In recent years there has been a massive increase in the number of studies conducted using animal-attached technology in order to elucidate aspects of the biology of larger marine animals. This approach has largely arisen as a result of necessity since visual observation of many of these animals is problematic. It has been possible as a result of remarkable development in solid state technology over the last two decades.

A comprehensive review of all of the techniques currently being used by researchers using animal-attached devices in marine systems would be a massive undertaking. The purpose of this paper is not to do this, but rather to present some of the more recently developed remote-sensing, animal-carried systems for examining larger marine animals and their environment and to consider where future research and technological advances might lead us.

In order to put this work into perspective, it is instructive to consider what we actually wish to know. The simple answer to this is ‘everything.’ So-called ‘conventional wisdom’ dictates what is desirable today and what is considered banal. However, conventional wisdom is fickle. It is in our interests to believe that we wish to determine as much as possible about all aspects of the lives of the animals we plan to study. This can be conveniently put into three groups: animal location, the environmental characteristics of these locations, and the activities of the animals at these locations.

Animal Location/Spatial Utilisation

There are a great many techniques for determining animal location using animal-attached devices. Transmission telemetric units will be ignored in this report because they are well described elsewhere. These units rely on the transmission of a signal generally from the animal to a receiver (e.g., acoustic, radio, satellite telemetry and Loran C systems), but also, more recently, from external sources to the animal (e.g., GPS). Transmission telemetry has a number of very substantial disadvantages for tracking in the marine environment when compared to terrestrial systems. Radio waves are not propagated appreciably underwater so that animals to be tracked using transmission telemetry must either be at the surface for an appreciable length of time for transmission to be affected, or workers must resort to acoustic systems which, in any event, only have a range of a few hundred metres.

Recently, logging technology has proved to be a real alternative to transmission telemetry. Loggers are animal-attached units that simply store, rather than transmit, data. Since the transmission of data is very energy-expensive, loggers can be considerably smaller than telemetric systems due to the savings that can be made from the power supply. This means that the animal-attached units can be much more animal-friendly (see later). Although pure logging systems can be built to function irrespective of the environmental conditions, they must be recovered in order to access the data. This is not always practicable and, in cases such as this,
pop-up tags often prove to be a useful compromise. Loggers can be used to determine animal position by one of two major methods: Global Location Systems (GLS)/geo-location or dead reckoning.

**GLS/geo-location**

GLS methodology uses loggers to store data on ambient light intensity at regular intervals. Consideration of the time of dawn and dusk with regard to Greenwich Mean Time and Julian day allows geographic location to be calculated because day length is latitude-dependent while the local timing of mid-day is longitude-dependent. Two positional fixes are obtained per 24 hours, once at local mid-day and once at local mid-night. This approach works throughout the year except for a few days around the equinox where latitude cannot be resolved. The accuracy of the system varies considerably and is dependent on environmental factors such as cloud cover and the position of the considered animal in the water column. Appropriate hardware and software exist for correction of many of the problems inherent in GLS methodology but there is considerable room for improvement. Various algorithms used to date in the calculation of location give positional accuracy between about 20 and 100 km for animals that spend most of their time above the water’s surface, such as albatrosses, penguins, etc. The accuracy of the system means that it is inappropriate for small scale movement of animals. However, it is extremely useful for migrations, or where animal position is to be considered over time periods of weeks to months. It has been used successfully to determine the over-winter movements of migratory penguins and albatrosses and shows promise on pelagic fish.

**Dead reckoning**

Dead reckoning necessitates that the logger store information on animal speed, animal vertical displacement (depth or flight height) and animal heading at regular intervals. This information is integrated together in vectorial calculations to determine the 3-dimensional route of the animal in question with the start point of the trajectory being taken as the point where the animal was released. Animal-attached dead reckoners are very recent and being used at present by very few research groups. A major reason for this is that it has proved problematic to design a small, reliable compass to determine animal heading. One solution to this problem uses a miniature ship’s compass consisting of a sphere containing a very powerful rare-earth bar magnet placed diametrically across its equator and weighted underneath with lead. When immersed in silicon oil, the weight holds the North-South long axis of the magnet parallel to the earth’s surface while the magnet orients itself according to the horizontal component of the earth’s magnetic field. In the animal-attached unit, the magnet-containing sphere is enclosed in a larger, silicon oil-filled sphere which has three Hall sensors placed appropriately on its external surface. The relative position of the inner sphere with respect to the outer sphere is sensed by the Hall generators which produce a voltage proportional to the magnetic field strength generated by the internal magnet. After appropriate calibration this can be resolved into an animal heading (and a dive/surface angle).

