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Overcoming the Constraints of Long Range Radio Telemetry from Animals: Getting More Useful Data from Smaller Packages[1]

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SYNOPSIS. Many species carry out their most interesting activities where they cannot readily be observed or monitored. Marine mammals are extreme among this group, accomplishing their most astounding activities both distant from land and deep in the sea. Collection, storage and transmission of data about these activities are constrained by the energy requirements and size of the recording loggers and transmitters. The more bits of information collected, stored and transmitted, the more battery is required and the larger the tag must be. We therefore need to be selective about the information we collect, while maintaining detail and fidelity. To accomplish this in the study of marine mammals, we have designed ''intelligent'' data logger/transmitters that provide context-driven data compression, data relay, and automated data base storage. We later combine these data with remotely sensed environmental information and other oceanographic data sets to recreate the environmental context for the animal's activity, and we display the combined data using computer animation techniques. In this way, the system can provide near real time ''observation'' of animal behavior and physiology from the remotest parts of the globe.

INTRODUCTION

No one would argue that controlled laboratory experiments do not play a crucial role in understanding physiological and behavioral processes. But the papers presented within this symposium have clearly demonstrated that the behavior and physiology of animals must be studied in nature to fully understand their adaptive significance and function. Technological developments in digital electronics and wireless telemetry make it possible to broaden the spectrum of measurements possible in the field and reduce effects of the measurement process on the creatures being studied. Miniaturization of electronic components and reductions in the power they require combined with increases in computing power have made it possible to program complex measurement and sampling operations into very small packages. However fundamental constraints remain to limit what we can do. Here we discuss approaches to circumvent some of the constraints of telemetry systems.

Telemetry or recording systems on animals are typically used to keep track of the position of particular individuals, monitor their behavior, gather information on their physiology and condition and/or send measurements about their environment. Each bit of information captured, stored and transmitted requires the use of a small amount of energy, typically from a battery. Because battery size often is the primary determinant of overall package, size and size and mass are usually crucial design considerations, a fundamental requirement is to capture as many useful bits of information as possible while minimizing energy utilized. How can we design our systems to accomplish this?

Marine mammals arguably present one of the most challenging situations for telemetry and effective field study. They spend little or no time ashore; they range over global distances; they spend most of their time at sea under water, often at great depths; and their streamlined, hydrodynamic shape make attachment of devices difficult. Thus they provide an interesting case study for a discussion of the development of effective telemetry systems and a consideration of fundamental constraints on them.

APPROACH

Data storage or transmission?

Transmitting information is often more costly in energy terms than recording it. Because it is now possible to store very large quantities of information in small volumes without large energy costs, animal-mounted recording devices that can be recovered some time after attachment present the opportunity to reduce energy costs. Time/depth recorders (devices that measure and store depth at predetermined intervals) pioneered by (Kooyman, 1965) revolutionized the study of marine mammal diving in the last 3 decades by providing a means of recording the depth trajectories of dives performed in nature. Modifications of this technique provide the most commonly used approaches to the study of marine mammal behavior at sea and have been extremely effective. As electronic digital data storage media become more compact, even capture of very broadband information such as audio and video may become feasible for extended periods. However, recording devices have limitations. They must be recovered, usually requiring that the animals they are placed on be recaptured. This is not always possible. Furthermore, recording devices can usually only provide information on animals that live to be seen again and this may bias the information collected. Indeed, we are often interested in not just animals that

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live but also those that don't and how and why they die.

Some form of telemetry provides a way to circumvent the constraints of recorders and can provide information in real or near real time and possibly provide for two-way communication with measuring devices. But telemetry systems also have limitations. Here we discuss several approaches to get around the fundamental constraints of any telemetry system; delivering maximum information from small, low power packages. We make no attempt to survey the range of commercially available products that utilize satellites to collect and relay position and dive behavior information. There are several suppliers that use different instruments and approaches (The monthly *Argos News Letter* ⟨*http://www.cls.fr/html/argos/general/newsletter_tout_fr.html*⟩ provides updates). Each has advantages and disadvantages, and choice usually involves trade-offs on size, longevity and data coverage. We will confine our discussion to a particular system designed by ourselves to study marine mammals but the approach is one that has broad applicability. In the most general terms, the idea is to put data collection, storage and transmission of information under the control of flexible, responsive software to produce ''intelligent'' data logger/transmitters that can structure information prior to transmission. These must incorporate models of the system being studied so that data can be organized, compressed and sent with minimum redundancy and appropriate resolution and so that each bit of information sent is important. By this means, we get the most useful bits of information per unit of energy expended. In this way, small packages can provide information on complex systems, with minimum impact on natural behavior.

