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Review

New steps in bio-logging science

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Abstract: Among a variety of remote observation systems for the study of marine creatures, data loggers emerged in the 1990's, following mechanical depth recorders (TDRs). Digital data loggers have played a critical role in studies on marine animal behaviour, ecology and physiology. Today, this field is called bio-logging science. Digitalization has allowed further miniaturization of logger systems, which is particularly important to this science so that the effect of device attachment to animals is minimized. At the same time digital techniques have enabled us to develop multi-sensor loggers, which has enhanced integration of information on many aspects of marine animal lives. Using advanced systems we are now able to determine when feeding occurs during dives, elucidate stroking patterns, 3-dimensional dive paths and even prey distribution along the dive path. This article traces the history of development of both mechanical and digital loggers developed at and used by the researchers of the National Institute of Polar Research, Japan.

key words: bio-logging science, data loggers, diving behavior, foraging behavior, three-dimensional position

Introduction

Bio-logging is a new word that was first introduced during the International Symposium on Bio-logging Science held at the National Institute of Polar Research (NIPR), Tokyo, Japan in March 2003. Because it is new, there is no clear definition for this word yet (but see Boyd *et al.*, 2004). However, within its definition lies its current field of application: the study of marine life *via* remote-sensing loggers. It has always been difficult to obtain detailed information about marine life because of the logistical difficulties of tracking marine creatures over long periods of time. A large proportion of marine animals often move or migrate over considerable horizontal and vertical distances, these movements occurring mainly beneath the surface of the world oceans. Thus, tools that can 'observe' and monitor remote marine life *in situ* have been necessary for understanding of the functioning of the global marine ecosystem. Several techniques have been developed. These have been generally referred to as "biotelemetry" (see review in Amlaner and MacDonald, 1980). Among the major biotelemetry techniques used on marine animals are VHF, satellite and acoustic telemetry, all methods primarily designed for tracking animal movements (Kato *et al.*, 2003a; Jouventin and Weimerskirch, 1990) and more recently for transmitting information on animal behaviour *via* satellite. Despite the substantial progress brought by satellite telemetry techniques, the amount of information has remained limited because data transmission is limited to a few meters below the surface of the water. By comparison, emperor penguins *Aptenodytes forsterii*, can dive as deep as 500 m (Kooyman and Kooyman, 1995). As a result, following extraordinary advances in microelectronic technology, new techniques have been developed to extend remote monitoring beyond the boundaries of biotelemetry. Data logging is one of the new techniques that allows researchers to pass beyond the physical boundaries that previously limited their investigations (see the definition of bio-logging science given in Boyd *et al*., 2004). Data are recorded in miniaturized electronic devices attached to free-living animals. This type of animal-borne observation and data-recording system was first used to study the diving physiology of seals (Kooyman, 1965). Later in the 1980's, this pioneering system was technically improved and its range of application extended considerably to various marine animal species (*e.g*. Wilson and Bain, 1984; Naito *et al*., 1989).

Since these first beginnings, remarkable progress has been made in understanding the behaviour, ecology and physiology of marine animals in relatively few years. We can now obtain considerable amounts of biological and physical data from the marine environment, and at the same time we have developed new methods of data analysis and management. Scientists engaged in developing this scientific approach have recently felt the need to operate under a new word that would help them gain recognition of their work. This word should present this particular scientific approach that delivers integrated information about environmental parameters *in situ*, using advanced micro-electronic data recorders. This growing need for a common banner under which scientists could regroup has led to the organization of a symposium where the term “Bio-logging Science” was proposed for the first time by a young scientist, Dr. Yan Ropert-Coudert, working at the NIPR. Overall, this word received agreement from the scientific community present at the symposium as the term was thought to satisfactorily encompass the research field, the general direction and the technology inherent to the approach.

The inception and development of bio-logging over the past decades is documented in detail in the current proceedings (Kooyman, 2004) and in the following review, I will, therefore, briefly present the development of data logging systems used by the NIPR, in association with Yanagi Keiki Co., Ltd. and Little Leonardo Co., Japan (see Muramoto *et al*., 2004, for technical details on digital data-logging systems) and that closely follows the progress in miniaturization and multi-sensoring systems. In addition, I also suggest some prospects for the future, explaining how such systems can contribute to the development of marine animal science and protection of the marine environment.

