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Wildlife tracking technology options and cost considerations

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Abstract

Context. Continued demand for long-distance remote wildlife tracking has resulted in the development of a variety of satellite tracking technologies. Choosing an appropriate satellite tracking system for a project involves financial, technical and operational tradeoffs associated with different systems.

Aim. The aim of the present research was to assess the technology options and associated costs to help wildlife researchers select the best tracking solution for their needs.

Methods. A technology-choice decision guide was developed to assist wildlife scientists select an optimal tracking technology. We undertook four satellite tracking case studies involving avian, aquatic and terrestrial species living in diverse environments around the world and use these case studies to validate and test the technology-choice decision guide and to calculate the cost effectiveness of alternative tracking methods. Technologies used in marine tracking were out of the scope of the present paper.

Key results. Choosing the tracking method best suited for a project requires (1) clearly specifying the data required to meet project objectives, (2) understanding the constraints imposed by the study species and its environment, and (3) calculating the net cost per datum of the various tracking methods available.

Key conclusions. We suggest that, in most circumstances, global positioning system (GPS) tracking is preferable to other options. However, where weight and environmental limitations prevent the use of GPS, alternatives such as Argos satellite Doppler-based positions (Argos) or very high frequency (VHF) can function adequately.

Implications. The present paper provides simplified criteria for selecting the best wildlife satellite tracking technology for different situations.

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Introduction

The development of biotelemetry began in the early 1960s with the advent of very high frequency (VHF) tracking (Cochran and Lord Rexford 1963). Satellite tracking followed in the early 1970s when, for example, Craighead *et al*. (1971) tracked a single elk (*Cervus canadensis*) using a transmitter linked to the interrogation, recording and location System (IRLS) on board the NIMBUS 3 satellite that was originally designed to monitor geophysical, oceanographic and meteorological data. Since then, satellite transmitters have made use of the Argos (C.L.S, Ramonville Saint-Agne, France) satellite system. Animal tracking using global positioning system (GPS) technology began its development in the early 1990s in response to researchers' need to collect fine-scale location data for far-ranging species (Rodgers *et al*. 1996).

Wildlife biologists are now using satellite technology to gather animal-behaviour data that a short while ago were considered impossible to obtain (Cohn 1999; Cargnelutti *et al*. 2007). These data, combined with others such as meteorological or geographical information system (GIS) layers, enable biogeographic hypotheses to be tested and provide important information to improve wildlife and ecosystem management decision making. This synergy between science and technology is fostering the emerging discipline of movement ecology (Cagnacci *et al*. 2010).

Ecological studies using satellite tracking technology have evolved from describing the movements of only a few individuals to more complex analysis and problem solving (Webster *et al*. 2002). Wildlife researchers now have the ability to understand more about the behaviour of a wide range of diverse endangered species by answering an increasing number of ecological questions. Hebblewhite and Haydon (2010) identified several ecological or conservation objectives that are addressed using satellite tracking technology. These include but are not limited to behaviour, migration, home range, human–wildlife conflict and climate change.

Continued scientific and commercial demand for long-distance remote tracking has resulted in the development of a variety of satellite tracking technologies. Although spoilt for choice, it is important to understand the strengths and weaknesses of the different options to ensure the selected system matches the ecological or conservation research objectives and the animal being tracked (Bradshaw *et al*. 2007). Frair *et al*. (2010) suggested that previous knowledge on species movement behaviour and precision of GPS locations is important when designing satellite tracking studies.

In the final analysis, the choice of which tracking system to use is a function of functionality and cost. Because satellite tracking technology is expensive to purchase, deploy and monitor (Mourao and Medri 2002; Lindberg and Walker 2007), and budgets frequently constrain the technical tools available to conservation researchers, understanding and considering all the associated costs is also important (Franco *et al*. 2007). In the current paper we present (1) guidelines for choosing the best wildlife satellite tracking technology, (2) assessment and validation of these guidelines on the basis of four case studies and (3) assessment of the cost of each technology.

Materials and methods

Descriptions of location-acquisition and data-download methods used for satellite tracking of wildlife are presented in Table 1. Location acquisition refers to the method used to calculate the position (longitude and latitude). Four location-acquisition methods are presented, two satellite and two non-satellite methods. Whereas the main focus of the present paper is satellite tracking, other non-satellite methods are presented. GPS, Argos satellite Doppler-based positions (Argos) and VHF are commonly used location-acquisition methods, whereas light-based geolocation methods are less common. The choice of location-acquisition method will affect both location accuracy and the frequency of collection, whereas data download refers to the methods used to transfer locations and biological data from the tracking device to the researcher. The data-download method influences the regularity of data transmissions, data-transfer method (satellite or non-satellite) and data format. Three of the four location-acquisition methods (Argos, VHF and geolocation) are restricted to a single data-download method, whereas GPS has several data-download options. It should be noted that geolocation data can be downloaded using satellite technology as in marine animals (pop-up archival tags, in combination with Argos), whereas marine tracking is beyond the scope of the present study.

Choosing the tracking method best suited for a project requires (1) clearly specifying the data required to meet project

