A Multi-Week Behavioral Sampling Tag for Sound Effects Studies: Design Trade-Offs and Prototype Evaluation

Mark Johnson, Peter Tyack, Doug Gillespie, and Bernie McConnell
University of St. Andrews
St. Andrews, Fife KY16 8LB, UK
phone: +44 1334 462624 fax: +44 1334 463443 email: mj26@st-andrews.ac.uk
email: plt@st-andrews.ac.uk
email: dg50@st-andrews.ac.uk
email: bm8@st-andrews.ac.uk

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LONG-TERM GOALS

The project will develop new tag technology needed to study the behavioral effects of sound on wild marine mammals over extended time intervals. This will enable fine-scale studies of sound exposure and responses under authentic conditions and will provide data needed to assess the biological significance of responses.

OBJECTIVES

1. Develop a multi-week behavioral sampling tag with archival and telemetry capabilities. This tag will be used as a test-bed to evaluate *in situ* behavioral sampling and data summary algorithms.
2. Develop robust data compression and event counting algorithms to deliver information about the baseline behavior of tagged animals and their exposure and responses to sound via satellite telemetry.
3. Evaluate the new methods in field experiments on marine mammals.

APPROACH

Studies of the impact of human-sourced sound on marine mammals require tags capable of sampling both the behavior of, and the sounds experienced by, animals. Short-term sound recording tags such as the DTAG have enabled controlled exposure experiments, yielding fine-scale data about how animals respond to sounds. The challenge now is to extend the duration and sensitivity of these studies to provide information about longer-term responses under more authentic sound exposure conditions. A target goal is to monitor animals during Navy sonar exercises that may last up to a week. Including baseline periods before, and return to baseline after, the exposure, a tag duration of 2-3 weeks is required. Given this duration, there is a significant risk that tags will not be recovered and so essential information must be transmitted via radio telemetry. There is a tremendous mis-match between the high data rates that can be collected on a tag and the low data rates that can be sent by telemetry, and so this constraint requires careful selection and compression of data. Power consumption is another limiting factor in a multi-week device. Thus, key challenges are to identify meaningful behavioral and

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environmental metrics that can be (i) acquired with low power by a tag and (ii) represented by very few data bytes for satellite telemetry.

Existing telemetry tags provide reliable long-term information about movements and diving rate but the low sampling rate of these tags makes them largely unsuitable for studying reactions to sound exposures. The approach taken here is to combine fast-sampling multi-sensor archival tag technology with smart data summary algorithms and store-and-forward telemetry. We envisage a tag that is capable of recording sound and fine-scale movement data continually for several weeks, computing a set of compact summary statistics for later transmission. Upon release from the animal, the tag will float at the surface transmitting summary data via GSM or satellite radio, powered by small solar panels. The tag will also contain a full archive of the sound and sensor data in case it is possible to retrieve it. There are significant technological challenges to overcome in creating such a device. First, the power consumption of current tags must be reduced substantially. Secondly, robust methods for detecting key behavioral and acoustic exposure events must be developed and implemented in the tag. The compression factors required are enormous (e.g., a million to one for Argos telemetry) making this a complex task. The third challenge is to learn how to draw statistical inferences from such highly compressed data and therefore how to design experiments or opportunistic studies that maximize statistical power. To meet these challenges, we are:

i) Developing a hybrid sound and movement sampling tag with both archival and telemetry capabilities. This device will be programmable and capable of advanced signal processing but will have low power consumption for multi-week deployments. The hybrid tag will be field-tested in settings where there is, at least initially, a high chance of recovery allowing direct comparison of the telemetered and archival data sets.

ii) In parallel, we are developing data summary methods that deliver the critical information needed for assessing behavioral responses within limited telemetry bandwidths. These algorithms are being tested with existing DTAG data and then ported to the hybrid tag for field evaluation.