Miniaturization of mechanical recorders

Bio-logging science started in 1964 when G.L. Kooyman measured the dive depth and dive duration of Weddell seals (*Leptonychotes weddellii*) in Antarctica, using a modified kitchen timer (*cf*. Kooyman, 2004). However this ambitious work was not followed by others until the 1980's, as the technologies in those days made it difficult to develop complex instruments. In the 1980's, I developed new Time Depth Recorders (TDR) and Time-Swim Distance Recorders (TSDR). These TDRs were modified fish net recorders and were primarily used to study the diving activity of loggerhead turtles, *Caretta caretta,* in Gamouda, Tokushima, Japan in 1983, although results were to be published only a decade later (Minamikawa *et al*., 1997). Back in 1983, the TDR and TSDR were 76 mm in diameter, 160 and 202 mm in length, 1150 (550) g and 1200 (450) g in air (and in water), respectively. Following these models, miniaturization of TDRs was achieved through collaboration with Yanagi Keiki. The 25×80 mm (80 g in the air), cylindrical TDR that resulted from our association contained a diamond needle with 70–80° sharpness (connected to a pressure bellows) which scratched 6–8 μm fine lines on a <10–12 μm thick carbon-coated or aluminum-evaporated paper. This small TDR could record continuously for >20 days and it was used to study the diving behaviour of Adélie penguins *Pygoscelis adeliae* at Syowa Station, Antarctica (Naito *et al*., 1990). The same logger also allowed us to obtain the first ever depth data from a flying-diving bird, the blue-eyed shag *Phalacrocorax atriceps* (Croxall *et al*., 1991; Kato *et al*., 1992). Finally, this TDR was also used on northern elephant seals *Mirounga angustirostris*. Continuous diving data were obtained for > 80 days, covering the complete period spent at sea by the seal, from departure to sea after breeding to arrival at the colony for molting (Naito *et al*., 1989; Le Boeuf *et al*., 1989).

Multi-sensor data logging system

Between the late 1980's and early 1990's, a revolution occurred when all mechanical TDRs were replaced by electronic, analogue data loggers, smaller and lighter than their 'mechanical' counterparts. The pros and cons of digital data loggers have been reported elsewhere in these proceedings (Muramoto *et al*., 2004) but the three main advantages of these loggers can be repeated here. Firstly, data do not need to be converted from analogue to digital, which is a lengthy process (a 2-week long analogue data set sometimes took more than a month to be digitalized). Secondly, further miniaturization can be readily achieved while memory size is simultaneously increased. Finally, multiple sensors can be installed into a single data logger. The first digital data logger produced in Japan, in 1992 by the NIPR, in association with Little Leonardo, was the NIPR-200 model, which could store 256000 depth data with 12-bit resolution over a depth range of 0–200 m (Watanuki *et al*., 1997). Thereafter, the NIPR and Little Leonardo produced various types of digital data loggers, which were subsequently termed micro data loggers. Over the last 10 years, large steps in the development of data loggers have been made, although several problems remain, such as, for example, battery size, capacity and the reliability of sensors for physiological measurement (*cf*. Muramoto *et al*., 2004). None-the-less, we expect, in the near future, to be able to develop an intelligent data logging system for behavioural, ecological and physiological studies.

The recent success of data logging systems is critically dependent on the technique used to attach the data loggers to the animals and the miniaturization of the devices. Initially, data loggers were attached to the animals by means of harnesses (Gentry and Kooyman, 1986), but quickly, epoxy glue became the preferred method of attachment, particularly in the case of deployment on haired or feathered animals. Thereafter, Wilson *et al*. (1997) proposed the use of marine (TESA) tape that preserves the integrity of the feathers or furs. Alternatively, implantation of a data logger can be a solution, especially in the case of fish or for long-term deployment of devices. Miniaturization of instruments is the other key-element in bio-logging science since smaller loggers allow researchers to obtain meaningful data (but see Ropert-Coudert and Wilson, 2004), while preserving the health of the animals (Hawkins, 2004).

