Recio *et al*. 2011) and this may not provide a true assessment of fix success over the life of the collar. In addition to location or signal precision issues, intermittent fixes may arise from a programming failure, where the collar does not turn on at the specified time, and/or a hardware failure, such as an interruption on the battery lead. Although some collar brands record fix attempts, others do not; however, having this information would help to distinguish manufacturing faults from satellite positioning problems.

In controlled tests of fix rates by Recio *et al*. (2011), collars were programmed to attempt fixes in less than 2-h intervals. In this mode, the GPS receiver estimates positions in a 'hot start' with current almanac, time, location, and ephemeris data (Tomkiewicz *et al*. 2010) and time to fix is improved. When collars are inactive for greater time intervals (~2–4 h), they may begin in a 'warm start', whereby they need to acquire new ephemeris, and time to fix can be longer (resulting in greater power consumption). Even longer intervals (e.g. >6 h from the previous fix) result in a 'cold start', whereby collars need to acquire new almanac, time, location and ephemeris (Tomkiewicz *et al*. 2010), and the effect on fix rates and accuracy of locations may be relatively large. In our studies, programming of sample rates or duty cycles meant that fixes frequently were recorded >2 h later than previous fixes,

Table 7. Summary of common problems among studies of GPS tracking of mammals in Australia

Issue	No. of studies		% collars
	Affected	Not affected	
Shorter GPS life than expected	15	7	47
Intermittent fixes (days without recording)	14	7	31
Fewer fixes per day than expected	16	6	–
Changes to fix schedule or duty cycle	11	7	18
VHF transmitter failure	9	14	14
Timed-release failure	4	2	19
Collar design issues requiring change	10	12	–
Additional unexpected costs	13	10	–

and the devices were likely to have operated in warm or cold start modes. To allow for the initial inaccuracy of 'first' fixes, some GPS engines discard a set number of fixes and store the third or later fix as the final position. The GPS firmware potentially could be programmed to discard an even higher number of fixes (e.g. recording the fifth or later position) if needed.

Shifts in sample rates and duty cycles

These shifts can have profound effects on the operating life of the collar and the usefulness of the collected data. Several studies reported shifts in sample rates to higher frequencies, which significantly reduced the operating life of the collars. In the case of one koala collar and one feral cat collar, scheduled 4-h fixes shifted to record locations every minute, resulting in exhaustion of the GPS battery within two days. Similarly, shifts in duty cycle presumably also caused significant reductions of operating life. For example, wombat collars were scheduled to turn off during the day when animals were expected to be in a burrow and out of view of the satellites. In this case, a shift in the duty cycle caused not only significant reductions in the number of position fixes because the collars were not logging at night when the wombats were active, but the collars were on during the day and rapidly drained the batteries when the GPS tried to acquire hourly fixes while underground. To avoid rapid exhaustion of batteries in locations or periods with poor satellite reception, some manufacturers offer the option of programming devices with a time-out period. This means that the GPS receiver will stop trying to acquire a fix if it has not been successful after a certain period (usually a few minutes). However, even with this time-out feature, a shift in duty cycle (e.g. to a period of underground activity) can result in considerably shortened operating life and reduced data acquisition.

VHF transmitter failures

The VHF component of GPS collars typically is not used for data acquisition. Rather, the VHF transmitter is critical for the retrieval of store-on-board GPS data-logging collars because it is usually the only means of locating them. In general, retrieval of GPS data-logging collars is more likely when collars are used on relatively sedentary species that are not expected to move far from their release location. For more mobile species capable of travelling large distances (e.g. dingoes, which have been recorded to disperse >550 km from their point of origin in 31 days: Allen 2009), satellite-linked GPS collars offer a practical solution to the loss of collars (and data) should the VHF transmitter fail. However, this solution incurs the cost of additional weight, power consumption and expense for data-downloads (approximately AU$800 per collar per year where collars are transmitting for 6 h per day). Considering the many possible reasons for premature exhaustion of the GPS battery, it is crucial that the GPS and VHF components in the collar are powered by separate batteries. This means that the device can still be located, collected data retrieved, and the collar refurbished even after the GPS has stopped operating, albeit with some difficulty. Nevertheless, problems may still arise when separate batteries are used to power the VHF beacon, as was the case in our studies with VHF transmitter failure. Despite VHF technology having been around for considerably longer than GPS, there are still frequent reports of unit failure from insufficient packaging (Gau *et al*. 2004; Blackie 2010). A robust and completely waterproof design is needed to prevent water ingress and damage to transmitters, and aerials need to be positioned in the collar to minimise their risk of being chewed or broken.

Timed-release problems and failures

Our experience showed that timed-release devices do not always result in the collar dropping off the animal on the programmed time and date. For example, activation of the release mechanism may occur, but dirt and debris may prevent the mechanism from separating until the animal grooms the collar away. This is a problem if the animal spends time underground, in a tree, or on a cliff, and the collar drops to where it cannot be relocated or reached. Thus, researchers are left with some uncertainty about when, if ever, they will be able to recover their collars. When collars release early or not at all, this is more likely to be due to a programming fault or hardware failure. These issues might become more problematic if animals are left wearing collars for the remainder of their lives.

Data accuracy

In most cases it is unlikely that all the locations recorded with a GPS collar will be accurate enough to be used for the study purposes (unless a coarse resolution is acceptable for the objective). An HDOP value (or sometimes a PDOP value) is typically ascribed to each recorded GPS fix, and many researchers use this as the primary means of discriminating and excluding fixes that are likely to be too inaccurate (D'Eon and Delparte 2005; see Appendix 2). However, it is important to note that there is no limit to the potential level of inaccuracy of any fix; even those with low HDOP values may still have low accuracy. Rather, HDOP values reflect the likelihood that the fixes were accurately acquired; therefore, not all fixes with high HDOP values will be inaccurate, but a greater proportion will be, and *vice versa*.

