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

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LONG-TERM GOALS

The project goal is to 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 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, this 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 prototype 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 work plan for the project comprised two base years and an optional third year. The goals in the base years were to: (i) establish the design philosophy and software infrastructure needed to implement a smart tag, (ii) develop on-board processing algorithms to calculate behavioural parameters from sensor data, and (iii) develop a prototype smart tag to act as a test platform for these algorithms. In the optional third year we proposed to transition the prototype design into a more integrated field-ready design suitable for larger-scale evaluation. This report covers the last months of the second base year. By agreement with the program manager, the optional third year was not activated. Instead, work in the current funding year was largely performed under a no-cost extension. This funding option was selected because of unexpected challenges encountered when developing the prototype smart tag which led to delays in fielding this device. The no-cost extension provided an opportunity to overcome the design issues and evaluate the prototype device before committing to a second phase of tag design. The extension also allowed us to take advantage of other funding opportunities to test prototype devices.

A workshop on smart tag design held in the first project year identified 8 sources of information as being fundamental to understanding the baseline performance and the impact of acoustic disturbance on marine mammals (Table 1). 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 existed at the time of the workshop and it was agreed that the *in situ* assessment of behavioural states, exposure level and body condition, in particular, are difficult problems requiring additional specification. Since the workshop, we have developed autonomous algorithms for 7 of the 8 information categories (a robust algorithm for body condition remains to be developed and is beyond the scope of the current project). Algorithm work in the current year has focused on establishing performance metrics for these algorithms and in evaluating them using data from the DTAG archive. The reference or ground-truth data used to assess performance has been derived either from more complex algorithms involving multiple sensor streams or from expert appraisal of carefully calibrated data. Complete implementations of the autonomous algorithms have been created in Matlab and the majority have also been implemented in C code for the DTAG to enable evaluation on a prototype smart tag. A paper describing the algorithms and the motivation for the smart tag processing concept is currently in preparation.

Work this year has also focused on the development of a prototype smart tag with the goals of demonstrating the readiness of sound sampling tags for extended duration deployments while providing a platform for field testing of the data summary algorithms. The protoype is based on the WHOI/SMRU DTAG-3, a sound and movement recording tag originally designed for short deployments. The DTAG-3 is the only tag design currently available with the range of sensors and the software and hardware flexibility needed to create a smart tag and so was the logical choice for the development platform. The prototype smart tag required the addition of a fast acquisition GPS, a combined ARGOS and VHF transmitter, and a new battery management circuit to radically extend the duration of the tag. Each of these design modifications has had ramifications on the physical, electrical and software design of this highly integrated tag. To reduce the risk of these changes and create intermediate milestones for testing, we identified two functional design end-points. The first of these is a short-term tag containing a GPS receiver and Argos transmitter but with the original power supply and longevity of the DTAG-3. This intermediate design is suitable for use on cetaceans using suction cup attachments and can operate for 2-4 days. The second design is a long-term smart tag which includes battery switching and power management enabling operation for up to 30 days. The greater size and longevity of this tag call for a different attachment method and we have designed this tag primarily for glue attachments as used on pinnipeds for initial evaluation. However, the tag design could be readily adapted to other attachment methods such as the LIMPET system developed by Russ Andrews and Wildlife Computers.

Several significant challenges arose in the development of these prototype tags which have required extensive design changes and testing. The status of these tasks is described in the following.

(i) High transient current consumption during Argos transmissions can lock-up the primary processor in the DTAG-3 leading to software failure. Although the lock-up condition can be detected and repaired, frequent outages result in instability and memory loss. This problem has been solved by re-programming the secondary processor in the tag for Argos transmission. In the 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 and has been trialed successfully in field deployments.

(ii) A substantial increase in battery capacity is required for long tag deployments and, to minimise size, this has been achieved by adding a primary (i.e., non-rechargeable) lithium battery. Physical design changes have been required to allow replacement of this battery after deployment (i.e., to re-fit the tag for another deployment) and significant circuit changes have been necessary to overcome the low voltage and high impedance of lithium batteries as compared to the lithium-ion cells conventionally used in the DTAG-3. These changes have now been made and are currently being evaluated in bench trials.

(iii) 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 reliable positioning in marine applications. We have therefore changed to a heavier ceramic antenna requiring the re-design of circuit boards, floatation and molds. These changes are now complete and the GPS is operational in the DTAG-3.