Table 1. Description of wildlife tracking methods used in the study

Method	Description
Location-acquisition method	
Argos satellite Doppler-based positions (Argos) (satellite)	A platform transmitter terminal (PTT) transmits a pulse detected by Argos polar-orbiting satellites located 800 km above the earth. The satellite passes over the PTT and has ~10 min to receive the frequency data (Doppler effect) and time stamps required. These data are then downlinked and processed at the Argos processing centres and locations calculated. The accuracy of each location point is assessed and assigned one of several location classes (LC). The standard deviation of positional error in latitudinal and longitudinal axes is claimed to be 150 m for LC 3, 350 m for LC 2, 1000 m for LC 1 and >1000 m for LC 0 (Argos user manual, www.argos-system.org/manual/). When three or fewer messages are received by the satellite, the accuracy levels are LC A and B (no estimation accuracy) or LC Z (invalid location). The location is transferred to the researcher using the Argos system.
Global positioning system (GPS) (satellite)	GPS tracking devices receive transmissions from a constellation of ~24 satellites located at 20 000 km above the earth (NAVSTAR). When four or more satellites are in view, GPS provides a location accuracy of <30 m (Tomkiewicz *et al*. 2010). The location is then transferred to the researcher by using one of the data-download methods described below.
Very high frequency (VHF) (non-satellite)	VHF transmitters emit a radio-frequency signal. These signals are located by a researcher by using an antenna and receiver from a plane, a vehicle or on foot. Signals can also be acquired using an automatic VHF tower. The location of the animal is calculated manually when the researcher triangulates multiple bearings or visually sights the animal or automatically using a VHF tower. This method provides a variable accuracy dependent on local conditions, instruments used and the skill of the operators to acquire locations, Precision of 200–600 m has been reported for locations of VHF devices acquired via triangulation and homing (Zimmerman and Powell 1995).
Light-level geolocation (non-satellite)	An archival tag is capable of storing data on light-intensity levels (sunrise and sunset times) and measuring the current light levels. A comparison of the two is used for location calculation. The locations are obtained by retrieving the archival tag and downloading the data manually. This method provides a location accuracy of 34–1043 m (Phillips *et al*. 2004).
Data-download method	
GPS/Argos	GPS is used for location acquisition and the Argos satellite system for remote data download.
GPS/Iridium	GPS is used for location acquisition and the Iridium satellite system for remote data download.
GPS/Globalstar	GPS is used for location acquisition and the Globalstar satellite system for remote data download.
GPS/geostationary (GEO)	GPS is used for location acquisition and a geostationary satellite system for remote data download.
GPS/global system for mobile communications (GSM)	GPS is used for location acquisition and a cellular network for remote data download.
GPS/store on board (SOB), VHF or ultra-high frequency (UHF)	GPS is used for location acquisition, storing the locations on the tracking device. A VHF or UHF receiver is used by a researcher to download the data manually in the field.
GPS/SOB drop-off	GPS is used for location acquisition, storing the locations on the tracking device. The data are then downloaded when the collar drops off at a pre-set time for manual retrieval in the field.
GPS/SOB recapture	GPS is used for location acquisition, storing the locations on the tracking device. The data are downloaded upon recapture of the animal and retrieval of the transmitter manually in the field.

objectives, (2) understanding the constraints imposed by the study species and its environment and (3) calculating the net cost per datum of the various tracking methods available. On the basis of these criteria, the present paper develops a technology-choice decision guide to assist wildlife scientists in selecting an optimal tracking technology.

We undertook four satellite-tracking case studies involving avian, aquatic and terrestrial species living in diverse environments of the world, including the following: three African elephants (*Loxodonta africana*), Kruger National Park, South Africa (Thomas *et al*. 2008; Thomas *et al*. 2011); five New Zealand bush falcons (*Falco novaeseelandiae*), central North Island, New Zealand (Thomas *et al*. 2010*c*); one estuarine crocodile (*Crocodylus porosus*), Darwin, Australia (Thomas *et al*. 2010*a*) and; three northern royal albatrosses (*Diomedea sanfordi*), Taiaroa Head, New Zealand (Thomas *et al*. 2010*b*). We use these case studies to validate and test the technology-choice decision guide and to calculate the cost effectiveness of alternative tracking methods.

Results

Technology

When comparing satellite tracking technologies, researchers are confronted by a plethora of complex information that can be overwhelming. We developed a tracking technology-choice decision guide to assist researchers (Fig. 1). The guide ultimately leads to the selection of one of three more commonly used location-acquisition methods, GPS, Argos or VHF. Ignoring cost considerations, the guide acknowledges GPS as the method of choice, except when constrained by the animal or its environment. This is because it can acquire accurate locations in rapid succession (Witt *et al*. 2010). The guide also considers the technical aspects of each location-acquisition method. The choice of location-acquisition method dictates the data-download options. To further assist wildlife researchers with decision making, a comparison between the commonly used data-download methods is presented in Table 2.

Tracking devices are powered by batteries that can be recharged with solar panels to extend the transmitter life or increase the regularity of locations. A table to assist the researcher in deciding between solar and rechargeable or a non-rechargeable battery is presented in Fig. 2.

The African elephant study (Table 3) was designed to provide daily locations for 5 years so as to trace movement between two adjacent wildlife parks. The GPS/geostationary (GPS/GEO) technology performed well for our purposes and we would choose it again on the basis of the guide in Fig. 1. However, because of the limited capacity of the built-in battery and the extended length of the project, we were limited to acquiring a single daily location, thereby precluding any analysis of within-day movements. A solar/rechargeable battery would be ideal but current solar designs would likely not withstand the rigors associated with elephant behaviour and habitat.

For our study of New Zealand falcons (Table 3), we required locations over a 3-year period within a plantation forest. Adult and juvenile falcons weigh between 250 and 600 g, so we chose Argos. The solar panel-powered devices performed well, despite the densely forested research area. Had the unit been light enough, GPS would have been the preferred technology.

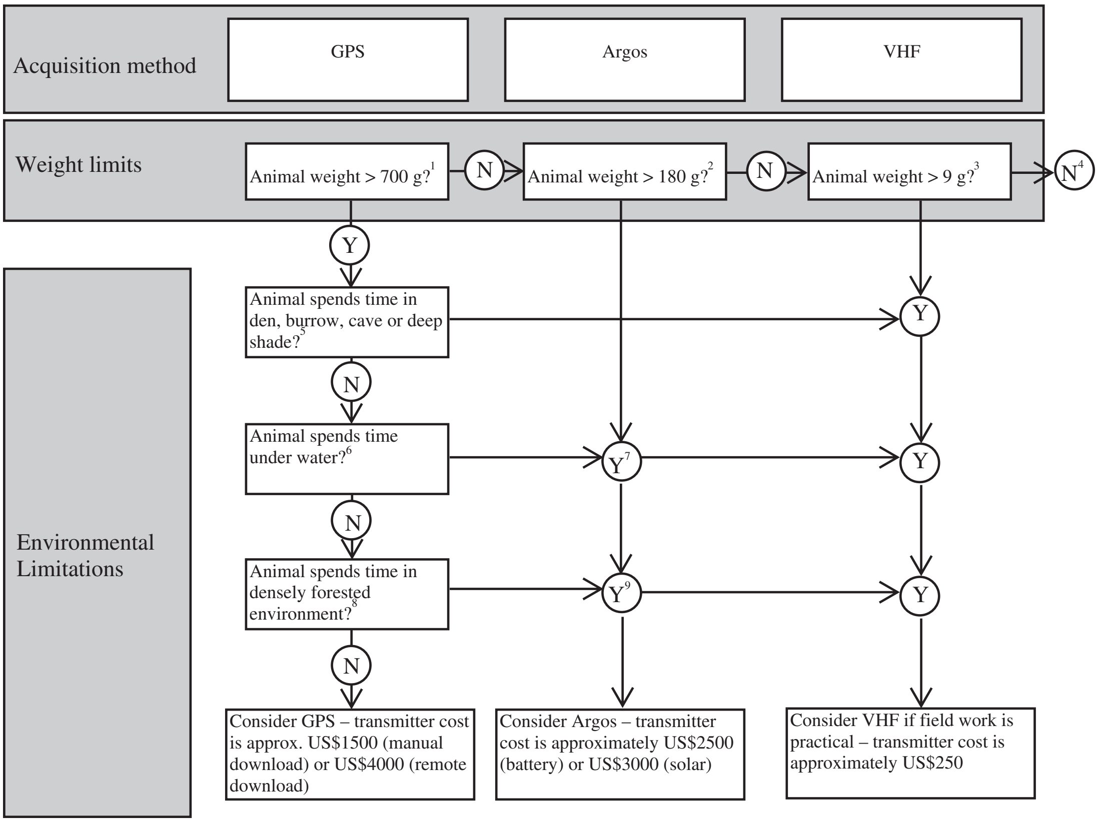
The objective of the estuarine crocodile study (Table 3) was to track movement within a riverine environment for at least 1 year. We used Argos, which was consistent with the technology used successfully to track crocodiles by researchers in Queensland (Read *et al*. 2007).However, in hindsight and on the basis of the guide in Fig. 1, the GPS location-acquisition technology would have been the preferred technology. This crocodile was large enough to have carried the heavier GPS transmitters and the environment was conducive to successful transmissions. The transmitter was placed on the back of the crocodile’s neck, which generally remains above the water. Although solar charging the batteries would have been ideal to extend the life of the study, the aggressive nature of this species, coupled with the extremely harsh environment in which they live, made this option unviable.

