# Designing an Archival Satellite Transmitter for Life-Long Deployments on Oceanic Vertebrates: The Life History Transmitter

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*Abstract*—**Despite the widespread use of sophisticated telemetry transmitters in behavioral, physiological and ecological studies, few studies on population dynamics of oceanic vertebrates use such technology, primarily due to the difficulty of obtaining multi-year records from individual animals. We present the first telemetry transmitter specifically designed for collecting vital data from marine vertebrates over extended periods, up to a decade. The implantable Life History Transmitter records data throughout the life of a host animal. After the host animal dies, the tag is extruded, and, while floating on the ocean or lying on a beach, transmits previously stored data to orbiting satellites. For tags relying solely on end-of-deployment transmission, reliability and proper recognition of tag state is crucial. The Life History Transmitter uses heuristic tag state determination, in combination with simple error detection and fault tolerance measures, to increase tag reliability and likelihood of data recovery. We used a computer simulation of tag deployments and various sensor failures on a PC platform, in combination with time-accelerated simulations running on the actual deployment platform, to test the functionality of fault tolerance and error detection protocols.**

*Index Terms*—**Error detection, fault tolerance, LHX tag, long term tracking, marine mammals, survival rates, tag reliability.**

## I. Introduction

EVER since the first deployment of mechanical depth recording devices on diving seals [1], [2], telemetry devices have provided a significant contribution to our understanding of the biology of oceanic vertebrates and their environments [3]–[7]. Increasingly sophisticated telemetry devices have progressively overcome difficulties in collecting data from animals that range extensively through ocean basins, and beneath polar ice. Using such devices, investigations have been conducted into the behavior and physiology of fish [8]–[11], of diving mammals, birds and reptiles [3], [4], [12]–[17], and into migratory patterns of oceanic vertebrates in air and water [12], [18]–[22]. Predators and their prey have been tracked. The adaptations of these animals to their environment [7], and the development of such adaptations and behaviors [23], [24] have been analyzed.

While earlier tag designs were archival [9], advances in battery performance, electronics miniaturization, and radio and satellite communications in the last three decades have enabled the use of devices that transmit a portion or all of recorded data [5], [8], [25]. Other substantial advances were made by increasing sampling ability of telemetry devices through sophisticated signal acquisition and processing, including visual imaging and three-dimensional sub-surface tracking [26], [27]. Pop-up archival satellite transmitters, devices that record data while externally attached to submerged animals, and transmit stored data after floating to the ocean surface following programmed release, are a recent innovation that has further advanced the field [8], [10].

However, for all the complexity and value of these instruments, substantial limitations remain, many related to the state of the available technology. Particularly limiting are methods of attachment of telemetry devices, battery life, and technology for data recovery. To facilitate data recovery, telemetry devices are usually externally attached. On pinnipeds and seabirds, most externally attached devices do not remain attached beyond the annual molt. As a result, many telemetry studies of oceanic vertebrates are based on short records ranging from a few days to several months [7], [8], [10], [13], [21], [28], and are often collected from dependent young or breeding females with a high degree of site fidelity, and at highly accessible locations [23], [28]. Implanted telemetry devices have been used in some studies to extend monitoring periods [29], although most such applications are restricted to the use of VHF beacons [30], [31], and are more commonly used in nonoceanic aquatic vertebrates [32]–[34], or in near-shore environments [29].

Whether using external or implanted archival data loggers or transmitters, few studies have managed to provide data over periods exceeding one year. The longest tracking record to date using external tags is three years on a single whale shark individual [20]. Recently, coelomic archival implants have successfully enabled tracking pelagic marine teleosts for periods up to five years [34]. As a result of these time-limitations, very few studies of long-term survival rates and population dynamics of oceanic vertebrates are conducted by means of telemetry devices. The few extant studies are based on short-term records necessitating a cross-sectional sampling design [35]–[37]. Since such designs prohibit repeat

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sampling of individuals, they require a significantly larger sample size. Most survival rate studies of marine mammals use shore-based classic mark-recapture approaches [38]–[40], and even those based on recent technological innovations such as mobile-phone (GSM) text messaging [41] are restricted to shore-based, cross-sectional designs. Telemetry-based survival rate determinations face the additional difficulty of having to distinguish between animal mortality and tag failure [29], [35]–[37].