There are a number of sensors available to determine animal speed. A popular sensor is the paddle wheel which is actually less rigorously accurate than many would believe. Since paddle wheels are invariably located close to the body of the recording unit, they are highly susceptible
to turbulence problems. This often becomes apparent during calibration, which should be performed on an appropriate model of the animal to be monitored. We have noted that in some units calibrated on penguins that, with increasing speed the number of forward paddle wheel rotations increases before decreasing to zero at a specific speed and finally reversing as the water flow over the body is further increased. This problem can be eliminated by measuring water flow rates at a point distant enough from the logging unit. There are a number of ways to do this but a successful application uses a Prandi tube linked to a differential pressure sensor. The differential pressure sensor measures the difference between hydrostatic pressure (acquired from depth) and water pressure resulting from the forward motion of the animal and has proved to be impressively accurate at both low and high swim speeds.

Depth transducers are used in most commercially-available loggers for marine animal application. After teething problems a decade or so ago, they all appear to have reasonable temperature correction so that base line drift problems are a thing of the past. Irrespective of their applicability in dead-reckoning systems, depth transducers are an essential part of space utilisation determination because they resolve the vertical component.

In a typical dead reckoner application, data are stored every few seconds, which means that the 3-dimensional position of the animal can be calculated on an accordingly appropriate scale. The system thus has a positional location every few seconds, each position being accurate, relative to its neighbour, to within a few metres. This very high temporal and spatial resolution cannot usually be obtained by other positional systems. Dead reckoning is, however, susceptible to drift errors. For example, if a marine animal does not swim but remains motionless within a current it will be transported away from its determined position although no change in speed has been registered by the speed sensor. This problem can be minimized by obtaining periodic fixes using other methodologies (e.g., with GLS) and correcting the route to accord. Dead reckoning has been used successfully, and quite extensively, in penguin studies. It has been shown to be extremely potent over time scales of hours to two or three days. Longer periods than this generally necessitate some drift correction.

**Properties of This Space**

In order to understand why certain animals utilise specific areas it is necessary to examine the characteristics of those areas. If done using standard ship-sampling methodology, this is extremely expensive. Fortunately, it can also be done using the animals themselves. Once there is a system for determining animal position, environmental parameters can be logged and subsequently assigned to specific positions. Combination of multiple animals equipped with multiple logging units allows for really extensive area coverage. Two major factors are of interest here: abiotic variables and biotic variables.

**Abiotic variables**

Possibly the simplest of the abiotic variables to measure is temperature. For example, five Wandering Albatrosses from Possession Island in the southern Indian Ocean were tracked over three weeks during which time they carried foot loggers which measured the sea surface temperature of 22 million km². Similarly, the 3-dimensional isotherms of a 90 km² area of the
Maxwell Bay adjacent to King George Island, Antarctica was measured by over 50 Pygoscelid penguins over the course of two weeks. Other abiotic sensors such as salinity and light extinction can equally easily be used. However, researchers wishing to use this technique need to consider carefully the speed at which their sensors work in relation to the time the animal spends in the zone to be measured. For example temperature sensors embedded in a mass of resin only equilibrate with ambient water temperature after a few minutes. This is of little use if the animal carrier conducts dives of two minutes during which time it descends and ascends the water column passing through marked isotherms.

**Biotic variables**

Biotic variables are considerably less straightforward than abiotic variables to measure. Nonetheless, it is possible to derive measures of, for example, prey abundance if the matter is considered carefully. Fisheries scientists regularly use Catch Per Unit Effort (CPUE) statistics to derive fish abundance and the principle is the same for animals. For this, however, it is necessary to be able to define and measure both 'catch' and 'effort.' 'Catch' is easily defined as that ingested by the animal. Food ingested by marine endotherms can be measured by logging stomach temperature since swallowed prey, at ambient temperature, cause a precipitous drop in stomach temperature. The time of the abrupt drop is indicative of the time when prey are ingested but, in addition, the approximate mass of the meal ingested can be calculated by consideration of the extent of the drop and the time it takes for the endotherm to heat the stomach contents to asymptotic temperatures. To date, this approach has been used in a number of marine endotherms ranging from seabirds to seals.

'Effort' can be defined by the researcher since the foraging behaviour of the study animal is generally fairly well understood. For example, in the case of penguins, effort can be readily defined as the distance traveled by the birds or the time spent underwater. Thus, in this case the units of CPUE are grams ingested per kilometre traveled. Prey density as determined by penguin CPUE have already been calculated and data compiled together for one region in the Antarctic. Ultimately the density values were given units of g/hour spent searching underwater/km2. This approach showed very well-defined 'hot-spots' which certainly merit further attention.

**Animal Activity in Their Defined Space**

Animal activity can perhaps be conveniently divided into two main groupings: behavioural activity and physiological activity.