WORK COMPLETED

The centrepoint of work this year was the two-day Smart Tags Workshop held in St. Andrews in February 2013. The primary objective was to define a minimal set of information needed in order to understand animal responses to disturbance and to explore the potential for *in situ* data summary methods to extract this information from animal-borne sensors. The workshop had 16 invited attendees (Table 1) comprising experts in animal behavior, tag design and statistical inference. In preparation for the workshop, we produced an orientation document summarizing the motivation for smart tags in behavioral response studies and the inherent trade-offs in the design of these devices. This enabled the workshop to focus on the central design issues and so maximize its efficiency. The orientation document and workshop outcomes are now being used as the basis for a paper describing the development of smart tag algorithms. The workshop provided clear support for, and helped to define further, the smart tag concept. Key outcomes were: (i) the identification of a set of high priority *in situ* processing needs (Table 2), and (ii) the identification of Argos-2 as the only available global telemetry system suitable for tag data forwarding. This second outcome limits the total practical data collection to about 250 kB (approximately 12 kB per day for a three week attachment and a one month post-detachment transmission interval). As Argos is a simplex channel (i.e., there is no return data or acknowledge capability) with no delivery guarantee, the data must be grouped into independent 28 byte packets which are transmitted multiple times for redundancy. This means an effective data rate of about 16 self-contained data packets per hour.

Table 1: Smart tags workshop attendees

Attendee	Institute
Akiko Kato	Institut Pluridisciplinaire Hubert Curien, CNRS, France
Bernie McConnell	University of St. Andrews, UK
Dave Morretti	NUWC Newport, USA
David Mann	Loggerhead Instruments / Univ. South Florida, USA
Doug Gillespie	University of St. Andrews, UK
Marie Roche	Scripps / San Diego State University, USA
Mark Johnson	University of St. Andrews, UK
Mike Lonergan	University of St. Andrews, UK
Mike Weise	ONR, USA
Patrick Miller	University of St. Andrews, UK
Peter Tyack	University of St. Andrews, UK
Phil Lovell	University of St. Andrews, UK
Rob Schick	University of St. Andrews, UK
Thomas Gotz	University of St. Andrews, UK
Tiago Marquez	University of St. Andrews, UK
Yan Ropert-Coudert	Institut Pluridisciplinaire Hubert Curien, CNRS, France

Prior to the workshop, we focused on establishing the performance envelopes of available sensors, acquisition hardware, algorithms and telemetry, so as to provide a snap-shot of the state of technology for the workshop. Following the workshop, we have focused on implementing and evaluating the methods highlighted as being highest priority (Table 2) within the constraint of Argos transmission. We have approached this task in two steps: (i) developing and testing data summary algorithms, and (ii) developing a hybrid medium-term tag and software environment for algorithm evaluation in the field.

The workshop identified 8 sources of information as being fundamental to understanding the baseline performance and the impact of acoustic disturbance on marine mammals (Table 2). Of these, information about behavioral states, foraging rates, body condition, locations and sound exposure were considered the most important. It was recognized that robust algorithms for only a few of these quantities exist and it was agreed that the *in situ* assessment of behavioural states and exposure level, in particular, are difficult problems requiring additional specification. Since the workshop, we have developed autonomous algorithms for 7 of the 8 information categories. The algorithms are all functional in Matlab and have been, or are currently being, tested with existing DTAG data. About half of the algorithms have also been implemented in C code for the DTAG and the remaining ports will be completed in the next few months. When fully tested, the implementations (Matlab and C) will be posted on the soundtags website (http://soundtags.st-andrews.ac.uk/). A paper describing the algorithms and the motivation for the smart tag processing concept is currently in preparation. We have also proposed a one-day workshop on tag design methodology at the 5th Biologging Symposium (Strasbourg, Sept. 2014) at which we will present the new methods.

The hybrid tag is based on the WHOI/SMRU DTAG-3 with the addition of a fast acquisition GPS, an ARGOS transmitter, and power management circuits. The software infrastructure is an extended version of the open-source D3 real-time operating system. Several prototype tags have been constructed this year but two significant problems have required considerable effort to overcome. The first problem pertains to operational robustness. Argos transmission involves a transient high current consumption which can cause lock-up of the primary processor in the DTAG-3. This problem has been solved by re-programming the secondary processor in the tag for Argos transmission. In this new scheme, Argos packets are prepared in a shared memory until the tag detaches from the animal. The primary processor is then disabled and the Argos data is transmitted by the ultra-low-power secondary processor using a simple robust algorithm. This new approach is now operational. The second problem relates to antenna design. To minimize weight and therefore tag volume, we had planned to use a short whip antenna for GPS but, despite promising early testing, this design has ultimately proven to give insufficient satellite detections for reliable positioning. We have therefore had to change to a heavier ceramic antenna requiring the re-design of circuit boards, floatation and molds. This has unfortunately delayed the production of fully-functional prototypes. These will now be ready for evaluation in late 2013 and will be incorporated into field work, funded by other projects, in 2014. As the end-date of the current project is now approaching, we plan to request a one-year no-cost extension to allow us to complete tag fabrication and field testing in 2014.