Nevertheless, the use of telemetry devices for such studies would offer substantial advantages, should the inherent limitations be overcome. Even though individual tags are usually very expensive, much smaller sample sizes would be feasible if longitudinal records of sufficient duration could be collected. Automated data recovery should substantially reduce observation and recovery efforts and expenses. In addition, animal disturbance should be reduced as sample sizes and observation efforts are limited.

In recent years, interest in obtaining long-term longitudinal records from individual animals has increased. This is accomplished by extending sampling to all seasons, and including less accessible or highly pelagic age groups or species. The increase of potentially adverse effects of anthropogenic actions on many declining species and the likely effects of decadal or long-cyclic regime shifts in oceanographic conditions [42], [43] make these data vital. In one specific example, research plans have highlighted the need to accurately assess survival rates and obtain long-term longitudinal records from individual juvenile Steller sea lions (*Eumetopias jubatus*), an endangered species [44]. Reduced juvenile survival has emerged as a leading hypothesis for the continuing decline of this species, yet it remains untested for lack of viable research approaches. Juvenile animals in particular are highly pelagic and difficult to monitor. Other apex foragers in the North Pacific and Bering Sea regions, including Northern fur seals (*Callorhinus ursinus*), have recently exhibited similar declining population trends [45], further highlighting the need for accurate survival rates and long-term longitudinal records.

Developers and manufacturers of such powerful long-term telemetry devices are thus faced with a unique set of challenges. Most prominent amongst these is the development of hardware and software that promises a significant improvement in longevity and reliability. In addition, new procedures need to be used to test such devices for projected multi-year deployment durations.

Here we describe a new type of telemetry transmitter, the Life History Transmitter, developed to address limitations inherent in existing data transmitter designs, and to enable new experimental paradigms. This new device is specifically designed to obtain long-term, longitudinal data records from individual animals over periods up to a decade, and for estimating age-specific survival rates of wide-ranging oceanic homeotherms. The Sections II–V describe the design constraints and resulting tag concept; the physical features of the new tag; the development of error-detecting, fault-tolerant software; the testing procedures; and the capabilities of the tag and resulting considerations for applications and experimental designs.

## II. Design Constraints and LHX Tag Concept

The new transmitter was required to be received globally, dictating the use of a satellite link for data recovery. The ARGOS system was the obvious choice as it is widely used for location and data telemetry of oceanic vertebrates [46], and many ARGOS-compatible miniature transmitter designs exist. This system uses receivers on low, polar-orbiting satellites to receive telemetry data and to determine the location of transmitters [46]. The tag also had to be implantable, the only means to ensure tag retention for periods exceeding ten years. These two requirements seem to be in contradiction considering that implantable tags need to have minimal size. Suggested size limits for implanted tags range from 1 to 10% of an animals' body mass. A one percent limit has been suggested for sea otters as the sole marine mammal species to have received intraperitoneal implants to date [29]. Suggestions range from 2 to 12% in marine teleost and anadromous fish [47], [48], and 5 to 10% in terrestrial mammals [49]–[51]. Early trials with standard transmitters placed inside animal carcasses indicated that it would likely be impossible to uplink to ARGOS satellites from reasonably-sized, fully-implanted tags. Even if the problem of uplinking from within the body cavity were solved, the size of battery required to support transmissions over a decade (or longer) would be prohibitive. The solution to this dilemma lay in a design similar to pop-up archival transmitters (PAT tags, [8]): Develop an implantable tag that would monitor and archive sensor data without transmitting while inside the host body and only commence transmissions after the tag is extruded from the decomposed or partially consumed animal after its death. The absence of any transmissions through the life of the host animals means that battery life is effectively limited only by the battery's self-discharge rate. As a result of this approach, the opportunity arises to document the life of the host animal from time of implantation to time of death, leading to the name of 'Life History Transmitter' or LHX tag.

The following specific design constraints for the LHX tag were considered. The tag should be:

1. Derived from existing ARGOS-compatible transmitter designs.
2. Implantable, which requires the tag to be:
   a) solidly encased in biocompatible material with an internal antenna.
   b) substantially less than 1% of body mass of our initial target species, the juvenile Steller sea lion.
3. Pressure resistant to 1000 m water depth for initial target species.
4. Positively buoyant and capable of ARGOS uplinks while floating or lying on the ground.
5. Capable of determining the state of the animal and the state of the tag with a high degree of reliability.
6. Capable of archiving data for the life of the host animal, up to one decade, and subsequently transmitting stored data with a high degree of reliability.