Choice of transmission modes

There are three ways to send information from marine mammals: acoustic, conventional radio to terrestrial or ship based receivers and satellite-linked radio. Combinations of modes are possible and often desirable. All are useful in particular circumstance and have been used successfully in studies of marine mammals (Bishop and Last, 1995; Andrews, 1998; Gillespie, 2001; Gunn and Block, 2001; Voegeli *et al.*, 2001). Because seawater is opaque to radio waves in the practical frequency bands, acoustic transmission is the only mode that allows information to be radiated in real time from marine mammals. However acoustic signals at realistic wavelengths tend to have limited range and require that animals be followed by boat. This is expensive, time consuming and often not practical. Radio telemetry offers the possibility for longer-range transmission, but because many marine mammals' most interesting behaviors and physiological responses occur below the surface, this modality requires that data be collected during dives and stored for later transmission when animals surface. Another limitation is that practical frequencies usually require ''line of sight'' to the antenna at the time of transmission. This means that receivers have to be relatively near to the transmitters or have to be located far above the ground to maintain contact. Given the near global distances that many marine mammals travel, relaying information using satellites is one of the few options that do not require tracking the animal with ships or aircraft. However, satellite relay imposes other stringent requirements. Signals must be strong enough to reach the satellite and conform to the communication protocols imposed by the satellite system. These can be restrictive. However, if these restrictions can be overcome, the potential of global near real-time ''observation'' and data collection from freely ranging animals, world wide, is a realistic possibility. This is the end to which we have worked.

Several different satellite relay systems that might be useful for animal telemetry have been developed and proposed (Bishop and Last, 1995). None (including Argos-see below) are designed expressly for animal telemetry; they are primarily for other functions such as global phone calls, text messaging or emergency use and none therefore are ideal. Several have been implemented but have failed commercially and have been decommissioned. Of the options available, the Argos system (System Argos, Toulouse France) has been the most successfully used for global animal telemetry. One of its stated primary functions is for ecological research and monitoring. While the greatest use of the system has been for sending data from oceanographic and weather buoys, animal telemetry is providing a rapidly increasing fraction. The system has some drawbacks for telemetry from marine mammals. Transmitters that are certified to communicate with Argos must conform to very strict frequency tolerances. Individual messages (termed ''uplinks'') may be up to 960 msec in duration and it takes 2 or more complete uplinks for the system to compute a location. (The accuracy of these locations depends on the number of uplinks received, the temporal pattern of these receptions and the position of the satellite relative to the transmitter.) Uplinks may contain a maximum of 256 bits (32 bytes) per message in a rigid format and Argos sets a minimum interval of 40 sec between transmissions (Argos, 1989). These restrictions, combined with the fact that animals are only briefly and infrequently at the surface (for example, 10% of the time in two minute segments for elephant seals), places unusually tight limits on bandwidth. These and those limitations caused by energy constraints both demand complex data collection software and extreme data compression, which in turn demand a sophisticated data collection platform. This bandwidth restriction is compounded by the fact that satellites are not always visible. However, the data transmission restrictions resulting from energy constraints and Argos restrictions do not interact in an additive way and steps taken to get around Argos limitations also serve to help avoid energy constraints.

The upcoming addition of two-way communication with the Argos system (planned to become operational in February, 2002) will allow the transmitter to ''know'' that a data string has been successfully received. This can potentially result in a dramatic increase in energy efficiency by avoiding the need to repeat transmissions, perhaps the single most important factor reducing efficiency at present. It will also open up the possibility for users to direct changes in sampling protocols in response to changes in the data being collected.

METHODOLOGY

What follows is an overview of the hardware and software we have developed to study marine mammals at sea using Argos to relay information. We emphasize the strategies of data collection, compression and transmission that make this possible. This system has evolved over the last decade. It has been in routine use for most of that time, while simultaneously being further developed to enhance its capabilities. Our original goal was to build a flexible system that would provide the basic information on where animals go at sea and what they do while out there. It would also have the capability to collect local environmental data from near the animal. We also wanted to express the data collected in a geographical context based on other oceanographic and geophysical data sets linked spatially and temporally to the animal's behavior. A further goal was to provide all this information in an easily accessible form. In effect, we wanted to achieve the next best thing to direct observation. Because the data necessarily involved complex spatially and temporally varying interrelated data, we also chose to present the collected data and other data sets within a data visualization system (MAMVIS) that would produce easily interpretable animated views of the animal's behavior and environment. This system is described in more detail in Fedak *et al.* (1996).