Despite the delays in fabricating full tags, we have taken advantage of opportunities to test partial devices at no cost to the project. A multi-month DTAG with extended memory, dual power sources and a preliminary version of the smart tag software has been developed as an autonomous recorder/detector and is now operational in Slocum and Seaglider platforms in the UK. A compact wide-bandwidth version of the tag has been deployed on six porpoises in 2013 in a cooperative project with the Universities of Hannover and Aarhus.

RESULTS

Significant progress has been made this year on autonomous data summary algorithms. To move forward from the big-picture perspective of the workshop, we first identified a set of Argos data packets that could deliver much of the information listed in Table 2. This involved first choosing data elements that would collectively summarize the required information and then estimating the number of bits required to represent each data element with minimal loss. For example, activity budgets require information about the proportion of time spent foraging, moving to and from foraging depths, resting at the surface, and socializing. For a deep foraging whale, this information is largely conveyed by the sequence of dive depths and durations, but depths can be log-coded to 6 bits and durations rounded to the nearest minute with little loss in data quality. Thus, these activity measures can be conveyed in less than 100 bits per hour. We concluded that 5 fundamental packet types (Table 3) are needed to convey the behavior, movement and sound exposure experience of a deep diving whale. These packets are compact and self-contained as needed for Argos transmission. Packet types 1-4 are transmitted continuously during a tag deployment. As each packet represents two or less hours of observation, the loss of some packets through Argos can be tolerated. To fit within the average channel capacity of 16 packets per hour of tag attachment, sound exposure packets (P5) can only be collected during pre-programmed time intervals, e.g., bracketing a scheduled playback. Packets collected during these intervals have increased value and so will be transmitted more times each to ensure delivery.

To populate the packets in Table 3, we have developed a set of 12 data summary algorithms (Table 4) which generate the majority of the information highlighted as critical in the workshop. These algorithms also collectively provide most of the information used to detect and evaluate responses in recent SOCAL and Autec BRS's. The methods have been explicitly designed for *in situ* processing and so require neither accurate sensor calibration nor behavioral context (Fig. 1). As many of the algorithms currently used to process tag data require operator supervision, these new methods represent a major step forward in autonomous data processing for tags. In developing these algorithms, we have focused on beaked whales both on account of the importance of this taxa in behavioral response studies and because of their relatively stereotyped behavior. However, the methods are, in most cases, generally applicable and will provide a strong basis for smart tag applications to other taxa.

The smart tag algorithms have been developed in a feedback process involving the assessment of errors and their impact on the resulting inferences about animal performance or environment. Errors arising from four sources have been addressed:

(i) Proxy errors: most of the methods involve an indirect measurement of the quantity of interest. For example, norm-jerk transients (i.e., peaks in the magnitude of the acceleration rate) are used as a readily-detected proxy for prey capture events (Ydesen et al. in prep.). To test the reliability of this proxy, we have compared it against buzzes (weak sounds made by echolocators during prey capture attempts, Madsen et al. 2013) that have been detected by visual inspection of tag sound recordings. Analysis of ROC curves computed from some 3000 buzzes gives an 86% detection rate and 6% false alarm rate for Blainville's beaked whales, allowing confidence intervals for foraging rates to be estimated. We have used the same ROC approach to establish the performance of algorithms detecting dives, strokes, clicks, respiration and gait changes.

(ii) Calibration errors: Size and power constraints in tags necessitate fairly inaccurate sensors which are improved by post-calibration. The algorithms developed here must use poorly-calibrated sensor data and so need to be inherently robust to calibration errors. This has been achieved in most cases (Fig. 1) but some remaining issues are identified in Table 4. Many of the algorithms are also insensitive to the orientation of the tag on the animal, a significant improvement over currently-used methods and especially relevant for tags that are deployed on unrestrained animals.