Next, we considered the suitability of different sensors for determining the state of the animal and transmitter, and for providing additional vital data on the animal. Two state transitions need to be determined by the tag through suitable sensors and evaluation algorithms: A mortality event, and tag extrusion event. A mortality event occurs when the animal dies, and an extrusion event from a dead body results in the tag either floating at the sea surface or lying on a beach, ready to transmit. Temperature or motion sensors are used in classic mortality-sensing transmitters. Motions sensors are problematic in marine applications since wave-induced motion may persist after death of an animal, or after a possible immediate extrusion of a tag following a predator attack. Therefore, only temperature was selected to determine the mortality event, assuming that a temperature outside of the normal physiological range of a homeothermic animal will occur shortly after death. A combination of light and a conductivity/immersion sensor was chosen to determine the extrusion event.

We decided to develop two versions of this tag, a minimalist version with just the temperature light-level and immersion sensors, called the standard LHX tag, and an enhanced LHX tag with additional pressure and motion sensors to provide behavioral data collected over the life of the host animal. Here, we present the core design concept of the standard LHX tag.

## III. Development and Physical Features of LHX Tags

To aid in the selection of components and physical- and software-designs for maximizing tag reliability, a review of the performance of past and current tag designs was conducted. Rather than provide a quantitative analysis of failures, this qualitative review ranked critical hardware and software elements by failure likelihood, based on previously experienced failures, as summarized in Table I. The ranking is based on well over 500 deployments of 10 different archival and transmitter tag designs including tags and data cited in [14]–[17], [23], [24], [26]. Deployments resulting in recovery of partial, erroneous or no data where a likely fault could be identified, were considered failures. For both archival and transmitter tags, faults could be classified by fault impact into mission critical (no data recovered) and noncritical (some data recovered). However, we did not specifically consider fault impacts in the rankings, since under the novel operational parameters of LHX tags, all of the ranked faults would be critical resulting in a failure to recover any data.

User error or attachment failures were not included in this ranking, but would have ranked foremost. Breaking of an external antenna due to mechanical stress, metal fatigue or corrosion was another extremely common occurrence in transmitter tags. This failure was also not ranked, due to the requirement of an internal antenna for the LHX tag.

The most common ranked cause of failure was the battery system. Battery failure occurred in two forms: Premature reduction in cell voltage when discharged by an amount substantially less than the nominal cell capacity; and excessive passivization. Passivization is the build-up of a poorly-conductive layer on the electrodes of the battery and is one reason why lithium batteries have such a long shelf-life: The passivization layer impedes battery self-discharge. Passivization can also cause an otherwise healthy battery to exhibit a supply voltage breakdown, usually after the initiation of transmissions. In a single-battery system, passivization can cause controller lockup if not properly managed. Physical damage of batteries did occur as a result of cracked housings, but was included under package failures.

TABLE I
Ranking of tag Components and Design Features by Failure Likelihood Based on Previous Deployments of 10 Different Types of Tags

| Rank | Failed system | Failure symptom |
|---|---|---|
| 1 | Battery | Premature depletion, passivization |
| 2 | Sensors | Mechanical damage, unresponsive |
| 3 | A/D conversion | Isolated pegged values |
| 4 | Tag package / housing | Cracked, leakage |
| 5 | Operational software | Lockup, operations improperly terminated |

The second-ranked cause of failure was sensor failure. Sensor failures included burst or mechanically damaged pressure transducers, as well as unresponsive sensors (light, temperature, immersion). However, different types of sensors have different degrees of reliability. Sensors with mechanical components or that are exposed to the elements, which includes most types of pressure and conductivity sensors, were deemed more susceptible to failure than internal, nonmechanical sensors such as temperature and light-level sensors.

Analog-to-Digital conversion failures were ranked next. These failures were usually manifest as single or isolated, unreasonable or pegged sensor values. While these recoverable symptoms could be related to sensor failures, they are listed separately from the nonrecoverable sensor failures.

The fourth most common cause of failures was related to housing or packaging material cracking or leaking. Secondary failures usually ensued, including battery- and sensor-failures, and software lockup as a result of short circuits. Housing/packaging failures were usually related to excessive pressure beyond stated range, or excessive mechanical stress, although we speculate that some may be related to repeated thermal cycling of multiple materials with differing thermal expansion coefficients.