In another study, we tracked the migration route of juvenile northern royal albatrosses from fledging through their first year at sea (Table 3). The solar-charged transmitter provided four GPS locations per day. The project was successful and the tracking devices with the Argos data-download option functioned extremely well. The albatrosses were big enough to carry a heavier transmitter with a larger solar array which would have provided more positions per day, giving more detail of movements throughout the day, but our decision was to minimise the weight wherever possible.

Costs

We found that the total cost of tracking each of our study species for 1 year was similar, ranging between US\$7000 and US\$9000, depending on which satellite tracking technology we used (Table 3). However, the cost per data point fluctuated widely, with the high number of locations in the albatross case study translating to the lowest cost per data point (US\$5.00). By comparison, this was 25% of the cost per data point of the GPS/GEO technology used on the African elephant and 10% of that for the Argos tracking devices used on crocodiles and falcons. Longer-term studies can reduce the tracking-device costs further. The New Zealand falcon was tracked for 3 years, reducing the cost per data point from \$53 in the first year to \$38 in the third year. The African elephant was tracked for 5 years and the cost per data point declined from \$25 after the first year to \$12 by Year 5.

One year of data costs from each of our studies was compared with cost estimates of alternative tracking methods using the same number of locations (Table 4). We found Argos technology to be the most cost effective option for tracking New Zealand falcons and the estuarine crocodile over 1 year, followed by GPS/Argos, whereas VHF and GPS/VHF were the least effective options. GPS/global system for mobile communications (GSM) was identified as the most cost effective option for tracking the elephant, followed by the GPS/GEO, GPS/Argos and Argos options. Geolocation tracking technology was the most cost effective option for tracking the northern royal albatross, followed by GPS/Argos and Argos. In all our case studies, the use of VHF as either the location-acquisition or data-download method gave a cost per data point at least three times greater than



Technical requirements[10]

Required location accuracy?[11]	High	Low	Medium
Number of locations required	High	Medium	Low
Accuracy of speed required?[12]	High	Low	Low
Altitude required?[13]	Yes	No	No
24 hour coverage required?	High	Medium	Low
Impact of human presence to animal?[14]	Low	Low	High
On-board location storage?	Yes	No	No
Number of download options?	High	Low	Low

GPS data download options and cost

Options[15]	Type	Frequency	Cost
Argos, Globalstar, Iridium, UHF or VHF	Satellite, satellite, satellite, non-satellite, non-satellite	Daily	Decreasing
Argos, Globalstar, Iridium, UHF or VHF	Satellite, satellite, satellite, non-satellite, non-satellite	Weekly	
Argos, Globalstar, Iridium, UHF or VHF	Satellite, satellite, satellite, non-satellite, non-satellite	Monthly	
SOB drop off	Non-satellite	No recovery	
SOB recapture	Non-satellite	On recovery	
GSM or GEO	Satellite	Daily, weekly, monthly	

Argos data download options and cost

Options	Type	Frequency	Cost
Argos	Satellite	Daily	Decreasing
Argos	Satellite	Weekly	
Argos	Satellite	Monthly	

The data must be acquired using either a manual receiver or automatic VHF tower that of alternative options. Despite the low initial cost of VHF transmitters, this method also requires high labour costs to support a tracker in the field.

Not all studies require a large sample of animal-location points. For studies that require fewer than 15 locations, VHF is usually the most cost-effective option because of low fixed costs, followed by Argos. For studies requiring a larger sample, GPS is the most cost-effective tracking method. For our elephant study, GPS/GSM was the most cost-effective option; however, Argos, GPS/GEO and GPS/Argos were only marginally more expensive. For tracking the albatross, geolocation technology was the most cost-effective option. After 8 months, the GPS/Argos option becomes more cost-effective than Argos.

Discussion

Technology

Free-ranging animals can be tough on satellite tracking transmitters and an understanding of a study animal's behaviour and habitat can influence technology choices. Although transmitter success is never guaranteed, failure rates can be reduced with early consideration of the exogenous variables.

Although GPS may be a preferred choice of a tracking system, there are some exceptions. When field work is confined to a small area or where only a low number of locations are required, then VHF may be a better option. This is due to low transmitter costs, easy site accessibility and reduced operational costs. Other potential limitations to using GPS include their relatively heavy weight and the potential effect on fix rate and signal precision from canopy closure and topographic complexity (Frair *et al*. 2010). However, newer GPS receivers have an improved sensitivity which may be starting to penetrate dense forest.

Sometimes the benefits of using a GPS are outweighed by an animal's physiology or environmental limitations. In these cases, we suggest that it may be necessary to compromise on the objectives, or that tracking may not be an appropriate use of conservation funding. For example, the researcher may require a very high location accuracy, but the guide may suggest the use of Argos because of the weight of the animal. A compromise may involve no longer expecting high-accuracy locations for fine-scale analysis, which may be acceptable for a long-distance migrant. Or if the species can be easily located, the use of a GPS tracking device with a non-remote download option may be possible, thus reducing the weight of the GPS tracking device. Another option may be to select a larger member of the species such as an adult to enable the use of GPS. Argos transmitters are generally smaller and lighter than GPS, but with a lower accuracy. A limitation of the Argos technology is the evidence of reduced satellite performance in southern Europe and central Asia (Dubinin *et al*. 2010). Despite this, Argos transmitters are especially effective when tracking avian species and for transmitting data related to marine species (Hays *et al*. 2001). VHF has the least functionality of all options and is the most disruptive to the animal because of human presence (Cooke *et al*. 2004). However, it is the lightest and smallest tracking device of the three and is still used to track very small animals or those with a small home range (Naef-Daenzer *et al*. 2005). This low weight, however, is offset by variable accuracy because of the dependence on both instruments and the skill of the operators to acquire locations.