(iv) Field evaluation of the standard DTAG-3, performed in parallel with the current project, highlighted several potential failure modes in the mechanical design. As these problems would have major impact on the performance of the medium-term device required here, we invested significant effort in improving the packaging of the DTAG-3. Specifically, we replaced the oil-filled electronics section with a solid casting, changed the molding materials to avoid light sensitivity, and re-engineered the antenna. This work was partly performed under a related project funded by ONR (see section Related Projects).

(v) The software infrastructure of the DTAG-3 was designed primarily for simple data processing and efficient memory storage but was not optimised for computational real-time processing. Significant extensions were required to support the intensive data processing needed for sound data analysis. The improved software system has been tested extensively and is now field-ready.

The first implementation of the prototype smart tag, a short-term suction cup attached tag with high frequency sampling, was completed in May 2014. Two units were delivered to colleagues at Aarhus University, Denmark, for field testing on harbour porpoise. All animal testing work was performed by Aarhus personnel as part of a separate project funded by the German Environmental Ministry (BFN). The short-term tags were first tested on captive porpoises at the Fjord & Baelt Center in Denmark to verify suitability for this species. The tag were then trialed on wild porpoises by-caught in fishing weirs under a permit held by Dr. J. Teillmann from the Danish Government. The porpoises were temporarily restrained (approx. 10 minutes) while the tags were attached and were then released from the weir. Tags were recovered 4 days later using Argos and VHF tracking. For the first wild deployment, the tags were programmed to send preset data in Argos transmissions rather than on-board processed data to minimize any risk of software failure. However, as both tags were recovered successfully, a subset of the smart algorithms will now be ported to these devices for field testing. Testing will continue until about the end of November 2014 and will likely resume in April 2015. All testing work has occured at no cost to the current project.

The second prototype smart tag design is the medium-term seal tag which is capable of 30 day operation at a 48 kHz sampling rate. Two units are currently being manufactured and will be trialed on captive animals in late 2014. If captive tests are satisfactory, devices will be deployed on wild animals in early spring 2015. We initially planned for this version of the tag to be released from the seal when hauled-out using a Wildlife Computers radio release system. However, due to production difficulties, this release has been withdrawn necessitating the development of a floating version of the tag together with an alternative, self-timing release. This modified tag is now being readied for evaluation.

In addition to the two prototype designs, we have also taken advantage of opportunities to test partial devices at no cost to the current project. In particular, a multi-month DTAG with dual power sources and a subset 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. This application has provided an opportunity to field test the software under relatively realistic conditions without requiring animal attachments and has highlighted a number of errors which have since been fixed.

RESULTS

Work this year resulted in the completion and fielding of prototype smart tags as well as continuing evaluation of robust real-time algorithms for data summary. Deployments of the prototype smart tags are important not only to verify operation of this system but also to evaluate the real data throughput of the Argos telemetry link. To date, two deployments of the short-term prototype on wild harbour porpoises have been attempted (Fig. 2). One tag remained attached for about 22.5 hours, a typical attachment longevity for suction cups on a porpoise, and then floated at the surface for the following 46 hours before recovery. While floating, the tag transmitted Argos data packets every 2 minutes. Of the 1385 transmissions made by the tag, 176 were received via the Argos system representing a potential average data throughput of 2 kbytes/day with a power cost of 0.5 J/byte. The high rate of missed transmissions is to be expected given the relatively low duty cycle of suitable satellite passes and probably represents a typical performance level. In practice, the achieved throughput will be even less than 2 kbytes/day as each data packet is transmitted several times to increase the odds that it is received, thus a number of the receptions will not contain unique data. The second prototype tag detached from the animal after only 0.5 hour due to high speed swimming when the animal was released. It then floated at the surface for 54 hours. Of the 1641 packets transmitted by this tag, only 12 were received giving a throughput of just 124 bytes/day at a cost of 8.8 J/byte. This poor performance was due to the tag being fouled by seaweed soon after it released from the animal. The seaweed load pulled the tag antenna partially below the surface and transmission was likely only possible when the tag was elevated by a swell. These results provide an indication of how sensitive the Argos telemetry link is to extraneous factors and serve as a reminder that performance will vary widely from tag to tag in real applications.