Finally, improper software operations did occur, although almost exclusively during testing, and only very rarely during actual deployments. In all instances where this could be assessed, we determined that software lockup was a result of another primary failure of batteries, sensors, or the housing.

Very rare and therefore unranked failures include timing system failures, resulting in failure of a tag to wake up for scheduled operations, and tag operations terminated for undetermined reasons.

We individually addressed each of these most common failures, either through component selections, or through implementation of a fault-tolerant design.

### A. Battery System

We decided to use two separate primary batteries for controller and transmitter operations. This design avoids supply-voltage breakdown and resulting controller software lockup when transmissions are initiated after extended standby periods when passivization would probably have occurred. Since a separate battery is used to power the controller and the power amplifier of the transmitter, a sudden current draw by the power amplifier will not cause the voltage of the controller battery to sag. A BCX85PC1 Lithium/Bromine-Chloride Complex primary battery (Electrochem Division of Wilson Greatbatch Technologies, MA) is dedicated to controller and signal acquisition operations. This battery has an open cell voltage (OCV) of 3.9 V, and a nominal capacity of 1 Ah at a rated discharge of 1 mA. This battery was chosen for its very low degree of passivization and extended operating temperature range of $-55$ to $+85°C$. An LSH26180 Lithium/Thionyl-Chloride primary battery (SAFT, Bagnolet, France) is used for operating the ARGOS transmitter. This battery has an OCV of 3.67 V, and a nominal capacity of 1 Ah at a rated discharge of 100 mA. This battery was chosen for its extended operating temperature range of $-40$ to $+85°C$ and high current pulse capability of up to 1A in a 1/3 C form-factor. Self discharge of both batteries is 3% per year at 25°C, resulting in over 70% capacity remaining after 10 years.

### *B. Sensors*

For the standard LHX tag we chose a YSI 44 017 thermistor (YSI Inc., Beavercreek, OH) as our temperature sensor, a TAOS TSL257 high-sensitivity light-to-voltage converter (TAOS Inc., Plano, TX) as our light-level sensor, and a proprietary contact-free immersion sensor (Wildlife Computers, Redmond, WA). The immersion sensor works by measuring radio frequency energy reflected from surrounding tissue, or salt water during a test transmission. We ranked the likely reliability of these sensors as highest for the thermistor, then the integrated circuit light sensor, and lowest, as it was a new and untested design, the immersion sensor. The immersion sensor was designed to detect a difference between the antenna portion of the tag being surrounded by saltwater or animal tissue, versus air. All of these sensors are internal to the LHX tag package, reducing likelihood of mechanical sensor damage, or moisture penetration into the package via electrical connections. We chose not to use backup or redundant sensors, as this would increase the number of components that could fail, and would only increase reliability if software protocols could be implemented that could distinguish between failed and functional, but redundant, sensors. Such protocols would greatly increase software complexity, and could introduce a further software failure potential. Instead, we developed software protocols to test sensors during deployments and determine sensor failures, thus implementing a fault-tolerant design.

### *C. A/D Conversion*

Potential analog-to-digital conversion problems were addressed through fault-tolerant software protocols, as described below.

### *D. Packaging*

A positively-buoyant package with sufficient pressure rating, an efficient, helical antenna with a cover transparent to UHF transmissions, and effective moisture proofing for life-long tag implantation, were the greatest challenges of this design. Mechanical stresses on the design derive from two sources: Pressure and temperature. Temperature cycling was deemed unlikely, since homeothermic animals will maintain the tags at a fairly constant temperature throughout most of their life, but close attention was paid to the pressure rating of the tag throughout the design process. The final material selection, wall thickness, and the overall tag shape gave a pressure tolerance in excess of 1000 m of water. After significant investigation, it was determined that the helical antenna needed to be surrounded by air to create a design that allowed efficient transmissions in a variety of tag environments. To meet these requirements and to facilitate assembly of tags and maintain compatibility with implantation, an epoxy-resin package was developed, illustrated in Fig. 1. The LHX tag measures 42 mm in diameter and 122 mm in length. The tag has a mass of 115 g in air, about 0.1% of the body mass of the initial target species. Buoyancy in salt water is $-38$ g. The design incorporates a triple moisture barrier to protect electronic components: The innermost layer is comprised of solid electrical resin into which the circuit-board, sensors and batteries are cast. This innermost layer is cast around the electronic components using a sleeve machined from syntactic foam as a mold. This creates an extremely light weight tag. The helical antenna is surrounded by air space which is covered by a float machined from the same type of syntactic foam as the casting sleeve. After assembly, the entire tag is coated with a 1 mm layer of medical grade epoxy (Epo-Tek 302-3M, Epoxy Technology, Billerica, MA). This material is certified for USP Class VI compatibility with implantation in both un-cured, and cured (polymerized) states, and is designed to prevent connective tissue growth and adhesion. This material is used for human and animal implants, and has the lowest moisture absorption rate of any resin suitable for implantation. Using multiple moisture barriers often combining such resins with metal casings, biomedical implants in humans have achieved longevity of 10 to 15 years, before requiring replacement due to limited battery life [52], [53]. The completely assembled and coated LHX tag is shown in Fig. 2.