Fig. 1. Technology-choice decision guide. See text and Table 1 for explanation of tracking methods. 1, The weight of a transmitter should be no more than 3–5% of the bodyweight of the animal (Kenward 2001). The smallest GPS tracking device weighs 22 g; therefore, on the basis of an estimate of 3%, the animal must be at least approximately 700 g to wear one. Note: the 22-g GPS tracking device refers to a unit with satellite download capability (as per our case studies). However, smaller GPS tracking devices are available, weighing 5 g (recapture required for data download) and 15 g (download via Bluetooth, but only have a 50–100-m range). If these technologies are viable, the weight restrictions should be adjusted accordingly. 2, The smallest Argos transmitter (PTT) weighs 5 g; therefore, the animal must be at least approximately 170 g to wear one (3% of bodyweight). 3, The smallest VHF transmitter weighs 0.26 g; therefore, the animal must be at least approximately 9 g to wear one (3% of bodyweight). 4, Animals weighing <9 g are currently too small to track. 5, Neither GPS or Argos transmissions can penetrate solid surfaces and could waste valuable battery power trying. Therefore, an estimation of the period of time spent in these black-out areas should be made. It is possible for a duty cycle to be set in an attempt to target likely times outside of these areas. VHF is still not guaranteed but may provide more successful transmissions in these situations. 6, Neither GPS nor Argos transmissions can penetrate water. However, it may be that the research animal does not spend much time under water or the transmitter can be placed on the animal where it predominantly stays above water. An example of this is the estuarine crocodile where the transmitter was placed on the back of the neck, an area on the crocodile which stays above the water for much of the time. 7, There are transmitters (pop-up archival) used in marine studies that utilise light-levels to calculate the location, then automatically release and transmit their data via Argos once above water. These kinds of transmitters can also calculate under-water dive depths. VHF is still not guaranteed but may provide more successful transmissions under water. 8, GPS transmissions cannot always penetrate densely forested environments and there is a known effect on fix rate and signal precision from canopy closure and topographic complexity (Frair *et al*. 2010). However, newer GPS receivers have an improved sensitivity that may penetrate dense forest. 9, Argos and VHF tracking devices are still not guaranteed but may provide more successful transmissions in a densely forested environment. 10, These requirements should be based on research objectives. 11, Where a balance between weight and power requirements is necessary (small animals), it is possible that you may not require the higher accuracy of the heavier GPS tracking devices, but rather your objectives are such that the lower accuracy from the smaller Argos will be sufficient. A good understanding of your project objectives should clarify this. For example, for small-scale habitat analysis of 1–10 km, high accuracy is required. However, if only a large-scale understanding of the home range is required, then a lower accuracy is sufficient. Although it would be prudent to always choose a high accuracy where possible, often, owing to weight restrictions or cost, this is not possible. As well, when the animals' weight is borderline between the use of either GPS or Argos tracking devices (~700 g), if high accuracy is not required, then any undue stress on the animal cause by a heavy transmitter should be avoided. 12, GPS tracking devices are capable of calculating speed at the time of the location with a high level of accuracy. Speed and can also be calculated from Argos and VHF devices by using point to point distance divided by time; however, the location error afforded by these technologies affects this. 13, GPS tracking devices are capable of calculating the altitude at the time of the location. 14, This disruption refers to the level of field work required. 15, These are all options for downloading the data from GPS tracking devices. In contrast to Argos/UHF or VHF, where an increase in download frequency increases cost, there is no change in cost for using the GSM or GEO option, because a monthly fee is charged for these, regardless of the number of downloads.

Table 2. Features of data-download systems for global positioning system (GPS) wildlife-positioning tracking devices
See Table 1 for explanation of data-download systems

Feature	Argos	Iridium	Globalstar	GSM	GEO	VHF	SOB/VHF or UHF	SOB/ recapture	SOB/ drop-off
Remote data download	Yes	Yes	Yes	Yes	Yes	No	No	No	No
Automatic variable download frequency (e.g. daily, weekly or monthly)	Yes	Yes	Yes	Yes	Yes	No	No	No	No
Data download only possible in-field	No	No	No	No	No	Yes	Yes	No	No
Potential time-lag for data download[A]	Low	Low	Low	Low	Low	Moderate	Moderate	High	High
Disruption to animal	Low	Low	Low	Low	Low	High	High	Moderate	Low
Cellular coverage required	No	No	No	Yes	No	No	No	No	No
Geostationary satellite coverage required	No	No	No	No	Yes	No	No	No	No
Antenna and receiver required	No	No	No	No	No	Yes	Yes	Yes[B]	Yes[A]
2-way capability to modify transmitter settings (e.g. duty cycle)	No	Yes	No	No	Yes	No	No	No	No
Ease of animal location for sighting or if recapture required	Moderate[C]	High[D]	Moderate[E]	Moderate[F]	High[G]	Moderate[H]	Moderate[I]	Moderate[H]	Moderate[G]

[A]The time lag is the time between transmitter attachment and data download. Researchers using VHF and UHF methods often sight or capture animals for other reasons and can download data during those times.
[B]Required only for relocating the animal and/or the collar.
[C]Often supplied with a VHF transmitter for locating the animal in the field but the battery for this may not last as long as the GPS or Argos transmission battery. However, depending on the regularity of the data download, it may be possible to locate the animal on the basis of the latest GPS location.
[D]Often supplied with a VHF transmitter for locating the animal in the field but the battery for this may not last as long as the Iridium transmission battery. However, depending on the regularity of the data download, it may be possible to locate the animal on the basis of the latest GPS location.
[E]Often supplied with a VHF transmitter for locating the animal in the field but the battery for this may not last as long as the GPS or Globalstar transmission battery. However, depending on the regularity of the data download, it may be possible to locate the animal on the basis of the latest GPS location.
[F]Often supplied with a VHF transmitter for locating the animal in the field but the battery for this may not last as long as the GPS or cellular transmission battery. However, depending on the regularity of the data download, it may be possible to locate the animal on the basis of the latest GPS location.
[G]Often supplied with a VHF transmitter for locating the animal in the field but the battery for this may not last as long as the GPS or geostationary transmission battery. However, it is possible to 'poll' these transmitters that can supply a GPS location within minutes. It is necessary to either have a networked laptop in the field or to have the location sent to a mobile phone for this to be effective.
[H]Location in the field, using either a VHF receiver or by visual sighting, is required to download the data.
[I]Location in the field, using a VHF or UHF receiver used to download the data, is required.