Since site conditions (e.g. canopy cover, terrain) impact satellite reception, it is strongly recommended that the relationship between HDOP values and on-ground accuracies be examined. This can be done either before collar deployments through stationary collar tests in a range of environments at the proposed study site (e.g. Recio *et al*. 2011), or after deployments to gauge the accuracy of the fixes obtained (e.g. Allen 2012). An assessment of HDOP values against on-ground accuracies will permit researchers to determine the appropriate HDOP threshold – rather than choosing an arbitrary number – for inclusion of fixes, and to establish the likelihood that fixes are accurate within acceptable bounds. Selection of accuracy thresholds should be heavily influenced by the study objectives and the level of movement resolution required (Ellis *et al*. 2011). For example, far greater resolution is necessary to determine which backyards are visited by dingoes in urban areas than to estimate home-range sizes of highly mobile dingoes in remote locations.

Welfare issues

Until recently, most studies using GPS collars have done so with collars weighing >500 g on medium-to-large mammals, usually predators and/or their prey. For example, Johnson *et al*. (2002) used 1.8-kg collars for caribou while Merrill *et al*. (1998) had 920-g collars for wolves and white-tailed deer. There is little published information on use of GPS collars <300 g on small and medium-sized mammals (Blackie 2010; Mattisson *et al*. 2010), but recent assessments indicate that they are suitable (Dennis *et al*. 2010; Recio *et al*. 2011). Here we present data from species weighing 1–74 kg, including several smaller species (koalas, possums, pademelons, rock-wallabies, and quolls) weighing less than 10 kg. When collars are attached to wild animals, several welfare issues need to be considered, including the need for collars to be well fitted (not too tight or too loose) to prevent injury, to avoid disruption of daily activities (e.g. grooming and sleeping), and to avoid interference with normal movement behaviour (Casper 2009). We found few instances of collars causing injury to study animals, but there were minor problems of hair loss and skin abrasions. A few pademelons died as a result of capture myopathy (McMahon *et al*. in press), a condition that is commonly seen in macropods following capture and handling (Vogelnest and Portas 2008). Consequently, the additional stress of handling while fitting collars needs to be considered for susceptible species. We were not aware of any of our study animals changing behaviour as a result of the GPS collar, although this would be difficult to identify and, in any case, was not explicitly studied.

One of the benefits of GPS tracking is that animals do not need to be followed to gather location information, thus reducing both labour costs and disturbance to study animals. In addition, some research programs use timed-release units so that animals do not have to be recaptured during the study. Consequently, there may be no regular monitoring of animal welfare following release. Among our studies, 60% of animals were recaptured after collar deployment, which meant that animal welfare could be assessed, for example through an examination of changes in body weight or condition, the fit of collars, and injuries incurred. Such monitoring gives researchers the capacity to respond to problems when they arise and improve animal welfare. However, for some animals, recapture may not be a practical option. In these cases, VHF tracking remains a valuable tool for monitoring animal welfare of highly visible species in real time, or for monitoring unusual movement behaviour of more cryptic species. For example, if animal locations do not change as expected, or if collars are fitted with a mortality signal (whereby VHF signal frequency changes after a predefined period of inactivity), lack of movement might provide an early indication of welfare issues. While VHF tracking somewhat defeats the advantages of GPS collars, it may be used to monitor animal welfare for short intervals throughout a study.

Timed-release devices allow collars to be recovered from animals without the need for recapture, and avoid restraint and handling of animals, which may cause stress. However, we found that 18% of timed-release devices failed, leaving collars attached to animals. This may be a significant issue if animals are encumbered with GPS collars indefinitely. Casper (2009) suggested that researchers should consider some of the anticipated consequences of attaching equipment to animals, and that they should be careful to avoid situations where the welfare of animals is compromised. An important consideration with regard to timed-release devices is the likelihood of the animal being recaptured to remove the collar if the mechanism fails. In particular, the use of timed-release collars on growing juveniles warrants careful thought because strangulation by the collar is possible if it does not release and it cannot be removed. Alternatively, several options for collar design could be considered to allow for the possibility of a timed-release unit failing. Options include expanding collars or elastic inserts, which permit growth, and the inclusion of weak links (e.g. a section of natural rubber), which eventually will fail, thereby ensuring that animals do not have to cope with wearing a failed collar for a long time.

An issue that needs to be explicitly addressed is the preparation of protocols for the use of GPS collars on mammals for submission and approval by animal ethics committees (AECs). The central question is whether the welfare of animals is likely to be compromised to a point that is unacceptable to an AEC. It is acknowledged that the use of animals for scientific research may involve interference with the animal, such as capture, and the imposition of a collar for the duration of the study. The first question to address is whether the collar causes injury to the animal or prevents it from carrying out its normal activities. The second question is the reliability of collar retrieval at the end of the study. As pointed out in Lunney (2012) and Jones *et al*. (2012), it is in the interests of the researcher to develop protocols that present a reasoned case for the approach and the level of risk, and not leave this to the AEC who may be less knowledgeable about the species or study system.

Costs

Wildlife tracking inherently is an expensive pursuit but, to complicate the situation, costs vary significantly depending on project objectives (Thomas *et al*. 2011). Given that ~75% of the case studies considered in this paper incurred additional, unexpected costs, we believe it to be imperative that when planning projects, researchers obtain funds not only for the initial costs of equipment and labour, but also to cover costs associated with poor collar performance (additional searches and/or capture of animals, collar refurbishment and/or replacement). Although it is impossible to provide a definitive measure of how large this contingency fund should be, if our results are indicative, allocating at least 25% of initial project costs would be advisable.

Our most significant, unexpected, fiscal expenditures related to attempts to retrieve lost collars, as well as for battery and/or collar replacement or repair. Indeed, the cost of refurbishment can rise after purchase to nearly half the cost of a new collar. However, other potential costs include those associated with researchers disassembling collars themselves (Blackie 2010). Incalculable costs include those associated with loss of time, data, and reputation (Kaczensky *et al*. 2010) and, consequently, a failure to fulfil project outcomes. For example, one of our case studies experienced so many problems in the first year that the project needed to be extended into a second. Since virtually all wildlife projects are conducted under tight timeframes and budgets, such delays can have serious ramifications. Delays and/or mass failures of GPS collars that occur during student projects can have particularly grave consequences.