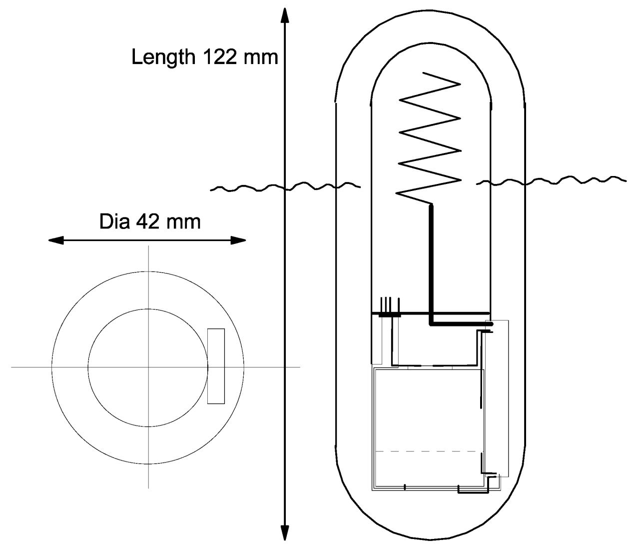


Fig. 1. Dimensions and configuration of standard LHX tag.

### *E. Software*

In our reliability evaluation and ranking, software lockup was always associated with a failure of sensors, batteries or housing.

Fig. 2. Photograph of encapsulated standard LHX tag. (Color version available online at http://ieeexplore.ieee.org.)

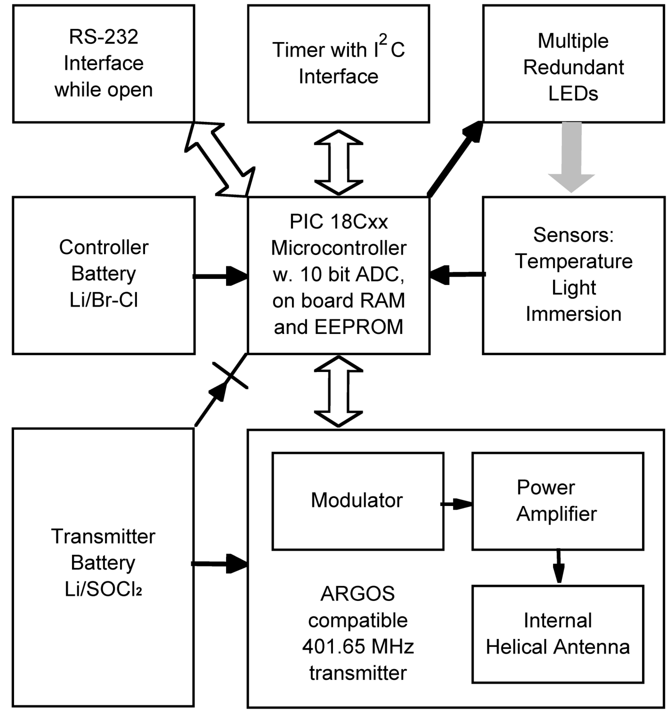


Fig. 3. Simplified block diagram of standard LHX tag.

Battery and housing failures have already been addressed. We decided to deal with sensor failure by developing error detection and fault-tolerant software protocols, and by extensively testing these protocols through simulations.

### F. Timing System

Since the occurrence of faults related to the timing system was extremely rare, we decided against the use of a watchdog timer (WDT) or any other backup timing system in the LHX tag. This was based on the likelihood of a WDT or similar backup system increasing the number of components that can fail, thus increasing failure likelihood, rather than decreasing it. Furthermore, inclusion of a WDT would significantly increase the overall current consumption through the majority of the deployment, requiring a more powerful (and larger) battery. In a separate telemetry development project, we concluded that only smart WDT's capable of determining which of multiple timing components has failed, are likely to increase reliability of timing systems [54].