New developments over the past few years have seen the testing and use of new wildlife satellite tracking options not available at the time of our case studies. 'Fastloc' is a type of GPS unit that does not require GPS ephemeris or almanac information to operate and, consequently, does not have the long cold and warm start times of traditional GPS receivers (Tomkiewicz *et al*. 2010). Therefore, it allows animal location data to be obtained almost instantaneously, for example, during a brief ocean surfacing period. It has been designed for use on species within the marine environment; however, it is now being used on terrestrial and avian species.

Two satellite systems, Globalstar and Iridium, have recently been incorporated with wildlife GPS tracking devices as remote data-download options, providing an alternative to Argos (Tomkiewicz *et al*. 2010). Only a few companies build tracking devices with these options, namely, Northstar Science and Technology, LLC, Virginia, USA,, and Lotek Wireless Inc., Ontario, Canada, for Globalstar, and Advance Telemetry Systems, Minnesota, USA, and Lotek for Iridium. However, whereas the smallest GPS/Argos tracking device weighs 22 g, the smallest GPS/Globalstar and GPS/Iridium devices range between 600 and 800 g, making them suitable for large terrestrial species only. Being able to remotely change the settings of the tracking device (2-way communication) is currently available with Iridium and Argos; however, this functionality makes these devices heavier.

Schwartz *et al*. (2009) trialled a new data-download method whereby GPS locations are downloaded with a new system of data transmission that uses spread-spectrum (SS) technology utilising the 902–928-MHz bandwith range. This technology takes advantage of spreading information across many channels, potentially providing an improvement over narrow-band frequency methods such as VHF or UHF and other tracking systems such as cellular and satellite (Argos). Juang *et al*. (2002) trialled a wildlife GPS tracking unit that downloads its data via a wireless-sensor network using

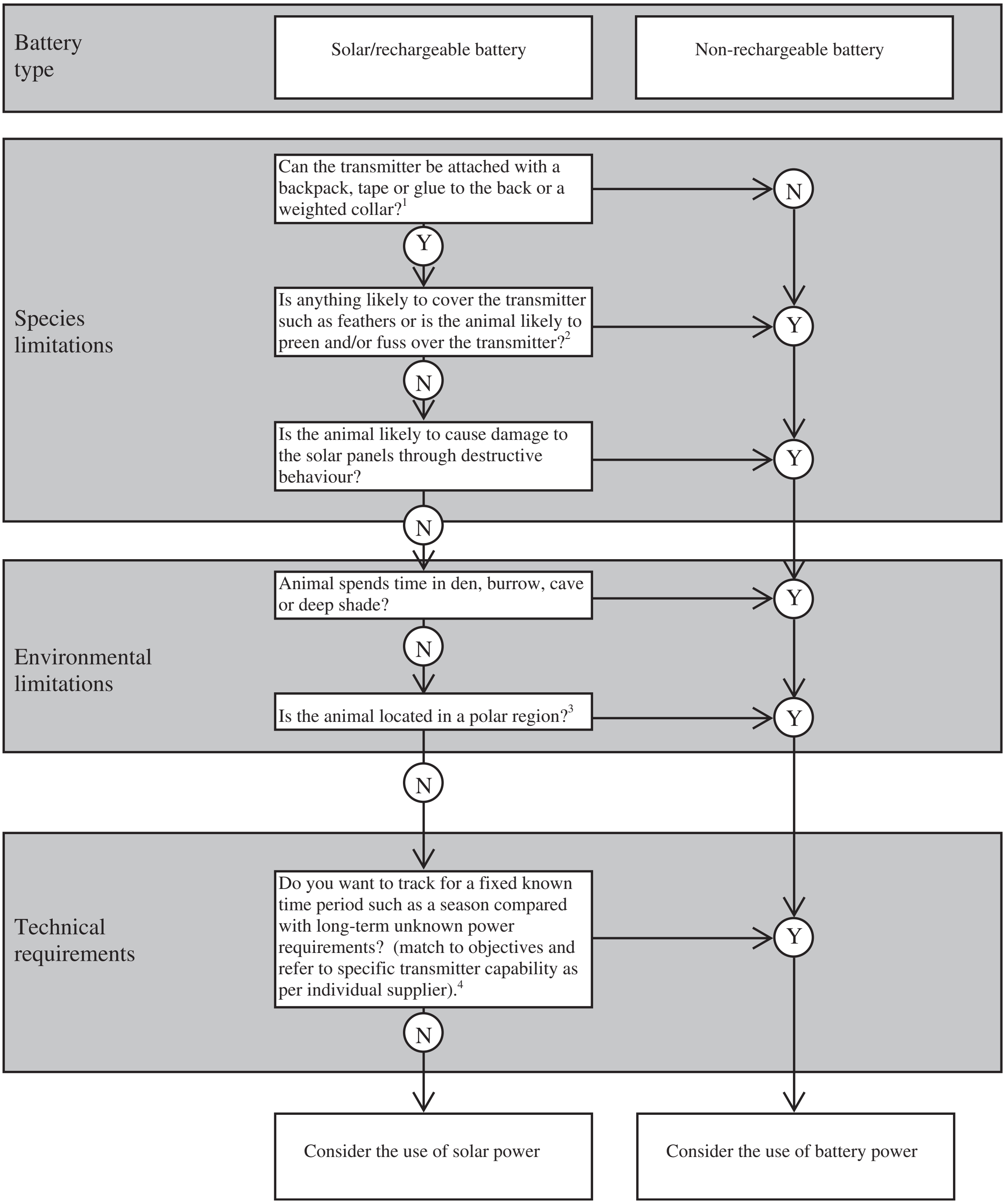


Fig. 2. Technology-choice decision guide for solar and rechargeable or non-rechargeable battery. 1, The solar panels on a transmitter need to be held upright at all times during attachment, for a maximum solar charge. 2, Solar panels need to remain clear of obstruction at all times during attachment, for a maximum solar charge. 3, Solar panels are difficult to charge in the polar regions because of the low angle of the sun. 4, Because of the risks involved in solar-panel obstruction during attachment, where possible, battery should be used. If you have only short-term tracking requirements or longer-term (generally a year) requirements with a duty cycle, a battery transmitter might be sufficient. However, for long-term studies (between 1–3 years), and where the risk of obstruction is minimal, solar transmitters could be suitable.