In spite of the inherent risks, we do believe that GPS telemetry is a powerful technique worthy of continued investment and one which, with continued advances, will become both more reliable and less costly. Indeed, despite wide variation, the current study's average cost per fix of $2.23 was substantially below that of previous estimates (e.g. US$14 per fix in one year and $8 in the second year: Hemson 2002). Cost per fix of our individual studies ranged between $0.02 and $129, showing how the success of collars impacts on this figure. Despite such variation, we concur with Thomas *et al*. (2011) that GPS is the most cost-effective tracking method for studies that require large sample sizes.

Recommendations for potential users

There is no doubt that GPS telemetry in many cases is the most effective technique to monitor the movements of animals, and should be utilised to its full capacity. Manufacturers are continually improving designs and incorporating new technology, and while some of our technical problems may now be rectified, several issues remain. On the basis of our experiences, we provide the following recommendations for potential users:

1. Talk to researchers who already have used GPS collars. There is no substitute for this hard-gained knowledge and experience from previous field deployments.
2. Undertake a stationary collar test and pilot study with one or two collars in the study environment to assess the efficacy of an approach before investing in expensive collars. Discovering what the collars can and cannot do in a particular study area (e.g. fix success and accuracy) enables adjustments to be made to study objectives and/or duty cycles to accommodate site or species-related issues before the start of a costly and time-consuming field-study.
3. Consider options to monitor operation of collars in the field, such as a VHF or UHF communication link, remote download, satellite link, or recapture program.
   - (*a*) A within-deployment communication link between the GPS unit and the researcher will allow for remote monitoring of the GPS performance. For example, some GPS collars indicate whether the last fix attempt was successful by transmitting a particular sequence of VHF 'beeps' (Merrill *et al*. 1998; Millspaugh and Marzluff 2001). Without such an arrangement, it is impossible to determine whether collars are operating until they are retrieved. In remote areas, recurrent recapture often is not feasible and by the time researchers realise that the units are malfunctioning, resolving and/or repeating the study may not be possible.
   - (*b*) Several remote download methods are available to recover data from store-on-board GPS devices (Tomkiewicz *et al*. 2010; Thomas *et al*. 2011). Close-proximity remote download allows researchers to download the GPS locations on the data-logger to a handheld computer when in close range of the collar, or via an unattended automatic remote download system. If remote download is attempted on a regular basis, proper functioning of GPS collars can be monitored. Use of this technology in combination with a remote timed-release system, would allow researchers to retrieve collars immediately when they are found to be faulty. Remote download technology also would allow the retrieval of data from collars dropped inside burrows or dens, even though the devices themselves may not be recovered. However, some researchers also report problems with the remote download procedures (Gau *et al*. 2004), particularly for animals that travel quickly and move out of range of the radio-signal during transmission. This may not be a problem for species that can be easily approached, or are relatively inactive during the day. Remote download was used with our Televilt Tellus GPS collars (PADE_Tas.) and Telemetry Solutions Quantum 4000 Enhanced GPS collars (QUOLL_Tas.) with great success, and on the rare occasion when remote download was unsuccessful, it was eventually achieved by simply getting closer to the animal. In most cases, the distance required for a successful remote download was substantially closer than the remote download distance quoted by manufacturers. Dense understorey, canopy cover, weather, and topography may all influence distance requirements. It may be useful to test the accuracy and distance required for successful remote download before collar deployment for species that are likely to be flushed on approach. It should be noted that GPS collars that offer the option to remotely download location data tend to be considerably more expensive than standard data-loggers, and frequent remote downloads will significantly increase power consumption and reduce battery life. Remote download also may require a laptop device to be taken into the field, making weather conditions important in planning activities. Features such as mobile phone download may suit some projects better, although there may be additional costs to factor in for this feature. Furthermore, we note that not all manufacturers offer remote download options.
   - (*c*) Satellite-linked collars (e.g. GPS/Argos, GPS/Iridium or GPS/Globalstar) hopefully will continue downloading data even if the GPS receiver or VHF transmitter fail, allowing the collar to be retrieved when the animal dies or the collar releases. Receiving satellite transmissions add substantial costs, but using satellite-linked GPS loggers for mobile species, or those that are remote and difficult to reach, may be deemed worthwhile.
   - (*d*) Capturing, checking whether the collar is functioning, and recollaring individuals as required every

2–3 months could be considered if researchers are attempting to follow animals for more than a few months and a communication link or remote download is not available, or if battery capacity does not permit extended monitoring periods. Recapturing animals would also allow the monitoring of potential animal welfare issues. However, researchers should carefully consider how repeated capture and handling may influence the welfare of animals, their behaviour and the study's objectives.