The system currently works by attaching a package (called a **S**atellite **R**elayed **D**ata **L**ogger or SRDL) to an animal (glued to the fur of seals or pinned through the dorsal fin of whales) to collect, compress, store and transmit data to the Argos satellite (see Fig. 1). The satellite then relays the data to ground stations that process the information, compute the location from which the message was received and place the location and raw data on a database. This Argos database is interrogated automatically every 3 hr by our computers and the data is automatically loaded into a local database and decoded. This decoded data is then viewed using the MAMVIS software that allows 3D views of the geographical and diving data to be created on screen along with other environmental information (see below).

Functionally, the SRDL consists of two parts, a data logger and a transmitter (Fig. 1). The logger is built around a controller (programmed in C) that is linked to data inputs and memory. It has two primary functions. The controller monitors the animal's behavior and processes and compresses this information into records of behavioral events such as dive cycles, extended surface periods or, in the case of seals, excursions on to land (haulouts). Depth, swimming speed, temperature and surface sensors are sampled at programmed intervals (*e.g.,* 4 sec for some seal species) and these raw data are organized into records of behavior which can be grouped in appropriate ways and stored in memory for later processing and transmission. For example, individual dive cycle records (consisting of a dive and the subsequent surface period) are created which consist of dive and surface duration information and depth-swimming speed profiles. In addition, information is collated into summary records, which can be programmed to cover longer periods (typically between 2–6 hr). These can include counts and times of events or states (such as haulouts or breaks in diving), average values (*e.g.,* of dive depths or surface durations), histograms, distance covered (odometer), temperature-depth profiles and many other parameters. The SRDL also collects and organizes ''diagnostic'' information about its own behavior and internal state and these can be included in transmitted messages.

The controller also schedules data transmissions. It groups data records into ''pages'' of information for transmission. These pages consist of information about particular aspects of behavior or tag diagnostics grouped together into 256 bit units, the maximum number of bits allowed in a single Argos message. For example, detailed data about 3 dives (including depth, swimming speed and surface interval information) can be combined with some diagnostic information and error checking/correcting codes to make up a page of 256 bits. Another page may consist of haulout and summary information. Other pages are formed with other combinations of information. Sets of pages can then be stored in a transmission queue and linked to information about when they were formed, how many times they have been transmitted and ''sell-by dates'' that determine their longevity in the queue. These pages can then be scheduled for transmission using this information and depending on the required probability of reception.

The controller determines when the antenna is at the surface and schedules which pages are to be sent. This can be done on a fixed or context-specific basis. It also adds error correction codes and other required housekeeping information. Control functions and data gathering functions are kept as independent as possible so that the SRDL software can be adapted to the behavior of a variety of species and scientific objectives.

The second part of the SRDL is a UHF transmitter which, when activated, sends selected data records, compressed and coded by the controller to Service Argos receivers on board one of two or three polar-orbiting NOAA satellites. It serves as a simple modem, broadcasting the pages at times decreed by the controller. We have used transmitters from a variety of external producers, including Toyocom (Tokyo, Japan), Microwave Telemetry (Maryland USA) and Sei-