Integration and diversification of bio-logging science

The application of this advanced microelectronic technology in the study of free-ranging marine animals has allowed us to establish a smart bio-logging methodology by which large amounts of quantitative and qualitative biological data can be collected. For instance, the simple monitoring of the changes in hydrostatic pressure through the pressure transducer of a data logger has allowed us to obtain an accurate image of the diving behaviour of marine animals, from which various other parameters can be extracted, such as dive profile, depth and duration of dives (maximum and mean), descent and ascent rates, bottom time, surface time, etc. Thus, we can investigate the features of diving activity in general, which has helped develop new ideas and hypotheses to explain the amazing diving abilities of marine vertebrates. However, it has become increasingly clear that as we progress in our understanding of the life of marine creatures, new questions and hypotheses were raised and these, in turn, required the development of new protocols, technologies, and experiments in order to be addressed. For example, some studies have focused on the relationship between the diving activity of elephant seals and the hydrographic features of the ocean regions exploited by the seals (Boyd and Arnbom, 1991; Hakoyama *et al*., 1994). Since fish are sensitive to change in the ambient temperature we had to develop a high resolution depth, temperature data logger in order to examine the relationship between the vertical temperature structure of the water mass and the diving behaviour of chum salmon, *Oncorhynchus keta* (Tanaka *et al*., 2000). Depth and temperature data loggers have been used not only to measure ambient temperature but also to detect feeding activity. This latter approach is based on the principle that when warm endothermic predators swallow cold exothermic prey, a drop in the internal temperature of the predators occurs. Thus, the continuous monitoring of the stomach (Wilson *et al*., 1992; Kato *et al*., 1996) or the oesophagus temperature (Ancel *et al*., 1997; Ropert-Coudert *et al*., 2000a; Charrassin *et al*., 2001) has allowed researchers to detect the exact time of prey ingestion. Salinity is another key parameter characterizing the physical properties of water masses. Depth, temperature, conductivity data loggers have been developed and applied to examine how chum salmon move from oceanic areas to fresh water areas of their native river for spawning (Tanaka *et al*., 2000). These data loggers are also used as salt-water switches to detect the precise timing of surfacing by penguins.

As memory size has increased, we have been able to measure more dynamic aspects of the underwater activity of marine animals. Besides the features of the diving activity revealed by TDR data, the development of a swim speed data logger allowed us to examine the descent and ascent angles of dives, the swim speed of each segment of the dive profile, the distance swum during a dive, etc., all of which are essential to understand the energetics of foraging activity. This is exemplified by the results of multiple data recording studies where the foraging strategies of animals are revealed. For instance, the simultaneous monitoring of swim speed, depth and oesophagus data (to monitor the feeding activity, *cf*. above) confirmed that penguins fed mostly at the bottom phase of dives and revealed that prey were mainly caught while the penguins were swimming in an upward direction, suggesting that penguins detect prey visually, using a backlighting effect (Ropert-Coudert *et al*., 2000b, 2001). These studies also revealed drastic changes in swim speed during prey capture (Ropert-Coudert *et al*., 2000b, 2001; Wilson *et al*., 2002). A further step in the complexity of the type of information collected was taken when we developed an acceleration data logger that could record dynamic and static acceleration along two axes, *in tandem* with swim speed, temperature and depth data. This sophisticated data logger allowed researchers to measure the locomotory movements and swim speed of marine animals, leading to exciting new findings. For instance, king penguins, *Aptenodytes patagonicus*, were shown to increase their swim speed without beating their flippers on their way back to the sea surface (Sato *et al*., 2002). Along with the results by Ropert-Coudert *et al.* (2001), this also suggests that animals determine their diving behaviour in relation to prey conditions and buoyancy (see also Wilson, 2003). The analysis of gravity data, which are extracted from acceleration data by low path filtering (see Tanaka *et al*., 2001 for details), allows us to examine how animals allocate their energy in the process of foraging dives. Using this approach, Weddell seals were shown to adapt their swimming activity in relation to their level of obesity (Sato *et al*., 2003). Furthermore, the analysis of the posture of animals using gravity data revealed that some Weddell seals drifted in an upside-down position during their dives (Mitani; personal communication). In addition to the detection of body posture, static (gravity) and dynamic acceleration (surge, sway and heave, for example) data, *in tandem* with depth and speed data, can be used to categorize the behaviour of animals on land, at sea and even in the air (Kato *et al*., 2003b). For instance, up to 7 different behaviours were identified and used to provide an accurate time-budget of free-ranging Adelie penguins (Yoda *et al*., 2001).