**Behavioural activity**

The list of animal behavioural activities that can be monitored by logger technology is almost endless and it would be inappropriate to try and list them all here. However, as a general comment, workers should be aware of the pitfalls of over-interpretation of their data where sampling interval or resolution are inappropriate. For example, diving behaviour in air-breathing vertebrates is a popular subject, with authors spending considerable time looking at the form of dive profiles. Here, the validity of the results from this type of analysis is dependent on the resolution with which depth is logged. Early depth loggers recorded data with 8 bit resolution
which results in a resolution which is equal to the maximum depth range potentially recorded by the sensor divided by 255. Thus, even though an animal may descend the water column smoothly, an 8 bit logger will provide a resultant depth profile which will be represented as a series of steps if the sampling interval is too high. Ultimately this can lead to inaccuracies in dive shape classification e.g., parabolic-shaped dive profiles being classified as U-shaped dives. By the same token, derivation of dive profiles recorded with high resolution (e.g., 16 bit) but low sampling interval can result in U-shaped dives being recorded as V-shaped and the overall number of dives recorded being reduced because surface intervals are sometimes missed in shallow dive series.

**Physiological activity**

For the most part, documentation of physiological activity requires invasive surgery. This is associated with substantial operational trauma and must be considered at a different level to externally-attached devices. Nonetheless, invasive surgery has been used to implant loggers to measure heart beat frequency and body temperature in free-living fur seals, albatrosses and penguins for periods of many weeks. Recently, a heart-beat frequency monitor for use in human athletes was used to record changes in heart beat rates in free-living penguins on land without invasive surgery. It is unclear the extent to which the system would have operated on the birds at sea but it might be worth further consideration.

Much of digestive physiology can be studied by getting animals to swallow loggers which are retained in the stomach recording data on, for example, pH or gastric churning. Digestive physiology loggers for free-living animals are a very recent development, but have been used successfully on a number of species of penguin.

**Future Directions**

There are a number of avenues that would be particularly beneficial for studies involving animal-attached remote-sensing devices.

There is a need for GLS technology to be researched so that positional location can be better derived from systems that can only measure light intensity underwater, as is the case in fish. Problems that need to be addressed are (1) the selective attenuation of specific light wavelengths as a function of depth underwater (in which wavelength area should the sensor be operating?); (2) variable light intensity with depth and the extent to which this changes with water turbidity; (3) the effect that the refractive power of water has on the angle at which light descends the water column and the consequent changed light absorption as a function of depth; (4) problems associated with total internal reflection which occurs at low sun angles; and (5) how all this may be affected by sea surface conditions.

Over and above GLS considerations, much of classic oceanography relies on optical assessment. Logger technology lends itself to this type of measurement so with very little investment it should be possible to measure water turbidity, depth dependent light attenuation and bioluminescence via passive sensors. Further work could also be conducted to measure productivity where the specific light source is provided by the logger in excitation studies.
Internal sensors, either in the digestive tract or otherwise promise, in the future, to enable us to be able to record biochemical changes going on in free-living animals. This might take the form of biosensor which might help identify prey types, for example. As noted above it is already possible to measure pH in free-living animals so lactic acid production in anaerobic dives could now be monitored.

Finally, as digital storage capacity increases we must expect that the number of studies conducted on free-living marine animals using animal-attached video or still photo recording equipment will increase. Although, for the most part such images will likely consist of formless water, the few images of species interactions promise to be spectacular.

A Sobering Note - the Skeleton in the Cupboard

The plethora of techniques available will tend to goad researchers into equipping animals with more and more technology. However, the limiting factor as to what can be usefully measured on free-ranging animals is the animals themselves. Potentially, anything that could be technologically measured in the laboratory could also be measured on free-living animals, were it not for the size problem. Who decides what is acceptable and what is not? Sadly, a primary approach used by many workers is to decide that attached devices cause no problems unless it is proved otherwise. This generous adoption of the 'innocent unless proved guilty' option is not acceptable. Over recent years it has been repeatedly shown that device-equipped animals do not behave in the same way as unequipped conspecifics. Thus, it seems more appropriate to assume that device-equipped animals will be bothered by the units (the guilty until proved innocent option). The extent to which the attached units are problematic can be assessed by looking at the length of time over which the animals can be equipped with no discernable ill effects on a time scale of hours to years. The longer, the better.

Ultimately, there are two factors which need to be considered. The first is the purely scientific premise, to consider the extent to which obtained results are truly representative of the species considered. The second is the moral issue and this is perhaps best summarized by two questions representing various degrees of moral sensitivity. One would be to simply say ’can I sleep at night doing what I do?’ The other would be ’would my mother sleep at night if she knew what I do?’ If everybody equipping free-living animals asked themselves this before embarking on their research programmes the quality of the results would be enormously enhanced and these complex animals we equip would be all the happier for it.

Related References


Service Argos Inc. Argos: Basic description of the Argos system. Brochure available from Service Argos Inc. of Largo, Maryland or through the Internet at http://www.argosinc.com.