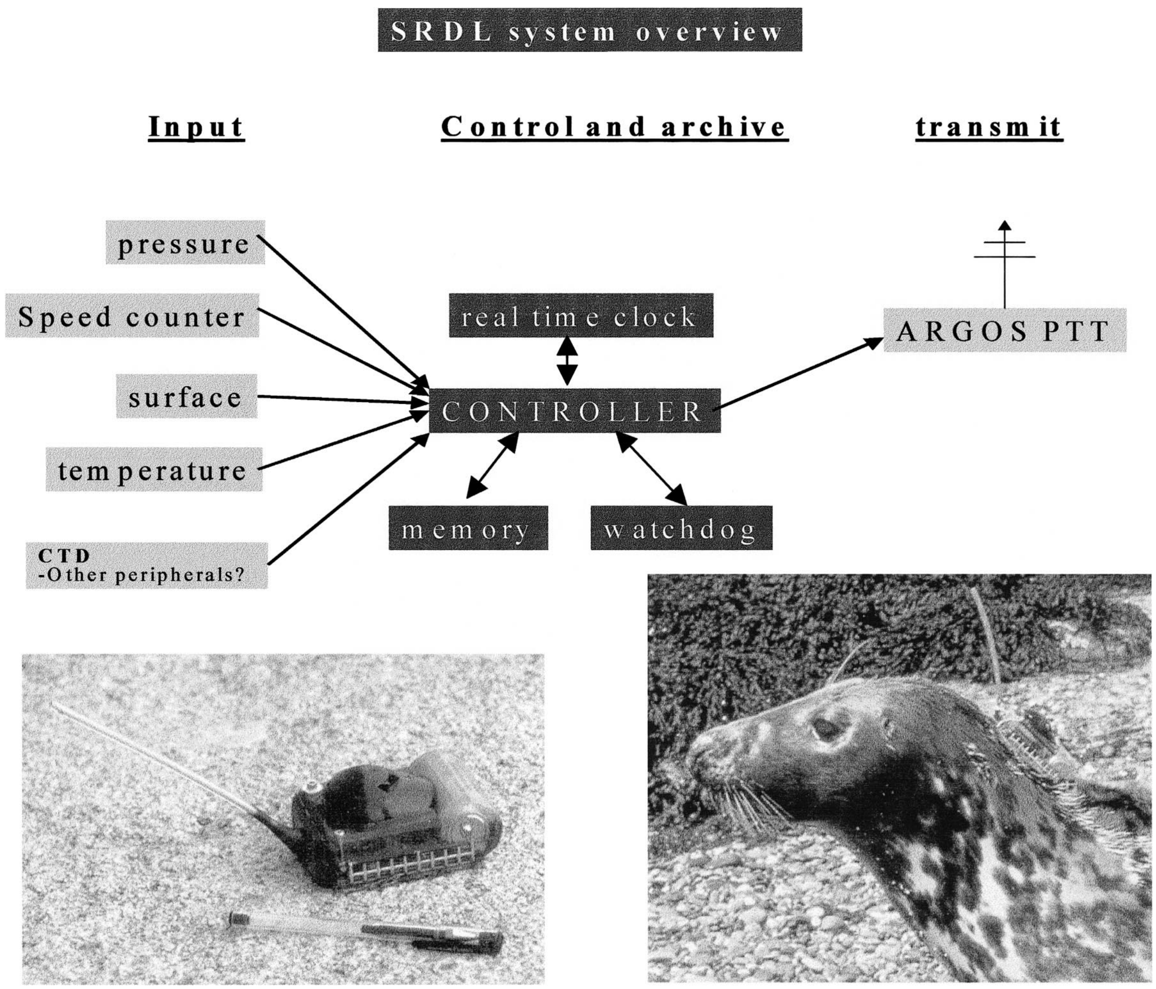

FIG. 1. A schematic of the functional elements within the Sea Mammal Research Unit's satellite relayed data logger along with photos of one version of the tag. The device contains a controller programmed in a high level language that controls data collection and storage functions as well as data compression and transmission strategies. It sends messages via the transmitter to the Argos system which relays information to ground stations for automatic dissemination to a local database. The left hand photo shows the tag in the form typically used on seals. The right-hand photo shows the tag glued to the fur of a yearling gray seal (*Halichoerus grypus*).

mac (Nova Scotia, Canada). The Argos system identifies the transmitter and calculates an estimate of the position on the sea surface from which it was sent. This information is disseminated over a computer network from an Argos ground station and processing center and is stored at SMRU on an Oracle database, where it is also automatically decoded.

Data collection, compaction and transmission strategies

The first challenge we face is to sample, without bias, a range of complex, sometimes rapidly changing data. We must then overcome the bandwidth and energy constraints of transmission by reducing the data volume without losing important information, necessary resolution or introducing bias. After receiving the data, we decode and expand it to produce an informative description of the animals' lives that is immediately accessible to individuals who may have little experience with the data collection methodology.

The key elements in our strategy to accomplish these ends were the following: First, we collect data at full resolution. Then we create effective models of behavior to segment and structure the data. An example of how this is done is shown in Figure 2. This allows data to be stored in an effective way and makes it possible to create useful summaries of the behavioral data. Then we describe the interesting aspects of each behavior type at the appropriate scale so that we can compact it sufficiently to fit within the narrow bandwidth available to send it. We do this by eliminating redundancy and selecting only the most salient data at the minimum necessary resolution. We invent indices that extract and emphasize only those aspects of the data that are of interest. We generate summaries and mix data types to create synergies and provide a combination of synoptic and detailed coverage.

For example, we may be interested in describing an animal's behavior when they are near the surface or in shallow water. To accomplish this we may need to de-

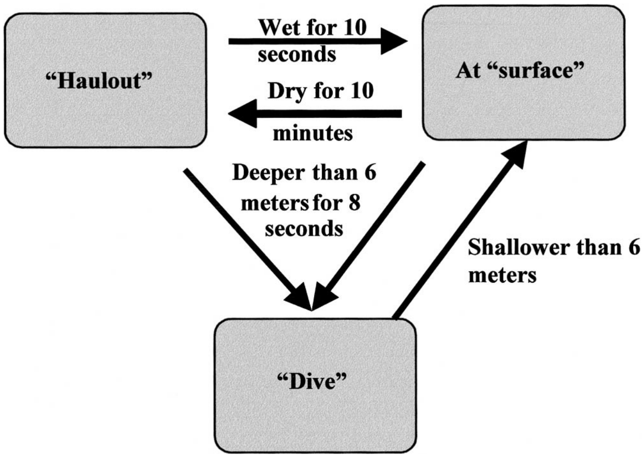

FIG. 2. The ''model'' of seal behavior used by the tag to assign data to appropriate behavioral states. The values chosen are typical for some deployments but can be set to whichever may be appropriate. As far as the tag is concerned the seal must be in one of 3 states; either diving, hauled out or at the surface. Using simple rules that can include hysteresis, the tag assigns the behavioral state and collects, synthesizes, stores and transmits data appropriately.