### G. Tag Architecture

The selected components were integrated into the primary ARGOS transmitter platform developed and used by Wildlife Computers. This proprietary platform integrates controller and transmitter on a single board of $17 \times 38$ mm dimensions excluding battery, housing and antenna. A simplified block diagram of a standard LHX tag is illustrated in Fig. 3. A Microchip PIC 18LF452 RISC type controller with on-board RAM and EEPROM is used. Timing functions are performed by a separate timing chip interfaced with the PIC via an $\mathrm{I}^2\mathrm{C}$ interface. A thermistor, light-to-voltage converter and proprietary immersion sensor are used. Sensors are activated by the PIC, and sensor output is digitized via the onboard, multiplexed 10-bit ADC. Battery voltage can also be monitored via the ADC function. Communications with an external host PC for programming, setting user-defined program parameters, and for downloading recorded data (in case of tag recovery) are via bi-directional, RS-232 serial interface. LED's are used to communicate tag-state to the user, and we also use these dual, redundant, parallel LED's to test the light sensor for correct functionality.

## IV. Development of Operational Software

### A. Fault Tolerance and Error Detection

Once deployed, most modern archival or transmitting tags operate in repeated cycles of sleep and active modes. In sleep mode, power consumption is minimal, typically 1–5 $\mu$A. In active mode, one or more of several possible sampling, data processing, archiving and transmitting protocols are run. The cycling between modes and selection of active modes may be modified by schedule or based on state of tag as determined from sensor data. For example, sampling or transmission protocols may be altered based on the immersed or surface state of a tag. The operational software for such mode cycling and protocol switching is simple and robust. Nevertheless, sampling errors through sensor or A/D conversion failures could result in unplanned termination of data collection or transmission. In the case of archival or directly transmitting tags, this would result in only a partial failure of a deployment. However, in the case of a PAT- or LHX-tag where transmissions are initiated solely at the end of a deployment period, all data may be lost. Such tags require exceptionally reliable mode switching algorithms. This basic cycling of operational modes is also used in LHX tags, and is illustrated in a simplified flow diagram in Fig. 4. From sleep mode, the standard LHX tag is woken every 30 minutes by a timer-driven hardware interrupt. The enhanced tag is woken at a user-defined sampling interval (10–30 sec) for pressure sampling only (Loop 2 in Fig. 4); the standard tag uses a 30-minute wakeup interval for all tag operations. In either case, every 30 minutes, a number of sensor-data acquisition, error-check and tag-state determination protocols are run.