'peer-to-peer' networking techniques without using a cellular phone service or other widely available telecommunications support.

It should be noted that as transmitter weights decline, the species weight restrictions in Fig. 1 should be adjusted accordingly. At the time of the present research, the smallest

Table 3. Total cost and cost per data point of wildlife satellite tracking case studies (US$)

The costs used in this table were calculated as at the time of each case study between 2006 and 2009. See Table 1 for explanation of tracking devices

Species	Location	Tracking device	Total cost per animal (US$)	Cost per data point (US$)	No of data points	Accuracy (m)	Duty cycle (h on/off)	Download frequency
Estuarine crocodile (*Crocodylus porosus*)	Northern Territory, Australia	Argos battery (300 g)	8545[A]	51	166	<150	24/96	Every 6th day
New Zealand falcon (*Falco novaeseelandiae*)	Central North Island, New Zealand	Argos solar (18 g)	8260[B]	55	150	<150	10/48	Every 3rd day
African elephant (*Loxodonta africana*)	Kruger National Park, South Africa	GPS/GEO (12.5 kg)[C]	9000[D]	25	365	<20	1 per day	Daily
Northern royal albatross (*Diomedea sanfordi*)	Taiaroa Head, New Zealand	GPS/Argos (30 g)	7000[E]	5	1460	<20	4 per day	Every 6th day

[A]Estuarine crocodile total cost includes transmitter US$2200, capture/boat staff US$1170, attachment materials US$75, Argos tracking US$1600 and statistical analysis US$3500. The manufacturer of this tracking device was Sirtrack Wildlife Tracking Solutions; Havelock North, New Zealand.

[B]New Zealand falcon total cost includes transmitter US$3150, capture and attachment US$350, Argos tracking US$1260 and statistical analysis US$3500. The manufacturer of this tracking device was Microwave Telemetry Inc.; Columbia, Maryland, USA.

[C]Half of the weight of this collar (6.5 kg) consisted of a lead weight designed to keep the GPS receiver upright.

[D]African elephant total cost includes transmitter US$3000, capture and attachment US$4000, satellite time US$500 and statistical analysis US$1500. The manufacturer of this tracking device was Africa Wildlife Tracking; Pretoria, South Africa.

[E]Northern royal albatross total cost includes transmitter US$4000, capture and attachment US$900, satellite time US$600 and statistical analysis US$1500. The manufacturer of this tracking device was Microwave Telemetry Inc.; Columbia, Maryland, USA.

Argos PTT satellite transmitter available weighed 5 g and the smallest GPS transmitter available with satellite data-downloading capability weighed 22 g, limiting the weight of tracked animals to 170 g. They will continue to reduce in size as technology improves, increasing accuracy, location-acquisition and data-download frequency, while also reducing in price. There are now transmitters as small as 2.5 g; however, at this stage, there is very limited storage capacity and no remote download. A 15-g GPS transmitter is also now available; however, it utilises Bluetooth technology for the remote download of the data, limiting its range to 350 m.

Costs

Wildlife tracking technology costs vary considerably. Whereas the present paper discusses the cost per animal and the cost per location, the total cost of a tracking project is predominantly influenced by the number of animals to be tracked, dependant on the project objectives. Some studies have suggested a minimum sample size of 30 as optimal and that the number of individuals, not the number of locations per individual, is important for making statistical inference at a population level (Aebischer *et al.* 1993; Hebblewhite and Haydon 2010).

Tracking-device costs can be reduced when more than one animal is being tracked. With larger sample sizes, the highest cost savings would be from VHF because the marginal costs of field work decline as study animal numbers rise (as long as animals are in the same general area). When using Argos or GPS, the cost of tracking additional animals would not significantly reduce the cost per animal. This does not mean that VHF tracking is always cheaper or even feasible when more animals are being tracked, just that cost savings may accrue.

The total cost of VHF tracking studies can be difficult to calculate because in addition to the fixed cost of the tracking devices, the field-work costs required for calculating the location can be variable and change with each project

Table 4. Cost per data point of wildlife satellite tracking case studies

The calculations are based on tracking the animal for 1 year and as near as possible obtaining the same number of data points and using the same data-download frequency. The Iridium and Globalstar data-download options are not included in the table because they were not available at the time of these case studies. Bold values indicate the technologies used in the case study. See Table 1 for explanation of tracking methods

Species	Cost per data point by technology option (US$)							
	Argos	GPS/Argos	GPS/GEO	GPS/VHF	GPS/UHF	GPS/GSM	VHF	Geolocation
Estuarine crocodile (*Crocodylus porosus*)	**51**	56	n.a.	142	n.a.	n.a.	126	n.a.
New Zealand falcon (*Falco novaeseelandiae*)	**53**	55	n.a.	105	n.a.	n.a.	167	n.a.
African elephant (*Loxodonta africana*)	26	26	**25**	n.a.	287	21	4018	n.a.
Northern royal albatross (*Diomedea sanfordi*)	5	**5**	n.a.	n.a.	n.a.	n.a.	n.a.	3

(Girard *et al*. 2006). When using GPS, however, the marginal cost of finding additional location points is effectively nil. For tracking the albatross and elephant, increases in the number of locations would not have resulted in an increase in costs; rather, the number of locations acquired were limited by the battery capacity and storage size. The cost of calculating locations using Argos would generally be between the cost of VHF and GPS methods. Users of the Argos system pay for the 'on' time or time used to calculate positions. Therefore, an increase in the number of locations in the crocodile and falcon studies would have increased the total project costs. Part of this added functionality, in terms of the capability to calculate positions at no extra cost, such as with GPS, is directly realised within the initial transmitter cost. Although GPS tracking devices have no location-acquisition cost, they are the most expensive.

Both Argos and VHF location-acquisition methods use inbuilt download systems. For GPS location acquisitions, however, there are several download options and cost savings may be made here. For research that does not require locations to be downloaded regularly, a manual download method such as VHF, GPS/store on board (SOB) drop-off or recapture is likely the most cost effective. It should be noted, however, that in addition to the risk of data loss associated with irregular downloads, there can be added cost if there is difficulty in locating an animal or its drop-off collar (Lizcano and Cavelier 2004). For research requiring a regular download schedule, a remote method such as GSM, GEO, Argos or more recent systems such as Iridium or Globalstar are suggested. Both our crocodile and falcon studies utilised Argos transmitters and any increase in the data-download frequency would have increased costs. The falcon data were downloaded every third day and the crocodile every sixth day, because of the transmitter's battery charge. It should be noted that although the use of light-based geolocation would have been a cheaper option for tracking the albatross, questionable location accuracy may have required additional analysis (Shaffer *et al*. 2005), thereby increasing total costs. Further, the albatross would have had to be recaptured to download the data. This can be difficult for juveniles who can take 5–8 years to return to their breeding ground.