(iii) Parameter errors: These arise from poor choices of acceptance parameters used to detect and classify events. For example, swim stroke detection requires parameters defining the minimum magnitude and the min and max duration of a stroke. Species dependent parameters can be selected from existing DTAG data but other parameters depend on the size of the animal or the location of the tag and so must be determined in situ requiring an additional algorithm. The robustness of each algorithm to parameter values is assessed in Table 4.

(iv) Representation errors due to the limited dynamic range and resolution available to telemeter the measurement. These errors have been evaluated by simulation and mitigated by changing the bit assignments for each data element or by changing the coding method.

Although several challenges remain, work this year has resulted in a major step forward towards an operational smart tag. Key milestones are now the completion of algorithm testing and demonstration of the data summary and telemetry algorithms in a functional multi-week tag.

IMPACT/APPLICATIONS

National Security

Concern about potential impacts on acoustically-sensitive cetaceans has constrained some Navy activities. The project is developing critical tag technology needed to study the effects of sound on cetaceans over extended intervals and under authentic conditions. This information will strengthen models of population-level consequences of sound and will aid in Navy planning.

Economic Development
Economic development brings increasing noise to the ocean from ship traffic, construction, and mineral exploration. An improved understanding of how noise impacts marine mammals will help to make economic growth sustainable.

Quality of Life
The project will contribute to our understanding of deep diving cetaceans and their sensitivity to human interactions. The techniques developed here will improve the efficacy of acoustic surveys facilitating improved regional management.

Science Education and Communication
The project is focused on disseminating information and developing capacity in the areas of behavioral monitoring of cetaceans and their responses to noise. Results from the project will be presented at conferences and in the scientific literature. Software and hardware products of the project will be freely available to the research community.

TRANSITIONS

A journal paper describing a sound compression algorithm has been published. This paper is supported by a web-site containing sound samples and open-source software to foster community-wide evaluation of sound compression and archiving methods. The compression algorithm has already been implemented in the open-source PAMGUARD software.

RELATED PROJECTS

Porpoises and seal tags (2012-2014): The German federal office of nature conservation (BFN) via a sub-contract with Hannover University is supporting the development and deployment of multi-day Argos-equipped DTAGs for porpoises and seals. These tags will be used to measure individual vocalization rates, movement patterns and ambient noise exposure of animals in Danish waters. The project has strong synergy with the ONR project: the BFN tags require a subset of the capabilities of the tag required for the ONR project thus creating intermediate milestones for development and evaluation. The BFN tag will be applied to by-caught animals that are temporarily restrained providing an opportunity to assess the performance of multi-day suction cup attachments on animals with known skin condition. Although ARGOS capability is required in the BFN tag simply to locate tags when they have released, we will use deployments of the tag as a low-risk opportunity to trial data summary algorithms developed under the ONR project.

Sound recorders and detectors for gliders (2012-2014): We are funded by NERC (National Environment Research Council, UK) and DEFRA (Department for Environment, Food and Rural Affairs, UK) to develop and deploy sound recording and detecting devices on ocean gliders. The devices are an adaptation of the Dtag-3 and use a prototype implementation of the smarttags software structure. They are thus serving as a no-cost development platform for the current project.
Long-term movement micro-tag (2012-2013): With funds from Aarhus University in Denmark, we are developing a miniature movement tag for marine and terrestrial animals. This ultra-low-power tag incorporates many of the design features that we propose here for smart tags and so will offer an implementation platform suitable for small animals and/or extended attachment times.

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Table 2: Summary of information needs agreed at the Smart Tags Workshop.