Advanced data logger systems also brought substantial information to another field of bio-logging which has received considerable attention in recent years, namely the use of marine animals as bio-platforms (see review of this field in Fedak, 2004). Here, data loggers are used to investigate the relationship between the diving activity of animals and hydrographic features or prey conditions. In this regard, bio-logging has clearly demonstrated that foraging activity does not occur randomly and that there is a close link between where animals forage and the characteristics of the environment on a local or sometimes much wider scale. When animals migrate over substantial distances, we have to consider the characteristics of the oceanic environment on a global scale and this means that we have to determine the animal position, using satellite tracking for instance, in order to define the exact locations of diving and foraging. At the other end of the scale, the detailed study of the diving processes and foraging behavior of animals in relation to prey distribution on a dive-by-dive basis necessitates the use of fine-scale tools that give 3-dimensional positional information. For this purpose, we recently developed a 3-magnetic field, 2-acceleration, swim speed and depth data logger to study the fine-scale, three-dimensional diving activity of animals and to reconstruct the diving paths of Weddell seals (Mitani *et al*., 2003). Along with dive paths, we also obtained information about the distribution of potential prey items at depths using digital still cameras attached to Weddell seals (Watanabe *et al*., 2003). This logger type, attached to the animal's back, took image data at given intervals along the seals' dive paths.

New challenges for bio-logging science: further steps

New challenges are constantly proposed to the bio-logging community which, in turn, constantly seeks new advanced technology. This can be exemplified by the recent development of a satellite-linked data transmission system and the appearance of satellite tags such as those developed by researchers of the Sea Mammal Research Unit (SMRU), University of

Saint Andrews, UK and the pop-up tags developed by Wildlife Computers, USA. These tags not only transmit location data but also other data, such as depth, salinity and swim speed, using the ARGOS system (*e.g*. Block *et al*., 2001). Similarly, GPS technology has also been recently used to investigate the location and migration routes, as well as the behaviour and characteristics of the environment of marine animals with an unprecedented level of precision (*e.g*. Grémillet *et al*., unpublished data). A major advantage offered by pop-up tags is that the animals do not need to be captured a second time to retrieve the tags. Thus, bio-logging is not restricted anymore to animal species that return frequently to land to breed and data loggers can be deployed on genuine pelagic species. This explains, in part, why satellite-linked systems were preferentially used to study cetaceans (but see Otani *et al*., 1998). Rapid advances in miniaturization and increases in the rate of bit transmission indicates that satellite-linked systems will play an important role in studies of marine animals in the coming years. In fact, these techniques are already being applied in the field by programs such as T.O.P.P. (Tagging Of Pacific Pelagics) which aims to understand the migration routes followed by animals and the oceanographic conditions that determine the use of these migration corridors, using animal-borne observation systems (Block *et al*., 2002).

Although satellite-linked systems offer great flexibility, they are limited in the amount of data that can be transmitted at once. Thus, in parallel to satellite-transmission advances, smart systems are required to compress data. This is particularly true in the case of image (still-image or movie) data loggers, for which data compression is a key issue. The development of such data compression systems would benefit programs such as the Deep Sea Look (DSL), Japan, which focuses on the study of the foraging behaviour of deep-diving animals and prey distribution. The DSL program proceeds along the same path that led to the creation of bio-logging science in the first place: the desire to visualize inaccessible phenomena that take place underwater motivated the creation of the first TDR. Now, the very same motivation will push us to investigate even deeper and to look for living inhabitants in hidden, deeper waters. Humans rarely venture into the mid-layers of the ocean where many marine creatures live, while large predators frequently visit these deep waters during their foraging activity. Thus, attachment of a digital camera system to large marine vertebrates, together with documentation of the 3-dimensional dive path via data loggers, would allow us to observe directly—and not merely to 'reconstruct'—the world beneath the water surface. Performed on a large scale on a variety of species, this program will lead to the establishment of a database that will compile the living features of marine organisms.

Finally, it should be noted that over the years, researchers have mainly studied the behavior of marine animals considered isolated from each other. It is only recently that a few attempts have been made to study how animals interact with each other in groups and societies at sea. Indeed, in most cases, animals live with other individuals and develop social systems. The possibilities to study animal interactions using a data logger system are substantial. We have already demonstrated that data loggers can help us categorize precisely the behavior of penguins. Equipping a hundred penguins from a small colony with such systems for several days would give us an accurate picture of the activity of the group over a short period of time. However, such an approach also involves the development of metadata processing systems.

We have introduced technology into the field of biology and oceanography, allowing us to monitor in detail the behavior, ecology and physiology of remote marine animals. The systems that we have developed are modern techniques which can also be applied to other science fields, as well as used on other species, such as terrestrial animals.

Acknowledgments

In this text I often used ‘we’ as a subject. This ‘we’ represents all the people who are engaged in the development of this science in Japan, most of them being young students, post-doctoral fellows and young researchers. Similarly, people involved in the technological development of bio-logging (who were also young at the dawn of bio-logging) are also included in this ‘we’. May all these numerous people be thanked here.

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