Some improvements in data throughput are possible. The tags could transmit at up to twice the rate (i.e., a transmission every minute) with a single Argos ID giving a throughput of 4 kB/day. It may also be possible to transmit with multiple Argos IDs to obtain a further doubling of the data rate. Thus, data rates of up to about 8kB/day may be achievable in good conditions but this would require a substantial power source (approx. 1 Whr per day) if a blind transmission scheme is used as in the prototype tag trials. Increased power efficiency could be achieved by scheduling transmissions to coincide with satellite passes. This requires that the tag is programmed with an almanac of Argos orbits before deployment and that it has a rough idea of its own location. While this is not impractical, it involves a substantial increase in code complexity with an attendant risk of failure.

Additional deployments of the prototype tags will be performed in 2014 and early 2015 funded under the German BFN grant and we will monitor performance during these to construct a predictive model for data throughput and power consumption. However, the results so far provide a useful indication of the potential performance of a smart tag. Evidently, realistic data throughputs are extremely low for Argos telemetry from a small floating tag and a power source of 15-30 Whr (depending on the efficacy of the transmit scheduling algorithm) will be needed to transmit the nominal 250 kB data summary from a 3 week animal attachment. An additional 15-20 Whr would be required to power sound and movement sampling in the tag during attachment. The combined power requirement for a 3 week smart tag is then 30-50 Whr, necessitating a lithium size D cell (approx. 55 Whr). Alternatively, the tag could be powered by a smaller C size cell while attached to the animal and could then harvest power with a solar panel, transmitting Argos messages whenever it has sufficient power to do so. This second option would result in a physically smaller tag making it suitable for a wider range of attachment methods but would likely provide a lower telemetry data rate.

In algorithm design work during this project we have identified 5 self-contained Argos data packet types (Table 2) that are needed to convey the behavior, movement and sound exposure experience of a deep diving whale. Packet types 1-4 would be transmitted continuously during a tag deployment. As each packet represents two or less hours of observation, the loss of some of these packets through Argos may be tolerable. To minimize data transmission, sound exposure packets (P5) would only be collected during pre-programmed time intervals, e.g., bracketing a scheduled playback. Packets collected during these intervals have increased value and so would be transmitted more times each to ensure delivery. To populate the packets in Table 2, we have developed a set of 12 data summary algorithms (Table 3, Fig. 1) which generate the majority of the information highlighted as critical in the workshop. These algorithms have been tested using DTAG data and improved iteratively to maximize performance and robustness. In doing so we have established that norm-jerk (i.e., magnitude of the acceleration rate) in a constant false-alarm rate detector is an excellent proxy for prey capture events in a range of species from seals (Ydesen et al. 2014) to beaked whales and pilot whales. We are currently preparing a paper demonstrating this by a receiver operating curve (ROC) comparison with independent foraging-rate information. We have used the same ROC approach to establish the performance of algorithms detecting dives, strokes, clicks, respiration and gait changes. We have also found that a combination of activity metrics, specifically ODBA (Wilson et al. 2006) and the sum of the instantaneous fluking rate cubed, provide a more consistent indication of energy use in dives than either metric alone, and we have completed robust algorithms for both proxies.

The data summary methods have been explicitly designed for *in situ* processing and so require neither accurate sensor calibration nor behavioral context. Many of the algorithms are also insensitive to the orientation of the tag on the animal, a significant improvement over currently-used methods with special relevance for tags that are deployed on unrestrained animals, e.g, with a pole or gun. 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 automated data processing in other taxa.

As this is the final report for the project, we offer some recommendations for follow-on work with smart tags. The hardware platform used here to demonstrate the smart tag approach comprises a substantial modification of the DTAG-3 which has been time-consuming to produce. Although this design has the advantage of a large memory array for continuous recording in case the tag is recovered, future disposable smart tags may benefit from leveraging existing commercial tag designs that have GPS and Argos capabilities and which already use the required long-term attachment, e.g., a LIMPET tag. These devices could be turned into smart tags at relatively low cost with the addition of a small sound and movement processing board communicating with the main tag processor. The extremely low realised data rates of the Argos link and severe battery power constraints may also require a re-evaluation of the data processing strategy. The dive-by-dive data summary algorithms developed under the current project are, by design, unaware of exposure condition when used in a behavioral response study. This has the benefit that the data is not confounded by changing resolution in the pre-, during, and post-exposure periods making it simpler to analyse. But more complex adaptive sampling strategies (e.g., lower duty cycle sampling outside of the interval around exposures) may be the only option to convey sufficient information within the telemetry and battery constraints. Both approaches have implications on both the probability of detecting responses and interpreting them reliably which must be evaluated carefully.