Type of information	**Priority [1]**	**Sampling interval**	**Data per day**	**Readiness [2]** *post / in situ*	**Caveats**
1. Behavioural states and activity budgets	H	hour	2 kB	C / C	Broad behav. states only. More specification needed to define states.
2. Energy expenditure	M	dive	< 1 kB	B / B+	Unknown BMR and relationship between movement and O_2 consumption.
3. Energy intake	H	dive	< 1 kB	B / B	Unknown prey quality.
4. Body condition	H	day	< 1 kB	B+ / B	Requires glides in descent and/or ascent. Deep divers only. May need speed sensor.
5. Ambient noise	L	minutes	2 kB	A / A-	Problem of flow noise. More validation required.
6. Exposure levels	H	minutes	15 kB	A / C	Needs more definition and validation. More difficult if detectors are required.
7. Vocalization counts	L	dive	200 B	B+ / B-	Limited to bouts of vocalizations. Group vocal behaviour is too difficult.
8. Locations	H	minutes to hour	1200 B	A / A	Fast-lock positioning involves some post-processing so tags can not know their positions.

[1] Priority of the information for the focus application: High, Medium or Low.

[2] Readiness was scored from A to C: Methods that we know how to do now scored an A. Methods that we still have little idea of how to implement scored a C. *Post* means in post-processing, i.e., with human supervision; *in situ* means an autonomous algorithm on a tag.

Table 3: Initial smart tag ARGOS packet definitions for beaked whales.

P1. Deep dive (approx. one per two hours)
General 31 bits
(duration, max depth, preceding IDDI[1], following respirations and surface duration)
Vocalisations 36 bits
(tagged whale click count, total click count, vocal duration, SOC[2] depth, EOC[3] depth)
Descent 40 bits
(duration, vertical speed, stroke count 0-100 m, stroke count 100-400 m, OBDA[4], sum sr3[5])
Bottom 26 bits
(movement index[6], OBDA, jerk events[7], median jerk depth)
Ascent 53 bits
(duration, vertical speed, stoke count 100-400 m, stroke count 0-100 m, B-stroke[8] count 100-400 m, movement index, OBDA, sum sr3)

P2. Dive and surface summary (approx. one per hour)
4 dives to any depth each with 46 bits:
(duration, max. depth, OBDA, sum sr3, movement index, following surface duration, respiration count)

P3. Ambient noise (two per hour)
3 ambient noise summaries each with 62 bits
(each is a 10 min average of L90 octave levels in 8 octave bands from 100 Hz - 20 kHz)

P4. Position (up to 8 per hour)
Single GPS acquisition with 186 bits
(precise time + SV number, SNR and pseudorange to up to 8 SVs)

P5. Sound exposure (15 per hour during exposure events)
4 sound exposure summaries each with 46 bits
(each is a 1 min average of L50 octave sound exposure level in 6 octave bands from 200 Hz - 10 kHz)

[1] Inter-deep dive interval in minutes.
[2] Start of clicking by the tagged whale.
[3] End of clicking by the tagged whale.
[4] Overall body dynamic acceleration as defined by Wilson et al. (2006).
[5] Sum of the stroking rate cubed, an alternative measure of locomotion energy.
[6] Index of straightness of travel using accelerometer and magnetometer.
[7] Peaks in the differential of acceleration, a proxy for prey capture attempts.
[8] Swimming gait changes related with anaerobic ascents in beaked whales (Martin Lopez et al. in prep.).
Note: all packets include a 38 bit header comprising date, time, packet type, and an error detection (CRC) code.

Table 4: Development status of smart tag in situ processing algorithms. Algorithm numbers correspond to the information class in Table 2.

Algorithm	**Method**	**Sensors**[1]	**Robustness**[2]	**Status**	**Applicable species**
1. Dive detection	Hysteretic detection	d	+ sensor + location	Matlab, C, tested	deep divers
1. Dive phases	Depth variation	d	+ sensor + location	Matlab, some testing	deep divers
2. Energy use	OBDA Sum sr3	a (OBDA) a, m (sr3)	+ sensor - location (OBDA) + location (sr3)	Matlab, C, tested	all
2. Gait	Specific acceleration estimation	a, m	+ sensor + location	Matlab, tested	Beaked whales
2. Respirations	Matched filter on depth	d	+ sensor + location	Matlab, C, some testing.	Beaked whales and some delpinids
3. Foraging	Differential of acceleration	a	+ sensor + location	Matlab, C, tested	all
4. Swimming strokes	Eigenanalysis of magnetometer variations.	m	+ sensor + location - parameters	Matlab, tested	all
5. Ambient noise	10 minute averages of L90 octave band levels	s	- speed - location	Matlab, tested	all
6. Exposure level	1 minute summation of L50 octave band levels	s	- speed - species	Matlab, testing required.	all
7. Click detection	Pre-whitened CFAR matched filter	s	+ ambient noise - parameters - location	Matlab, C, tested	Beaked whales and some delpinids.
8. Geographic position	FFT processing of GPS acquisitions	g	- location	Matlab, tested	all
8. Movement index	Direction of travel analysis	a, m	- sensor + location	Matlab, tested	all