4. Consider the timing of collar deployments. If a particular time of the year is critical to the study, it is advisable to deploy or check collars immediately before this period. In the case of seasonal comparisons, and if sufficient collars are available, we recommend, as a precaution against premature failure and loss of performance over time, that a proportion of the devices be deployed at the start of each season rather than all at once.
5. Understand where study animals are likely to be, because VHF tracking sometimes cannot be relied on to help retrieve collars at the completion of the study. This means that some conventional tracking at discrete intervals is required to locate study animals during deployment.
6. Sample more often than is needed. Doing so may overcome the problem of not acquiring all the fixes needed to meet the study objectives, and it is better to have more data than less. The frequency of fixes (or duty cycle) will have a substantial influence on the types of analyses that are achievable. If possible, know something about the fine-scale movements of your animal before you start, and then sample as frequently as practicable. While there is little value in collecting a multitude of fixes in one spot for an animal that sits in the same place all day, it is important not to miss movements of animals that wander. Expected home-range size, battery life, and study objectives should determine the duty cycle, and not the other way around.
7. Understand how the data to be collected will be used or analysed. Many of the analytical and statistical techniques for animal movement data were developed for radio-telemetry data, and may become outdated or superseded by more modern approaches. Methods of space use calculation are in drastic need of revision now that much finer-resolution data can be collected to track where the animal has been.
8. Factor into research budgets the additional costs required for recovery of failed collars (also recommended by Gau *et al*. 2004). Within a tight budget there is often a desire to maximise the number of collars deployed. However, it may be better to invest more money in monitoring collar function during the deployment period, and recovering data from collars when they fail.
9. Consider using user-replaceable GPS batteries, because refurbishment of collars by the manufacturer to replace batteries housed in an epoxy-moulded casing can be expensive and usually takes several weeks. Note that these batteries are likely to be a different voltage than standard batteries, and often are more expensive (about AU$25 each for AA, or $50 for D-cell lithium chloride), but are nonetheless essential. Most manufacturers can accommodate custom design specifications, so if the researcher's choice is to use replaceable batteries, this needs to be specified to the manufacturer before purchase so that the capsules holding the batteries (one for the VHF transmitter, the other for the GPS unit) are provided with a removable cap. It should be noted, however, that these capsules add to the weight and cost of the collar, and may not be as rugged, or waterproof, as a moulded casing. Furthermore, user-replaceable batteries places the onus on the researcher to change the batteries and do extensive testing on each collar before redeployment.
10. Ensure that collar manufacturers have had experience in making collars for the required conditions and/or species, given that GPS collars for wildlife require a specialised understanding of animal behaviour, field conditions and terrain. Collars must be operational at the time of attachment to the study animal, so users must be confident that preattachment tests are reliable. In our experience, it is better to pay a higher price for more robust equipment than trying to save money with substandard or untested equipment. Ultimately, the acquisition of reliable data is most important, and studies may end unsuccessfully when equipment fails. Researchers should expect lower performance than is stated in manufacturers' specifications for the collars (often theoretical 'best-case'), and factor in a margin of error when designing a study, by increasing the number of fixes or deploying more collars. From our experience, we recommend deploying 20% more collars than what is needed for adequate sample sizes. Order equipment several months in advance, because manufacturers usually have a backlog of orders and may deliver the products later than anticipated. This affects the timeframes allocated to deploy collars in the field, which could involve hiring trappers, traps, booking vehicles, accommodation, arranging volunteers and various other logistical procedures. A good relationship with the manufacturer is therefore important.
11. The weight of the collar, and its physical dimensions, becomes increasingly important as smaller species are studied. The standard configuration is to place the bulk of the VHF/GPS unit in one place – typically under the chin, to provide a counterweight to the GPS antenna at the top of the collar; consider a customised design to shape or spread the load around the collar, and consult the manufacturer on the advantages and disadvantages of alternative collar designs for your study species. The weight of the timed-release unit also adds to total collar weight, so consider dispensing with the timed-release unit when study animals are easily recaptured.
12. Collar-tightness is an animal ethics matter as well as one of practical concern. When too tight, the skin around the animal's neck is rubbed, even broken; when too loose, the collar may fall off, or the animal might be able to push a leg through the collar and become stuck. A pilot study on a captive animal (e.g. zoo, animal in care, or in the university animal yard) can be useful to test suitable collar tightness. For most medium-sized mammals, 3–4 fingers fitting under the collar, and a single finger for smaller mammals, are good rules-of-thumb. If it is the first time that the GPS collars have

been used on the study species, trialling one collar on a captive animal before ordering all of the collars allows researchers to observe the behaviour of collared animals, and may assist in optimising collar design.

13. Work with manufacturers to improve collars. Provide feedback on equipment performance, both good and bad. This is especially important with regards to physical design as manufacturers tend to be staffed by highly trained engineers who may lack field experience fitting collars to animals. For example, some manufactures supply collars that require tiny nuts and bolts for attachment, but alternative designs that are quick to deploy, easy to release, and that can be fitted by one person, may be available on request. Collars that are easily and quickly fitted may help reduce the likelihood of capture-related problems (such as those described above for pademelons) from developing.
14. Finally, be prepared for the unexpected. Try not to be confined by preconceived ideas about animal behaviour (e.g. inactive during the day), because much of our knowledge comes from studies that have not been able to evaluate this easily. In many cases, with novel technology and insight, we have learned that animals do not always behave in conventional ways.

Acknowledgements

This study arose from informal discussions among the authors at scientific meetings of the Australian Mammal Society (AMS) and the International Mammalogical Congress. All studies were undertaken with approval from Animal Ethics Committees and details can be obtained from individual authors. Each research program was generously supported by numerous volunteers, organisations and funding bodies that have been acknowledged in individual study publications, or will be in future publications of ongoing work. A. Matthews thanks the Institute for Land, Water and Society for travel assistance to deliver this paper to the joint meeting of the American Society of Mammalogists and the AMS in 2011. We thank Chris Muller from Sirtrack for his critical comments on a draft of this manuscript.

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Appendix 1.

Study descriptions

BFRW_SA. Ten black-footed rock-wallabies (*Petrogale lateralis* MacDonnell Ranges race) were collared in the Anangu Pitjantjatjara Yankunytjatjara Lands, north-western South Australia, in June 2008 (Ruykys *et al*. 2011). Each rock-wallaby was fitted with a custom-made collar (Sigma Delta Technologies, Western Australia) which weighed 80 g. Collars had an active deployment of 10 months, during which time the VHF component was programmed to operate for 4 h per day and the GPS component to operate for four months. During these four 'active' months, the GPS was programmed to acquire a location fix every 1.5 h. Collar components were mounted on Teflon tubular ribbon, with the Teflon strands held together using an epoxy–resin mix and veterinary sutures. The study area was in granitic mountains in the arid zone and experiences annual mean temperature ranges of 13−38°C and unreliable, low (average 255 mm) rainfall.