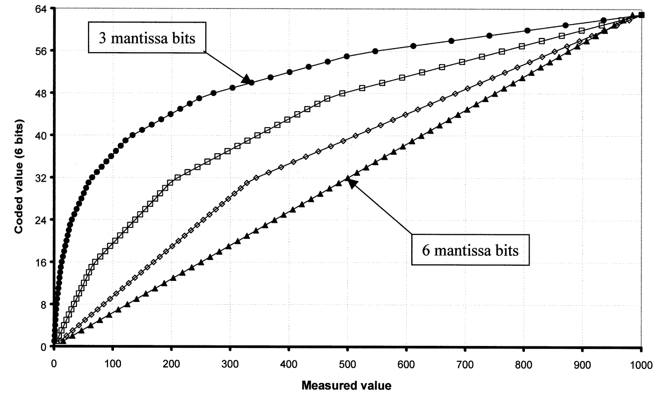

FIG. 3. An example of ''pseudo-log encoding'' that allows variable resolution to be delivered based on requirements related to the absolute value of the data being encoded, thus saving bandwidth. The plot shows a family of four pseudo-log curves that each represent a measured value (*e.g.*, depth) in the range 0 to 1,000 using 64 discrete values (6 bits). The straight line, shown with solid triangles, is equivalent to a pseudo-log with 6 mantissa bits and no exponent bits. Its resolution is equal throughout the range of measured values. The codings shown by diamonds (5 mantissa, 1 exponent), squares (4 mantissa, 2 exponent) and circles (3 mantissa, 3 exponent) provide successively finer resolution for small measured values at the expense of coarser resolution for larger values.

liver depth data at a resolution of 1 m. But when an animal is diving to depths of 1,000 m or greater, a resolution of 10 m or even 100 m might suffice. We can save bandwidth by adjusting the resolution of the dive depth data sent to that required at the particular depth of the dive by presenting the data in ''pseudo-logarithmic'' form (Fig. 3). By choosing appropriate mantissas and exponents, we can increase the resolution at shallower depths and degrade it at greater depths.

The time/depth profiles of individual dives can often tell us much about the behavior of marine mammals and provide clues as to what they might be doing (*i.e.*, feeding, resting, travelling, etc.). However, the data content of a profile in its raw state as collected is much too large to be realistically accommodated within the available bandwidth. Therefore we developed algorithms to select and send only the important inflection points within that profile (Fig. 4). This can dramatically reduce the number of bits of information required to describe a time/depth profile while retaining the essential information. While the tag collects depth information on a very fine temporal scale (typically taking a depth every 4 sec), the transmitted profile contains only a few of the most important time-depth pairs, including the maximum depth and time as well as a measure of the fidelity of the simplified profile to the full resolution profile.

We also send data on many dives for which only the maximum depth and duration of the dive are transmitted, drastically reducing the information sent. To add value to this information, we have created an index related to the dive profile shape whose value tells us where the animal centered its activity in the range of depth visited in a particular dive (Fedak *et al.*, 2001).

The effectiveness of the data reduction can be illustrated with an example of a typical 20-min dive of a southern elephant seal (*Mirounga leonina*). If dive data were sent at full resolution as collected by the tag, a single dive including a time/depth and speed profile would require approximately 6,000 bits of information. The same dive sent as a detailed dive record including inflection points and swimming speeds in each dive segment requires only 78 bits (including various over-