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. Real-time sound detecting devices based on the DTAG-3 and smart tag algorithms are currently being used in ocean gliders to detect and estimate the abundance of cetaceans.

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 smart tags 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 1: Summary of information needs agreed at the Smart Tags Workshop.

Type of information	Priority1	Sampling interval	Data per day	Readiness2 *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.

1Priority of the information for the focus application: High, Medium or Low.
2Readiness 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 2: Initial smart tag ARGOS packet definitions for beaked whales.

<table>
<tr>
<td rowspan="4">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)</td>
<td>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)</td>
</tr>
<tr>
<td>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)</td>
</tr>
<tr>
<td>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)</td>
</tr>
<tr>
<td>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)</td>
</tr>
</table>

[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 3: Development status of smart tag in situ processing algorithms. Algorithm numbers correspond to the information class in Table 1.

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	deep divers
2. Respirations	Matched filter on depth	d	+ sensor + location	Matlab, C, some testing.	most non-logging surfacers
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, porpoise 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.

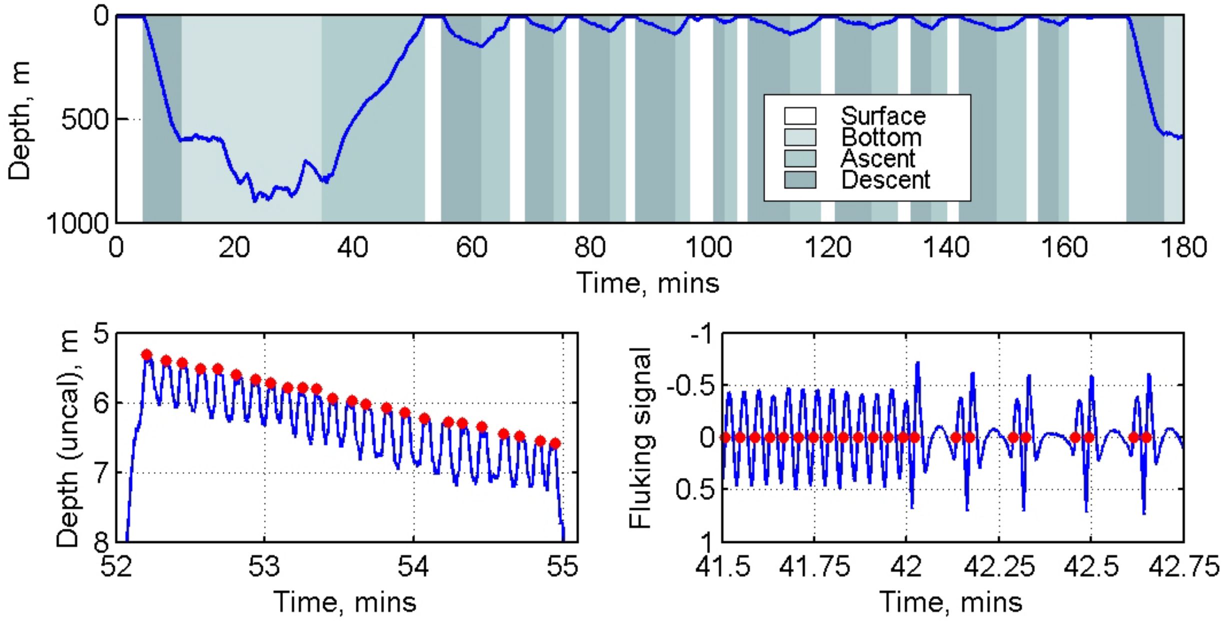

Figure 1: Performance of three in situ data processing algorithms. Upper: dive profile of a deep dive cycle by a Blainville's beaked whales with background colors indicating dive phases determined automatically from uncalibrated pressure data. Bottom left: surfacing interval from the same dive profile 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.

Figure 2: Prototype high frequency smart tag attached to a harbour porpoise in Denmark. This short-term version of the tag can record and process data for two days at the high sampling rate needed for porpoises. Operation for up to 4 days would be obtained on lower frequency cetaceans such as beaked whales.