DINGO1_NSW. Twelve dingoes (*Canis lupus dingo*) were collared in the southern section of the Greater Blue Mountains World Heritage Area during 2005–06 (Purcell 2010). Six GPS data-logging collars that were programmed to store data on seasonal movements were deployed during the breeding season (April) in 2005 and 2006 ($n = 12$ over two years). GPS receivers were mounted on leather collars fitted with automatic, timed-release drop-off mechanisms (Sirtrack®, Havelock North, New Zealand). A VHF transmitter was also built-in to aid recovery of collars. The final weight of each collar was 350 g. Collars were programmed to store one location on the hour for 3 h, followed by an 8-h interval to obtain a cyclic dataset. The timed release mechanism was programmed to release during the 14th month of deployment. The study area comprised ~2200 km^2 between latitudes 33°43′00″ and 34°18′00″, and longitudes 150°00′00″ and 150°30′00″. Climate was temperate, with average temperatures ranging between 5°C and 16°C during cooler months and 16°C and 29°C in warmer months. Annual rainfall for this area ranges from 812.6 mm to 1410 mm. Altitude varied from 160 m to 1158 m above sea level (a.s.l.) from the eastern to the western borders of the study area respectively. Predominant vegetation communities include dry forests (45%), woodlands (38%) and heaths, low woodlands, moist forests and rainforests. Some areas remain cleared of native vegetation due to previous agricultural practices.

DINGO2_NSW. Five dingoes were collared in the southern section of the Greater Blue Mountains World Heritage Area during the breeding season (March) in 2007 (Purcell 2010). GPS collars were programmed to store one location every 10 min to collect data on short-term movements over a deployment period of 52–54 days. Collar type and site description was the same as DINGO1_NSW above.

DINGO1_NT. Fifteen dingoes were fitted with GPS collars (new and refurbished) in the Tanami Desert, Northern Territory, between April 2008 and April 2010. Collars were manufactured by Sirtrack® (Havelock North, New Zealand) and were programmed to obtain one fix every hour for up to 10 months. All collars contained a GPS data-logger, VHF transmitter and a preprogrammed timed-release unit. Nine of the collars had an Argos-linked satellite transmitter. The climate of the Tanami Desert is semiarid and monsoonal, and habitats are dominated by loamy sandplain with hummock grasses. Less extensive habitats include lateritic sand-plains, rocky rises (chert and laterite) and elevated drainage depressions.

DINGO2_NT. Seven dingoes were fitted with GPS collars in the Tanami Desert, Northern Territory, between April 2008 and April 2010. Collars were manufactured by BlueSky Telemetry® (Aberfeldy, Scotland), and were programmed to obtain one fix every hour for up to 10 months. All collars contained a GPS data-logger, VHF transmitter and a preprogrammed timed-release unit. Site description was the same as DINGO1_NT.

DINGO_Qld. Nine dingoes (10–32 kg) living in urban areas of north Brisbane and the Sunshine Coast were collared between October 2005 and May 2006. Sirtrack® GPS collars (weighing ~450 g) were programmed to acquire one GPS location every 5 min from 1700 to 0900 hours and one GPS location each hour outside these times during the day. The collars contained a GPS data-logger, VHF transmitter and a preprogrammed timed-release unit. The GPS data-logger was expected to collect and store location information, the VHF transmitter was used to recover the collar, and the timed-release unit was used to avoid the need for recapture. The area contained fragmented urban, agricultural (primarily sugarcane) and forested landscapes. Mean annual rainfall was ~1650 mm and average temperatures ranged between 7.5°C (July) and 29.2°C (January).

DINGO_SA. Sixteen dingoes (13–23 kg) living in arid desert areas of north-eastern South Australia were collared between November 2008 and June 2010. Sirtrack® GPS collars (weighing ~450 g) were programmed to acquire one GPS location each 30 min continuously. The collars contained a GPS data-logger, VHF transmitter, and an Argos-linked satellite transmitter. The GPS data-logger was expected to collect and store location information, the VHF transmitter was used to recover the collar, and the Argos link was used to monitor the location of the animals weekly to save time trying to locate the collars solely with VHF. The area was predominantly open grassland with sparsely vegetated drainage lines. Temperatures ranged between −4°C and 54°C, and mean annual rainfall was ~160 mm.

FERAL_SA. Fourteen feral cats (*Felis catus*) and four foxes (*Vulpes vulpes*) were collared between April and August 2006 within a 50-km radius of the Arid Recovery Reserve in northern South Australia (Moseby *et al*. 2009). Each adult cat and fox was fitted with a 135-g Sirtrack® (Havelock North, New Zealand) GPS data-logging collar made of synthetic belting, with the units housed in epoxy resin. Collars were programmed to record GPS locations every 4 h, and the VHF transmitter had a mortality sensor, triggered after more than 24 h without movement. The study area is typically hot and dry with 160 mm annual mean rainfall. Mean minimum and maximum temperature during the study was 5.4°C and 20.6°C, respectively. The study area supports a variety of habitats and associated vegetation, including dunes (dominated by *Acacia ligulata* and *Dodonaea viscosa*), sandplains (*A. aneura* and *Calitris glaucophylla*), chenopod swales (*Atriplex vesicaria* and *Maireana astrotricha*), swamps (*Eragrostis australasica*), claypans, and creeklines, with less than 5% overstorey canopy cover.

Appendix 1. (*Continued*)

KOALA_NSW. GPS collars were fitted to 51 koalas (*Phascolarctos cinereus*) on the Liverpool Plains near Gunnedah, NSW, during 2008–11 (Lunney *et al*. 2012). The study area consisted of a combination of natural woodland and environmental tree plantings on farmland. Koalas were fitted with GPS collars that were custom-made (Sirtrack®, Havelock North, New Zealand) and initially weighed 180 g (the koalas weighed 4–10 kg). Each collar contained a GPS receiver (mounted at the top of the collar loop) as well as a VHF transmitter and battery, component housing and GPS battery (mounted at the base of the collar loop so as to sit beneath the animal's chin). Collars were initially programmed at manufacture to log their position every 4 h during the evening starting at 1700 hours, with the GPS unit turned off for 8 h during the day. After the final deployment, the program was for every 4 h, i.e. yielding 6 readings per day. For the purposes of the calculations, we used the 31 koalas that had been tracked when the study for this paper was initiated, but a further 20 koalas were tracked during the last year of the study. The collar weight on these final deployments was reduced to 150 g by leaving out the timed release. There were fewer problems with the collars in the last year of the study.