The geostationary satellite system used to download the data in the elephant study incurred a monthly charge irrespective of the transmission rate. For the elephants, it was possible to remotely reconfigure (2-way) the download schedule, with the only limitation being the life span of the batteries. The albatross GPS data were downloaded every sixth day (using Argos) because the transmitter's memory could store only the past 24 location points (four per day). This limitation can dictate the regularity of data downloads; however, GPS tracking devices with manual data-download options do not have these limitations and are often able to store a higher number of locations on board (Tomkiewicz *et al*. 2010).

The more recent satellite download options of Iridium and Globalstar were not compared directly in Table 4 because they were not available at the time of the present case studies. However, their current costs are likely to make them the cheapest data-download options for GPS data, but their heavier weights still restrict them to very large terrestrial animals only.

In some instances, researchers have reduced costs by manufacturing their own GPS tracking device. Zucco and Mourao (2009) developed GPS harnesses to track pampas deer in Brazil for half the cost of a commercial tracking device. They spent US$2262 to deploy four adapted GPS radio-collars on 19 deer, obtaining 31 596 fixes at 5-min intervals, giving a cost per data point of US$0.07. Mourao and Medri (2002) also developed a GPS tracking device to track a giant anteater (*Myrmecophaga tridactyla*) in Brazil and spent US$490 (including GPS and VHF), obtaining 1373 fixes over 215 h. Limited budgets often force researchers to use alternative materials and adapt tracking devices that are bought off the shelf. However, when costs of researcher-built systems are compared with commercial systems, it is important that the cost of design, build and test is also included by the researcher. Unexpected transmitter failure can cause significant increases to total research costs, not to mention lost time and data. Thus, more expensive systems may be more cost effective overall, as long as they are robust and provide more accurate data.

Conclusions

In the present paper, we have presented guidelines for choosing the best wildlife satellite tracking technology, assessed them on the basis of four case studies and discussed the cost of each technology. It is not intended that the specific details discussed be the focus, but rather the emphasis needs to be on the process and considerations necessary for selecting the most appropriate technology.

GPS technology is generally preferable to other wildlife tracking methods because of its ability to provide more frequent and precise locations (Dodd *et al*. 2007). It also has a higher number of data-download options. However, its limitations include greater size and weight, and reduced performance under forest canopies, under water and underground. Where these limitations prevent the use of GPS, alternatives such as Argos or VHF are usually adequate, notwithstanding their lower accuracy and transmission rates.

GPS technologies can be very cost effective over medium- and long-term studies. Nevertheless, VHF is still the least expensive option for very short-term studies where a small number of locations is needed or when field work is practical and required anyway. However, consideration of the costs and benefits of alternative methods can be complex and should be assessed on a project by project basis.

The present paper is very time sensitive. With new advancements such as GPS 'fastloc', SS technologies, new data-download options, continued weight reductions in satellite technology and increased sensitivity of satellite technology, the decision-making process of how to choose the best technology for a research project will simplify. Costs will also continue to change and affect cost per data point and overall project costs. As the technology becomes more cost effective and accessible, the amount of data on animal movement and behaviour will increase. It will then be the responsibility of the researcher to ensure that the appropriate data analysis is conducted to ensure that important ecological and conservation objectives can be addressed.

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References

Aebischer, N. J., Robertson, P. A., and Kenward, R. E. (1993). Compositional analysis of habitat use from animal radio-tracking data. *Ecology* **74**, 1313–1325. doi:10.2307/1940062

Bradshaw, C. J. A., Sims, D. W., and Hays, G. C. (2007). Measurement error causes scale-dependent threshold erosion of biological signals in animal movement data. *Ecological Applications* **17**, 628–638. doi:10.1890/06-0964

Cagnacci, F., Boitani, L., Powell, R. A., and Boyce, M. S. (2010). Animal ecology meets GPS-based radiotelemetry: a perfect storm of opportunities and challenges. *Philosophical Transactions of the Royal SocIety. B. Biological Sciences* **365**, 2157–2162. doi:10.1098/rstb.2010.0107

Cargnelutti, B., Coulon, A., Hewison, A. J. M., Goulard, M., Angibault, J. M., and Morellet, N. (2007). Testing global positioning system performance for wildlife monitoring using mobile collars and known reference points. *The Journal of Wildlife Management* **71**, 1380–1387. doi:10.2193/2006-257

Cochran, W. W., and Lord Rexford, T. Jr (1963). A radio-tracking system for wild animals. *The Journal of Wildlife Management* **27**, 9–24. doi:10.2307/3797775

Cohn, J. P. (1999). Tracking wildlife: high-tech devices help biologists trace the movements of animals through sky and sea. *Bioscience* **49**, 12–17. doi:10.2307/1313488

Cooke, S. J., Hinch, S. G., Wikelski, M., Andrews, R. D., Kuchel, L. J., Wolcott, T. G., and Butler, P. J. (2004). Biotelemetry: a mechanistic approach to ecology. *Trends in Ecology & Evolution* **19**, 334–343. doi:10.1016/j.tree.2004.04.003

Craighead, J. J., Craighead, F. C. Jr, Varney, J. R., and Cote, C. E. (1971). Satellite monitoring of black bear. *Bioscience* **21**, 1206–1212. doi:10.2307/1296018

Dodd, N. L., Gagnon, J. W., Boe, S., and Schweinsburg, R. E. (2007). Assessment of elk highway permeability by using global positioning system telemetry. *The Journal of Wildlife Management* **71**, 1107–1117. doi:10.2193/2006-106

Dubinin, M., Lushchekina, A., and Radeloff, V. (2010). Performance and accuracy of Argos transmitters for wildlife monitoring in southern Russia. *European Journal of Wildlife Research* **56**, 459–463. doi:10.1007/s10344-009-0354-4

Frair, J. L., Fieberg, J., Hebblewhite, M., Cagnacci, F., DeCesare, N. J., and Pedrotti, L. (2010). Resolving issues of imprecise and habitat-biased locations in ecological analyses using GPS telemetry data. *Philosophical Transactions of the Royal Society. B. Biological Sciences* **365**, 2187–2200. doi:10.1098/rstb.2010.0084