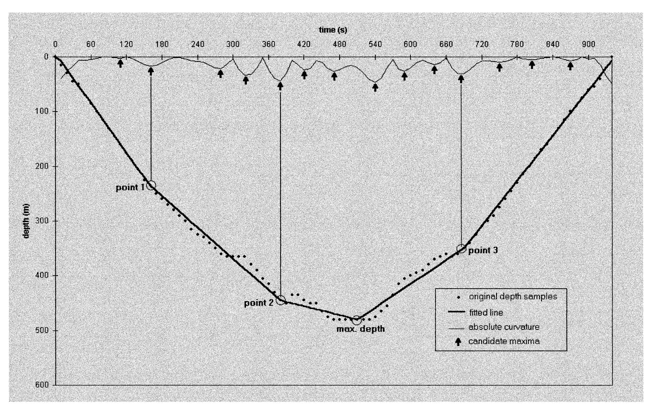

FIG. 4. Choosing inflection points from a seal time/depth profile. The example shows a full temporal resolution plot of depth values collected from an elephant seal dive along with a plot of the curvatures along that profile. The SRDL uses an algorithm based on the absolute curvature of the profile (*i.e.*, second derivative of depth with respect to time) to select the times within the dive where the dive trajectory changes most quickly (Fedak *et al.*, 2001) thereby creating an abstracted representation of the dive profile using fewer bits of information. It returns the maximum depth of the dive along with the time during the dive when it occurs along with the other three most significant depth/time pairs and with a measure of how the simplified profile deviates from the full resolution profile. The profile effectively breaks the dive up into segments to which other measures (*e.g.*, swimming speed measures) can be related.

heads) and only requires 18 bits when sent in the least detailed form (where only maximum depth, duration, average speed and shape index are sent).

A tag on a typical deployment collects about 500,000 bits of information each day but only attempts to send about 10% of these bits as compacted records. But there is an even more dramatic loss in the amount of information successfully received without error by the satellite. Of the approximately 500,000 bits collected each day, 50,000 bits are sent but typically only 5,000 bits are received either because no satellite was above the horizon or other signals interfered with reception. Further, we have no way of determining which messages have been successfully captured. We can only make probabilistic estimates of reception by modeling the likelihood of messages being sent and satellite availability. To achieve an acceptable probability of receiving a particular item of information, we must send that information several times. This lack of feedback on successful reception is the single most important factor influencing the energy cost per bit of information received. It is this problem that two way communication could solve, provided the space and power requirements of the necessary receiver on board the tag are kept very low.

Choosing which data to send and when to send it therefore can make large savings in transmission requirements. Since we can only relay a sample of all dive records, we must insure that our sampling protocol avoids bias. For example, the probability of a successful data uplink may be greater when an animal is resting near land in shallow water compared to when it is travelling at sea. If we were simply to send the last dive records obtained prior to transmission, there would be a bias towards shallow dives. We have used a variety of strategies to both avoid bias and to maximize behavioral coverage with the minimum of attempted transmissions. We store and resample data to insure that transmitted data are representative and so that the probability of data being received is independent of the transmission schedule. Because of the one-way transmission of information, we never know whether a given transmission is received successfully. This requires that we prioritize data in relation to energy cost and required coverage. Messages that must have a relatively high probability of reception need to be sent more often than those that are less important. For example, if we want to receive complete behavior summary information over the entire deployment, messages containing this information will have to be repeated many times. Less critical information can be sent less often with the proviso that some of it will not be received. By using large message buffers to store information for transmission, we created a pool of information that can be randomly sampled and sent over time without too much repetition. By attaching ‘‘sell-by dates’’ to this information it can be purged from transmission buffers so that new information can be added.

We can also make the choice of information sent depend on the behavioral state of the animal. For example, different transmission strategies are employed when animals are ‘‘hauled out’’ on land compared to when they are at sea, diving. We can take account of satellite availability and enable transmissions only when there is a certain probability of a satellite being overhead. We also give the tag control over managing its own power budget, to a certain degree. Because the tag can log the number of transmission it makes and has a clock that keeps track of real time, it can be given a transmission budget, broken down in pre-programmed times of day, which it can not exceed, based on the desired longevity of the tag. But if it fails to get the opportunity to reach that limit, it can use the surplus at another time so that it makes full use of the energy supplies on board and runs out of energy when it should.

The lack of feedback on successful reception is the single most important factor influencing the energy cost per bit of information received. If the Argos system provided this feedback in a way that does not place unsupportable power or space demands on tags, it would have profound implications for the amount of data collected from a deployment. Given the system in place at the time of writing, all we can do is make judgements about the coverage of each behavior category that is desirable, consider the cost of the information in bits, model the likely reception rate, choose a ‘‘page schedule’’ that seems to fit and put out the tags and hope.

Data visualization software

Despite the data bottleneck that results from Argos constraints and energy limitations, the quantity of data received can seem overwhelming. The role played by the MAMVIS visualization system is a crucial one in allowing us to get the full value of the information we send and allow us to gain an immediate appreciation of the activities of the animals we study and the environment through which they move.

Remote sensing, ship based surveys, topographic databases and sophisticated models now provide detailed but very complex information on many aspects of the marine environment. The inter-relationships between the three-dimensional movements and behavior of animals and the spatially and temporally mapped oceanographic data sets can be extremely difficult to explore numerically. Therefore we developed a system that allows the simultaneous display and exploration of these data sets. MAMVIS is based on AVS (Advanced Visual Systems Inc., U.S.), a three-dimensional visualization environment and consists of a network of AVS modules, most of which were written specifically for this project. The software development was originally funded in part by the U.S. Office of Naval Research and the UK Natural Environment Research Council, and both the AVS modules and network are in the public domain.