KOALA1_SEQ. GPS collars were fitted to nine koalas (*Phascolarctos cinereus*) in the east Coomera area of south-east Queensland, during 2009–10. The study site comprised numerous forest fragments (dominated by *Eucalyptus robusta* and *Melaleuca quinquenervia*) that were separated by recent urban residential development. Forest fragments were searched on foot for koalas, which were then caught and fitted with GPS collars that were custom-made (Sirtrack®, Havelock North, New Zealand) and weighed 150 g (<4% of the mass of the smallest collared koala). Each collar contained a GPS receiver (mounted at the top of the collar loop) as well as a VHF transmitter and battery, componentry housing and GPS battery (mounted at the base of the collar loop so as to sit beneath the animal's chin). Collars were programmed at manufacture to log their position every 2 h (i.e. 12 fixes per 24-h period).

KOALA2_SEQ. As for KOALA1_SEQ except that the GPS collars were programmed on a different logging schedule, and fitted to six koalas. Collars were programmed at manufacture to log their position at 4-h intervals using a duty cycle of 16 h on and 8 h off (i.e. 5 fixes per 24-h period). Collars were activated with a magnet at 1600 hours and therefore entered the 8-h off period at 0800 hours each day.

KOALA_SWQ. Seven koalas were collared in the semiarid areas of south-western Queensland, comprising portions of the Mulga Lands, Mitchell Grass Downs, and Brigalow Belt South bioregions. Rainfall is variable and unreliable, but annual averages range from 750 mm in the east to 250 mm in the west. During the hottest months, the mean maximum and minimum temperatures are ~35°C and 19°C, respectively, while during the coolest months mean maximum and minimum temperatures are ~19°C and −5°C respectively. Seven GPS data-logger collars (Titley Scientific), modified to fit koalas, were programmed to record a fix every 4 h. Tracking was conducted from August to December 2010.

MARE_NSW. Three Maremma livestock-guarding dogs were collared on a sheep property fronting the Apsley River gorge, near Yarrowitch, New South Wales, in summer 2009. The study area is a tablelands agricultural property adjoining other semicleared and pastured properties to the west, south and east, and separated from the forested gorge country to the north by a dog-proof fence. The terrain is undulating, with patches of woodland and forest, and ranging in elevation from 900 and 1076 m above sea level. The area has a cool temperate climate, with frosts common in winter and annual mean temperature ranging between ~6 and 20°C, and mean annual rainfall of 800.5 mm. Each collar comprised a GPS logger housed in a waterproof box attached to an adjustable strap that ensured the GPS antenna remained at the top of the animal's neck throughout deployment. Each collar weighed ~400 g, and was programmed to take a location every 10 min from deployment until the battery ran out. In practice, the collars were collected after 44 days and the batteries were still functioning.

MARE1_Vic. Three Maremma sheepdogs were collared in central East Gippsland, Victoria, in June 2009. Each collar consisted of a GPS device and VHF unit mounted on a biothane collar. The GPS logged the data, but also had a remote download and reprogram option available. Each collar weighed ~600 g, and was programmed to take a location every 30 min until the battery ran out. The study area was an agricultural property surrounded on all sides by a mixture of dry and wet sclerophyll forest, with some patches of native vegetation remaining on the property itself. The terrain is undulating, with an approximate elevation between 250 and 450 m above sea level on the property itself, but going up to 700–800 m in the area surrounding the property. The area has a temperate climate, with an annual mean temperature ranging between 6 and 25°C, and a mean annual rainfall of 813 mm.

MARE2_Vic. Four Maremma sheepdogs were collared in north-eastern Victoria in March 2010. Collar type was the same as MARE1_Vic. above. The collars were set to take a location every 30 min until the battery ran out, but their programming was changed a couple of times through remote communication to take a location every 15 min for 24 h, followed by a location every 2 min for 1 h, followed by a location every 15 min for 24 h again, after which they went back to their normal 30-min schedule. The research area was an agricultural property situated in an agricultural zone. Surrounding the property are other agricultural enterprises and pine plantations. Large tracts of uncleared native vegetation remain in the area, which mostly comprise grassy dry forest. The research property is hilly, with an elevation of ~200 m above sea level in a river valley and ~800 m on the hill tops. Slopes are steep. The climate is temperate, with mean temperatures ranging between 4.3 and 30.9°C, and a mean annual rainfall of 693 mm.

PADE_Tas. Thirteen Tasmanian pademelons (*Thylogale billardierii*) and 17 red-necked wallabies (Bennett's wallabies, *Macropus rufogriseus rufogriseus*) were collared in north Scottsdale, north-eastern Tasmania, in December 2008 (Wiggins *et al*. 2010; Wiggins and Bowman 2011). Each pademelon was fitted with a Televilt Tellus Basic™ 3H2A GPS collar equipped with a Tellus RC_DropOff mechanism (Followit Wildlife, Lindesberg, Sweden). Collars were deployed for eight months, with collars programmed to record daily positions in the following three time blocks: (1) 0150, 0200, 0210 hours, (2) 0550, 0600, 0610 hours, and (3) 2150, 2200, 2210 hours during summer, or 1 h earlier during winter. These times were selected to collect information on crepuscular and nocturnal

Appendix 1. (*Continued*)

activity patterns when animals are most active. Each GPS collar contained a remote UHF data-download feature, which was accessed with an RCD-04 Portable Terminal (Tellus GPS System, ZoHa EcoWorks, Calgary, Canada), and data viewed using the Tellus Project Manager (TPM) Software package (Followit Wildlife, Lindesberg Sweden). The study area was concentrated around two agricultural properties, spanning an approximate area of 285 ha. Dry eucalypt forest/woodland and agricultural land were the dominant habitat types in this area.