Franco, A. M. A., Palmeirim, J. M., and Sutherland, W. J. (2007). A method for comparing effectiveness of research techniques in conservation and applied ecology. *Biological Conservation* **134**, 96–105. doi:10.1016/j.biocon.2006.08.008

Girard, I., Dussault, C., Ouellet, J.-P., Courtois, R., and Caron, A. (2006). Balancing number of locations with number of individuals in telemetry studies. *The Journal of Wildlife Management* **70**, 1249–1256. doi:10.2193/0022-541X(2006)70[1249:BNOLWN]2.0.CO;2

Hays, G. C., Akesson, S., Godley, B. J., Luschi, P., and Santidrian, P. (2001). The implications of location accuracy for the interpretation of satellite-tracking data. *Animal Behaviour* **61**, 1035–1040. doi:10.1006/anbe.2001.1685

Hebblewhite, M., and Haydon, D. T. (2010). Distinguishing technology from biology: a critical review of the use of GPS telemetry data in ecology. *Philosophical Transactions of the Royal Society. B. Biological Sciences* **365**, 2303–2312. doi:10.1098/rstb.2010.0087

Juang, P., Oki, H., Wang, Y., Martonosi, M., Peh, L., and Rubenstein, D. (2002) Energy efficient computing for wildlife tracking: design tradeoffs and early experiences with ZebraNet. In 'Tenth International Conference on Architectual Support for Programming Languages and Operating Systems (ASPLOS-X), San Jose, CA, 2002'.

Kenward, R. E. (2001) 'A Manual for Wildlife Radio Tagging.' (Academic Press: London.)

Lindberg, M. S., and Walker, J. (2007). Satellite telemetry in avian research and management: sample size considerations. *The Journal of Wildlife Management* **71**, 1002–1009. doi:10.2193/2005-696

Lizcano, D. J., and Cavelier, J. (2004). Using GPS collars to study mountain tapirs (*Tapirus pinchaque*) in the central Andes of Colombia. *The Newsletter of the IUCN/SSC Tapir Specialist Group* **13/2**, 18–23.

Mourao, G., and Medri, I. M. (2002). A new way of using inexpensive large-scale assembled GPS to monitor giant anteaters in short time intervals. *Wildlife Society Bulletin* **30**, 1029–1032.

Naef-Daenzer, B., Fruh, D., Stalder, M., Wetli, P., and Weise, E. (2005). Miniaturization (0.2 g) and evaluation of attachment techniques of telemetry transmitters. *The Journal of Experimental Biology* **208**(21), 4063–4068. doi:10.1242/jeb.01870

Phillips, R. A., Silk, J. R. D., Croxall, J. P., Afanasyev, V., and Briggs, D. R. (2004). Accuracy of geolocation estimates for flying seabirds. *Marine Ecology Progress Series* **266**, 265–272. doi:10.3354/meps266265

Read, M. A., Grigg, G. C., Irwin, S. R., Shanahan, D., and Franklin, C. E. (2007). Satellite tracking reveals long distance coastal travel and homing by translocated Estuarine Crocodiles, *Crocodylus porosus*. *PLoS ONE* **2** (9), e949. doi:10.1371/journal.pone.0000949

Rodgers, A. R., Rempel, R. S., and Abraham, K. S. (1996). A GPS based telemetry system. *Wildlife Society Bulletin* **24**, 559–566.

Schwartz, C. C., Podruzny, S., Cain, S. L., and Cherry, S. (2009). Performance of spread spectrum global positioning system collars on grizzly and black bears. *The Journal of Wildlife Management* **73**, 1174–1183. doi:10.2193/2008-514

Shaffer, S. A., Tremblay, Y., Awkerman, J. A., Henry, R. W., Teo, S. L. H., Anderson, D. J., Croll, D. A., Block, B. A., and Costa, D. P. (2005). Comparison of light- and SST-based geolocation with satellite telemetry in free-ranging albatrosses. *Marine Biology* **147**, 833–843. doi:10.1007/s00227-005-1631-8

Thomas, B., Holland, J. D., and Minot, E. O. (2008). Elephant (*Loxodonta africana*) home ranges in Sabi Sand Reserve and Kruger National Park: a five-year satellite tracking study. *PLoS ONE* **3**, e3902. doi:10.1371/journal.pone.0003902

Thomas, B., Holland, J. D., and Minot, E. O. (2010*a*). Home range and movement patterns of an estuarine crocodile *Crocodylus porosus*: a satellite tracking pilot study. *Northern Territory Naturalist* **22**, 60–74.

Thomas, B., Minot, E. O., and Holland, J. D. (2010*b*). Fledging behaviour of juvenile northern royal albatrosses (*Diomedea sanfordi*): a GPS tracking study. *Notornis* **57**, 135–147.

Thomas, B., Minot, E. O., and Holland, J. D. (2010*c*). Home range and habitat use of the New Zealand falcon (*Falco novaeseelandiae*) within a plantation forest: a satellite tracking study. *International Journal of Ecology* **2010**, 829702.

Thomas, B., Holland, J. D., and Minot, E. O. (2011). Seasonal home ranges of elephants (*Loxodonta africana*) and their movements between Sabi Sand Reserve and Kruger National Park. *African Journal of Ecology*. in press.

Tomkiewicz, S. M., Fuller, M. R., Kie, J. G., and Bates, K. K. (2010). Global positioning system and associated technologies in animal behaviour and ecological research. *Philosophical Transactions of the Royal Society. B. Biological Sciences* **365**, 2163–2176. doi:10.1098/rstb.2010.0090

Webster, M. S., Marra, P. P., Haig, S. M., Bensch, S., and Holmes, R. T. (2002). Links between worlds: unraveling migratory connectivity. *Trends in Ecology & Evolution* **17**, 76–83. doi:10.1016/S0169-5347(01)02380-1

Witt, M. J., Åkesson, S., Brodericka, A. C., Coynea, M. S., Ellickd, C. J., Formiae, A., Haysf, G. C., Luschig, P., Stroudh, S., and Godley, B. J. (2010). Assessing accuracy and utility of satellite-tracking data using Argos-linked Fastloc-GPS. *Animal Behaviour* **80**, 571–581. doi:10.1016/j.anbehav.2010.05.022

Zimmerman, J. W., and Powell, R. A. (1995). Radiotelemetry error: location error method compared with error polygons and confidence ellipses. *Canadian Journal of Ecology* **73**, 1123–1133.

Zucco, C. A., and Mourao, G. (2009). Low-cost global positioning system harness for pampas deer. *The Journal of Wildlife Management* **73**, 452–457. doi:10.2193/2007-492