MAMVIS generates a three dimensional scene of underwater topography (Fig. 5), based either on global

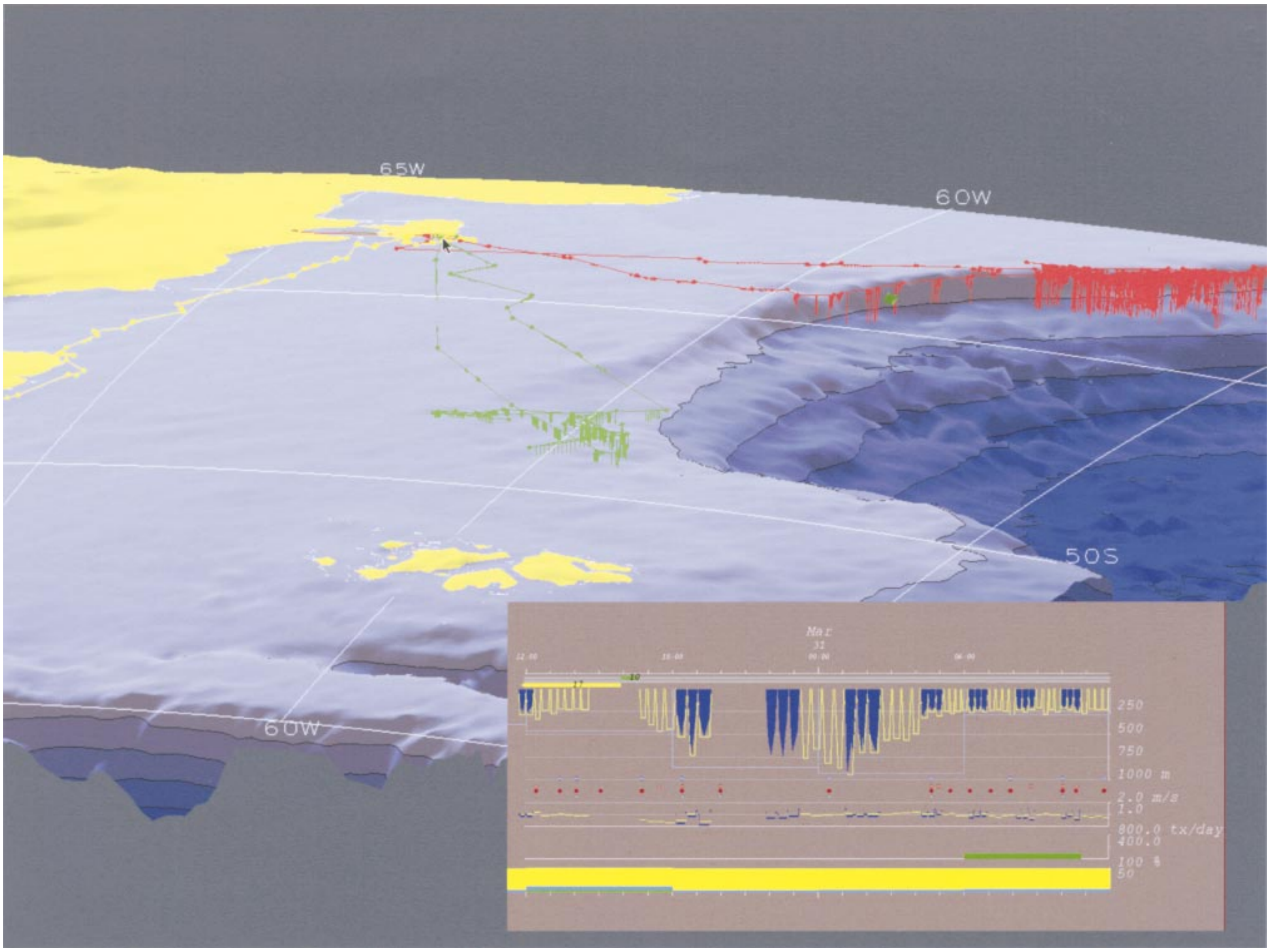

FIG. 5. A sample of MAMVIS visualization windows showing the tracks and dives of male southern elephant seals (*Mirounga leonina*) on their post breeding foraging trips from Peninsula Valdez, Argentina. Land is shown in yellow and the seabed in shades of blue changing with each 1,000 m contour. The geographic view shows Peninsula Valdez in the background and the Falkland Islands in the foreground. The tracks of the 3 seals are shown as red, green and yellow lines at the position of the sea surface with dives shown as downward projecting lines below the tracks (data from Campagna *et al.*, 1999).