POSS_Vic. In order to study dispersal and ranging behaviour, 29 mountain brushtail possums (or bobucks, *Trichosurus cunninghami*) were collared in the Strathbogie Ranges, in north-eastern Victoria, during 2007–10 (Eberhart 2011). Deployment periods were four months, and always included the dispersal period in February/March or September/October. The total weight of the Wildlife GPS data-loggers (Sirtrack), comprising a VHF transmitter and GPS receiver mounted on a synthetic fabric collar, ranged between 110 and 130 g. The VHF beacon was only operational during the day, whereas the GPS was programmed to acquire one location fix every 60 or 45 min during the night. The Strathbogie Ranges form a plateau at ~700 m altitude where temperate climate prevails with monthly mean maximum temperatures of 10−18°C in winter and 19−27°C during summer, and an average annual rainfall of 970 mm. Most of the area is cleared for pasture; however, bobucks only rarely leave the remaining sclerophyll forest.

QUOLL_Tas. Seven adult female spotted-tailed quolls (*Dasyurus maculatus*) were collared in March and April 2011 at Cape Grim, north-western Tasmania. Each quoll was fitted with a 70-g Telemetry Solutions Quantum 4000 Enhanced GPS collar equipped with a GPS logger, single-stage VHF transmitter, and UHF transmitter, mounted on suede fabric. The GPS logger was programmed to record a location every 2 h for five days per week, and every 15 or 20 min for two days per week. The VHF transmitter was used as a real-time tool to monitor the collared quolls' welfare, collect information on den use, and to recover collars. The UHF was used to download GPS data remotely to a computer via an antenna connected to the computer and a base station. The study area spanned ~4400 ha of a flat, undulating agricultural property with maximum elevation 120 m, annual mean rainfall of 762 mm, and temperature range of 8.2–19.5°C. The property is heavily cleared for beef and sheep farming and pasture is extensive. Remnant vegetation comprises dry eucalypt forest and woodland, coastal scrub and heath, grassland, melaleuca swamp forest, and small patches of wet eucalypt forest.

QUOLL_WA. Six western quolls (*Dasyurus geoffroii*) were collared in the northern jarrah forest of Western Australia during February 2008. Each quoll was fitted with a custom-made tracking device (Sigma Delta Technologies, Floreat, WA), which incorporated a GPS data-logger and VHF transmitter mounted on a Teflon ribbon collar. Each unit weighed ~25 g. The GPS units were programmed to record a location fix every 8 h for 90 days before deactivating. At a fixed date shortly thereafter, the VHF transmitter was programmed to activate to aid retrieval of the collar. The study area was in dry sclerophyll forest (~30% canopy cover) in flat to moderately undulating terrain around 300 m above sea level. The area experiences a Mediterranean climate with hot, dry summers and cool, wet winters. Annual mean temperature ranges from 10 to 30°C and annual mean rainfall is 1250 mm.

ROO_ACT. Twenty-six eastern grey kangaroos (*Macropus giganteus*) were collared during 2009–11 in the urban area of Canberra, following a one-year design trial. Data-logging collars manufactured by Sirtrack® (Havelock North, New Zealand) were fitted to kangaroos with an internal timed release, but all collars were retrieved before programmed release time. Collars were programmed to record locations every hour on a duty cycle of 24 h on and 3 days off. The study area is within the urban matrix of Canberra with some open grassy areas, woodland and forest. Canopy cover ranges from <2% to >50%. Mean minimum and maximum temperatures in Canberra are 6.4°C and 19.6°C respectively, and annual mean rainfall is 616 mm.

ROO_NSW. Twelve eastern grey kangaroos (*Macropus giganteus*) were collared at Jooriland in the Warragamba Special Area of New South Wales. Each kangaroo was fitted with a GPS data-logging collar from Sirtrack® (Havelock North, New Zealand) that was programmed to record one location every 45 min, with a battery life of ~60 days. The collars also comprised a VHF assembly, operating in the frequency range of 150–151 MHz and emitting an individual signal of 40 pulses min^{-1}. A mortality sensor was added to each transmitter, whereby a rate of 80 pulses min^{-1} was emitted if there was no movement after 24 h. After ~60 days, each animal was radio-tracked, its location was determined and it was recaptured to remove the GPS collar. The study area contains large areas of improved pasture, from former farming practices, and patches of regenerating box gum woodland and riparian vegetation (10–15% canopy cover). Mean minimum and maximum temperatures are 16°C and 29°C, respectively, and annual mean rainfall is 603 mm.

WOMB_NSW. Thirteen common wombats (*Vombatus ursinus*) were collared in the Snowy Mountains during 2008–09 (Matthews and Green 2012). Each wombat was fitted with a custom GPS data-logging collar from Sirtrack® (Havelock North, New Zealand), which incorporated a programmed external timed-release unit, and weighed ~300 g. Collars were programmed on a 60-min sample rate on a duty cycle of 8 h on, 16 h off, and were estimated to operate for 12 months. The study area was in subalpine woodland (~15% canopy cover) in undulating to moderately rugged terrain from ~1500 to 1900 m above sea level. Annual mean temperature ranges from 0 to 11°C and annual mean rainfall is 1800 mm, falling as snow during winter.

Appendix 2.

Here we describe the components of GPS collars and how they operate, and provide definitions and explanations for some terms associated with the technology (see also Tomkiewicz *et al*. 2010 for a glossary of terms of GPS and associated technology).

Satellite versus GPS

Satellite collars incorporate a platform transmitter terminal (PTT) which transmits a radio signal to overhead satellites (in the Argos system). As the satellite passes overhead it receives these signals in successive intervals and a Doppler positioning technique is used to determine the location of the transmitter on the ground (Rodgers *et al*. 1996; Thomas *et al*. 2011). With GPS telemetry, the roles of transmitter and receiver are reversed, such that continuously broadcast radio signals from the (NAVSTAR) satellites are received and stored in the collar. The configuration of multiple satellites is used to calculate the location of the animal. Consequently, the largest on-ground difference between satellite and GPS tracking is the resolution of the location. For satellite tracking, the resolution is approximately ±1 km, which will not provide the fine detail needed to follow the movement of animals in small home ranges. For GPS tracking, the accuracy of locations is constrained by the capabilities of the hardware, and is typically <30 m (Tomkiewicz *et al*. 2010; Recio *et al*. 2011).