[1]Sensor types: d = depth, g = GPS baseband capture, a = 3-axis accelerometer, m = 3-axis magnetometer, s = sound
[2]Robustness factors: + location = robust to tag location and orientation on the animal, + sensor = robust to sensor calibration errors, - parameters = sensitive to parameter choice, etc.

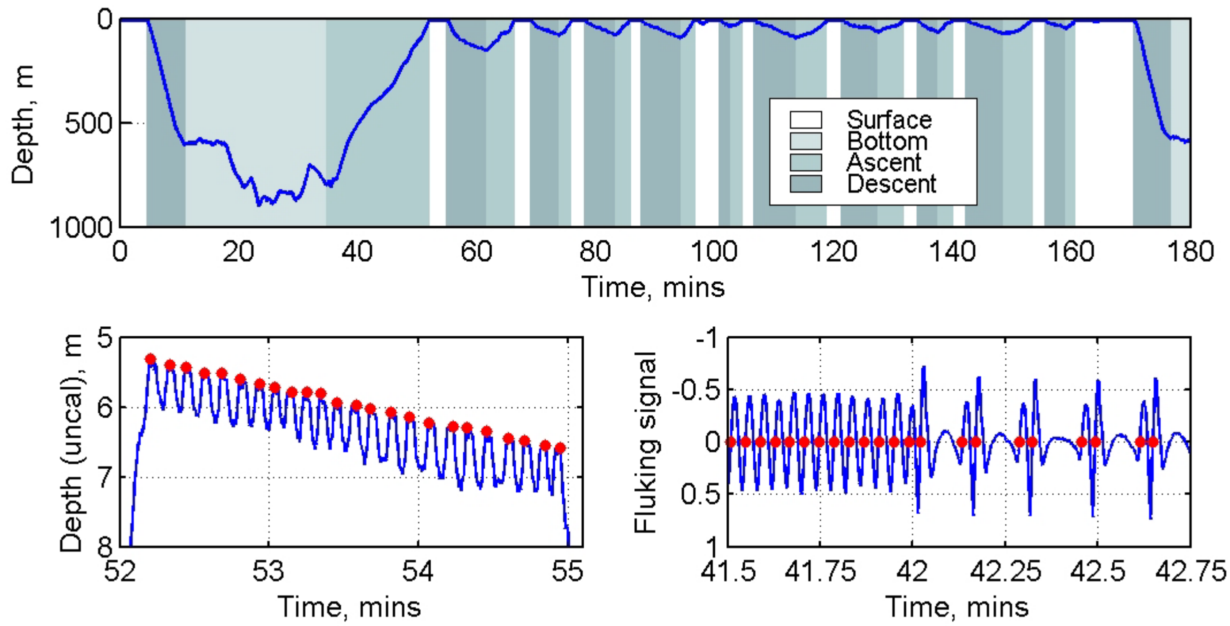

Figure 1: Performance of three in situ data processing algorithms. Upper: dive profile of a deep dive cycle by a Blainville's beaked whales with background colors indicating dive phases determined automatically from uncalibrated pressure data. Bottom left: surfacing interval from the same dive profile showing a temperature-related offset error. Red dots indicate respirations detected automatically. Bottom right: stroking signal derived from uncalibrated magnetometer data. Each oscillation indicates a fluke stroke and red dots show where these have been detected by the algorithm. The algorithm automatically compensates for the unknown orientation of the tag on the animal as well as the offset and drift of the magnetometer. The five large magnitude fluke strokes in this figure are an alternative gait employed by beaked whales to ascend from deep dives and which may indicate near exhaustion of aerobic resources in a dive.