The lower right window shows an example of the ''strip chart'' output window, which provides 2-D views of behavioral and technical information. It shows only a few of the information types that can be displayed. The horizontal axis represents time (month, day and hour). The window can be scaled to suit the level of detail required and two windows at different scales are ordinarily displayed. All windows are linked and the selection of a point along the strip chart axis or a geographical point can cause all windows to shift that place or time to the ''present.''

Several sorts of information are shown in this view and we describe them as they occur from top to bottom in the panel. Colored horizontal bars immediately below the time line indicate the onset and end of behavioral states with green indicating time spent in a haulout, yellow indicating time spent in uninterrupted diving and blue indicating periods of surface activity. Each occurrence is given a number in order of its occurrence so that we can tell when a change of state has been missed. The gray lines indicate that no incidences of a state occurred between the occurrences transmitted. Dives for which we only sent maximum depth, duration and TAD index are shown as yellow outline profiles. Dives for which we received inflection points are shown as solid blue profiles. These can be colored according to other variables. Seabed depth at the estimated location of these dives can also be shown as a green line at the appropriate depth over the duration of the dive (not visible in this view). Red dots dots indicate the times that error free transmissions were received. Pink dots indicate transmissions that contained error. Grey dots indicate when locations were calculated by Argos. The yellow and blue lines below those indicate average speed for the dive and detailed swimming speed profiles respectively. The single green histogram bar below that is the average daily transmission rate for that day. The lowest colored band shows the proportion of time spent in each behavioral state (yellow = diving; blue = surface activity; green = hauled out). See text.

or more detailed regional bathymetric data sets. The topography can be contoured at selected intervals and the vertical dimension can be exaggerated to emphasize physical features. Secondary features such as seabed sediment type may be texture-mapped onto the sea bed surface. Coastlines taken from the World Vector Shoreline data set may also be displayed. All control is affected by simple graphical interfaces via mouse clicks on choices displayed on screen.

A three dimensional display of tracks and dive data, accessed directly from the Oracle database, may be overlaid on the topography scene. The tracks and dive data may be animated forwards or backwards through time showing a variable time-window of track information (*e.g.*, the last n days of data or all data since SRDL deployment). The representation of dives may be color-coded based on any dive parameter. For example, dive shapes may be color-coded with the time of day that the dive took place, with swimming speed, or with other parameters. Time dependent oceanic data may be linked to track animation. For instance, satellite-derived sea surface temperature data may be animated through time with track data.

The display may be explored by changing viewpoint and hiding or swapping certain coverages provided by other linked data sets (for example sea surface temperature or mixed layer depth).

MAMVIS provides two other extremely useful ''windows'' for viewing the data (Fig. 5). These can be set to include representations of most information types, all plotted against time along with added information from the other environmental data sets used in creating the 3-D views. The temporal scope can vary from 1 hr to the time of the entire deployment. The second window presents a view at an increased temporal resolution, allowing ''zoomed-in'' views of a particular time (For details, see Fig. 5).

All three windows are linked so that if the data is animated, the temporal advance is co-ordinated between all three. Further, if one clicks on any place within a window, the time base in all three windows shifts to that time, as does the geographical view. This makes it possible to quickly shift to interesting locations or behaviors and examine the location in which they occurred as well as relevant environmental conditions.

Figure 5 presents only static views of the sort of output that MAMVIS delivers. A better appreciation of this can be gained from the Sea Mammal Research Unit web site ⟨http://www.smru.st-and.ac.uk⟩ (particularly the technical section) where a general description of the data types delivered is shown along with map and dive behavior data from a number of deployments. Because the data sent by the SRDLs is automatically updated and decoded every few hours and posted on the web site, researchers can keep abreast of the progress of their animals from any location that has web connections, regardless of where on the globe they or the animal may be.

CONCLUSIONS

We see the system as an observational tool that has few logistic or geographic limitations, a sort of hi-tech combination of binoculars and a notebook that opens a global window through which to study marine mammals. It has the additional advantage over simple observation that the data can be viewed from any vantage point and be animated and replayed. As data is collected it is stored permanently in an organized database so that other analytical tools such as statistical packages and GIS can readily be linked to it to test formal hypotheses based on the insights that the observations generate.

We believe that this approach has the potential to work in many field situations where animals are large enough to carry such telemetry packages and in future can help to take detailed behavioral and physiological studies into the field. The capability to structure data collection using previously developed models means that even fairly rapidly changing physiological measurements could be sent with acceptable bandwidth.

Looked at another way, the system can bring field observation into the laboratory.

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