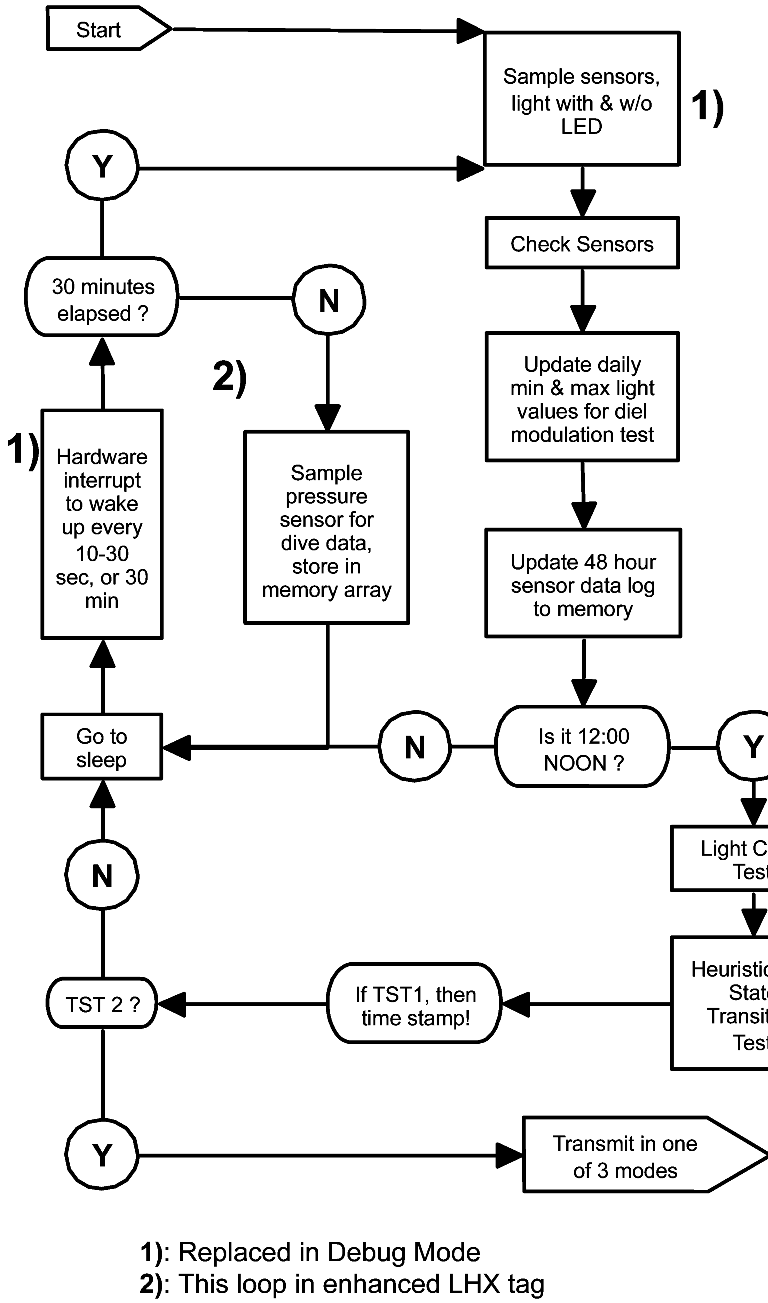


Fig. 4. Simplified flow diagram for LHX tag operational software.

In LHX tags, low level fault tolerance is simply based on disregarding improbable sensor readings, and is accomplished in the ‘Check Sensors’ protocol which is run after sensor data acquisition (Fig. 4). Sensor data either exceeding a preset range of likely ADC values, or reaching conversion extremes of 0 and $2^{10} - 1$, are ignored. In our past experience, isolated pegged ADC counts do occur. For example, since the chosen thermistor exhibits a resistance range of 5 kΩ to 200 kΩ over the expected temperature range, any measured resistance value outside this range would indicate a thermistor failure. Isolated, unreasonable values are ignored but they are tallied. After a user-defined number of sequential, unreasonable values a recoverable sensor error is declared. When a sensor error is declared, data from this sensor are ignored for tag state determinations. Sensors will continue to be sampled, even when a recoverable sensor error has been declared. Recoverable sensor errors can be cleared after a user-defined number of sequential, reasonable values occur.

In addition to implementing low level fault tolerance, the Check Sensors protocol performs one of two tests of the functionality of the light sensor. When dark, the light sensor is tested by briefly flashing the adjacent parallel, dual redundant LED’s. If there is no response to this LED flashing for a user-defined number of sequential tests, a nonrecoverable light sensor error is declared. When the tag is exposed to bright daylight, LED flashing is insufficient to elicit a detectable response. In this case, an extended test is conducted over the next 24–48 hour period in which the presence of a diel light variation (exceeding a user-defined threshold) is determined. The absence of a variation over a user-defined number of sequential 24-hour periods results in a nonrecoverable light sensor error. This test for diel light variation is evaluated on previously-collected light-level data once every 24 hours at 12:00 noon in the Light Cycle Test protocol.

### B. Heuristic Tag State Determination

In LHX tags, two Tag State Transitions (TST's) need to be accurately recognized, in order to implement appropriate changes in mode cycling, and to correctly initiate transmissions. The transition from being in a live animal to being in a deceased animal (TST1) needs to be determined correctly, followed by the transition from being inside a host body, to being outside and in a position to transmit (TST2). The time stamp of the first (TST1) of these sequential state transitions form the most important data to be transmitted by the tag. TST2 is particularly important for initiating transmissions, and has to be recognized even if TST1 was missed. In principle, state transition determinations are based on temperatures outside of a user-defined physiological temperature range for TST1, and on daylight levels and/or the immersion sensor detecting air for TST2.