Satellite-linked versus data-logging (store-on-board)

Satellite-linked (or Argos-linked) GPS collars may be confused with satellite (PTT) collars. However, satellite-linked collars use the GPS system to acquire locations that are stored within the collar. At programmed uplink periods, these data are then transferred in messages via the Service Argos satellite system to the ground-station processing centres in Landover, USA, or Toulouse, France (Rodgers 2001). While the Argos link may be used to retrieve stored GPS data, doing so is very expensive, and this functionality has typically been used by Australian researchers to check the location of the collar intermittently in order to reduce the time it takes to locate the collar using VHF tracking at a later stage. A further limitation of the Argos link is that it is highly unlikely that all the GPS data will be received because transmissions to Argos need to coincide with a satellite pass overhead. Each position needs to be repeated at least 30 times to increase the chance of it being received, but there are still no guarantees. Alternative satellite download methods include Iridium and Globalstar (Thomas *et al*. 2011).

Data-logging (or store-on-board) collars store the GPS locations on board the collar, and the collar must be retrieved to download the data. Retrieved data are transferred from the collar to a computer using a cable and interface unit. Thus, GPS data can be downloaded from the collar while it is attached to the animal, provided that the animal can be restrained, or once the collar is removed.

Scheduled fix intervals and duty cycles

Scheduled fix intervals are programmed (often by the collar manufacturer) before deployment and determine the frequency with which the collar will attempt to acquire a GPS location. Compromises must be made between the number of locations per day and the duration of the study, and this depends on the research questions being asked. At issue here is the capacity of the battery – the more times it is used per day, the fewer days can be studied. For example, establishing fine-scale movements may require a fix schedule of one fix per hour or shorter, whereas annual home-range estimates may require just one fix per day or longer. To increase battery life, collars can also be programmed to turn off and back on again at defined periods (e.g. 12 h on, 12 h off). This is known as the duty cycle, and can be valuable at times when the animal's position is not required (e.g. at night). The duty cycle is generally activated when the collar is started, rather than being programmed to a set time of the day. Thus the timing of collar deployment must either fit in with this schedule, or collars need to be started at the appropriate time before animals are captured.

Almanac update

To estimate its position and time of day, each GPS collar receiver needs to acquire navigation messages from GPS satellites at or near the location where it will be deployed. The navigation message includes both satellite ephemeris (a correction term applied to the orbit of a GPS satellite) and almanac data (parameters used to determine the approximate position of all satellites) (Tomkiewicz *et al*. 2010). Thus, before collars are fitted to animals, they should be stationed in an open area at, or near, the study site and left turned on for a short period (~30 min) for the navigation message to be received and the almanac to be updated. This will ensure that subsequent fixes are acquired in the fastest possible time (within ~30 s) once deployed, compared with 12–13 min if a random search for satellites needs to be initiated (Rodgers *et al*. 1996; Tomkiewicz *et al*. 2010). Fixes taken >4 h apart may need to acquire a new almanac (Rodgers *et al*. 1996), and time to fix will be slower for collars that are in a 'cold start' condition, compared with a 'warm start' or 'hot start' (Tomkiewicz *et al*. 2010). The requirement for a valid almanac may be less of an issue with newer, more sensitive GPS devices.

Horizontal dilution of precision

The horizontal dilution of precision (HDOP) is a measure of the precision of a location that takes into account satellite geometry. Other measures of dilution of precision are vertical (VDOP), 3D positional (PDOP), and time (TDOP). When data are downloaded from GPS collars, an HDOP value is usually recorded with each location as a unitless number up to 99. An HDOP value close to 1.0 indicates that the satellites used to determine the collar location were favourably arranged (satellites are further apart and have wider angular separation) for

Appendix 2. (*Continued*)

the GPS hardware; these fixes are generally the most accurate (usually 2–4 m error on-ground). Conversely, a high HDOP value indicates that the satellite arrangement was less favourable; these fixes are generally, but not always, less accurate (D'Eon and Delparte 2005; Recio *et al*. 2011).

In addition to HDOP, some manufacturers quote a circular error probability (CEP) estimate, which indicates the percentage of fixes that will be obtained within a specific range of on-ground accuracy. For example, CEP 80% for GPS collars with 10-m accuracy indicates that 80% of fixes will be within 10 m, but, conversely, 20% of positions will be outside this range.

GPS is designed to work best by running continuously and averaging as many positions as possible to achieve a statistically accurate position. Unfortunately, its high power requirements make this very difficult for wildlife tracking where a small battery is used to keep the weight down and battery life is critical to achieve long deployment times. Wildlife GPS engines are usually required to turn on, take a fix as quickly as possible with little or no time for averaging, then turn off again. Therefore, GPS positions collected by wildlife telemetry GPS engines can reasonably be expected to be less accurate than 'regular' GPS positions.

Timed-release unit

Several remote release mechanisms have been developed to aid retrieval of GPS collars. Timed-release units are programmed to activate on a set time and date, while others can be programmed to drop off when the battery system nears exhaustion (Rodgers 2001). In some devices, the release mechanism is triggered by the researcher using a radio signal when in range of the animal (Rodgers 2001). External timed-release mechanisms are self-contained units that are incorporated into the attachment point of the collar. They have separate programming hardware and software, and will need to be activated, along with the GPS unit and VHF transmitter, when the collar is deployed.

Collar hardware, software and firmware

Knowing the difference between hardware, software and firmware helps to identify any problems experienced with GPS collars and communicate them back to the manufacturer. Hardware refers to all the physical electronic equipment including the GPS, battery, antenna, download interface and cables. Software is the term for the programs that run on the hardware. This is the program needed for the collar and computer to communicate. Firmware is software that is placed inside the hardware – it is the internal collar software – that governs the on-board programming, such as the duty cycle, fix schedule, and time-out period.