Tag State Transitions are only evaluated once every 24 hours, at 12:00 noon, by the Heuristic Tag State Transition (HTST) test protocol (Fig. 4). Conflicting sensor information may result from certain sensor failures. For example, detection of ambient light without previous occurrence of TST1, and in the absence of previously declared errors could indicate a) a faulty temperature sensor and tag extrusion from a deceased animal, or b) a faulty light sensor with the tag still located in a live animal. To deal with such potentially conflicting sensor data, the HTST protocol was developed around a heuristic algorithm (highest likelihood of making correct decision), based on several operational concepts:

1. Single sensor failures may occur, yet the tag should be able to make a usable TST determination based on the highest likelihood of making the correct determination.
2. To reduce the chance of incorrect TST determinations, a user-defined number of sequential TST-passing sensor data need to occur, with any declared sensor errors taken into account.
3. HTST determination should take into account sensor reliability rankings, previously declared errors, and results of sensor tests that can be performed by the tag.
4. TST2 should be determined based on data from at least two sensors (including the temperature sensor), unless sensor errors have been previously established.
5. TST2 detection should assume prior TST1 occurrence, unless a thermistor failure is likely, however, if TST2 is positively detected with a higher degree of likelihood than temperature sensor error, TST1 should be assumed.
6. While the TST1 time stamp is valuable, optimizing TST2 determination is the most important operational requirement.

To implement these concepts, the heuristic algorithm follows these basic rules:

In case of nonconflicting sensor data, TST determinations are straightforward: If temperature is outside the user-defined physiological range (UDPR), and no errors are currently declared, TST1 is determined. Subsequently, TST2 can be determined by sensing light and air, or light alone, since a tested light sensor is deemed highly reliable. Air detection by the immersion sensor alone is not deemed sufficiently reliable to determine TST2, unless a light sensor error has been declared.

Conflicting sensor data are resolved based on their likelihood of occurrence, sensor testing and reliability ranking. If air is detected, but a tested light sensor indicates dark and TST1 is not set, a nonrecoverable immersion sensor error is declared. If light is detected by a tested light sensor, but TST1 has not been declared, and air is not detected, a temperature sensor error is set, and TST2 declared. As a result of its untested reliability, the immersion sensor provides little input into the heuristic algorithm under no-fault conditions. However, if a temperature sensor error has been declared, detection of air alone becomes sufficient to declare TST2. In addition, various user-defined delay periods allow additional time to evaluate the sensors. This is done to accommodate possible delayed responses by any of the sensors (need to wait for daylight, wait for tag to float to surface, or for remaining tissue to fall off tag). Delay periods can be used to maximize the success rate of the heuristic algorithm.

The HTST protocol provides the Heuristic Degree of Confidence (HDC) count, a simple measure of the confidence in the HTST determination, based on the number of error-free sensors on which the determination is based.

In a marked difference to conventional tags, once an LHX tag is cycling through the wake/sleep modes as illustrated in Fig. 4, the only way to leave this cycle is by declaring TST2, which initiates data transmission.

### C. Data Transmission

The final and irreversible operating mode of the LHX tag is thus to enter one of three possible user-described transmit protocols. These three protocols are selected based on the HDC count and only differ by the ratio of active to inactive transmission days, and, hence, by overall duration. If TST2 is determined based on three sensors (HDC count of 3), the fastest transmit protocol is initiated. An HDC count of 2 results in an intermediate transmit protocol, and an HDC of 1 invokes the slowest protocol. LHX tags should be capable of approximately 14 400 data transmissions after 10 years. With transmit rates of $1\ \mathrm{min}^{-1}$, 10 days of active transmissions are possible. If the fastest protocol uses 1 day on 1 day off, the tag will transmit for 20 days after TST2 has been declared. If the slowest protocol uses 1 day on, 9 days off, the tag will transmit over the course of a 100 day period following TST2. These three protocol options are used to further maximize data recovery in case of low confidence in HTST determinations. The lower the confidence of a TST2 declaration is, the longer the period over which transmissions will be stretched, giving, for example, more time for a tag to be extruded, if this has not yet happened.

Both versions of LHX tags will transmit the time and date stamp for TST1, and 96 half-hourly temperature values equally spanning TST1. Enhanced LHX tags will additionally transmit three weekly summary dive effort data: the percent of time spent diving (at greater than a user-defined threshold depth), the number of dives, and the cumulative vertical displacement (the sum of twice the depth of all dives). LHX tags can encode up to 15 8-bit data words in addition to the tag ID code and the data packet identifier in one ARGOS transmission. Status messages with TST1 time stamp, HDC, error codes and other tag diagnostic data are alternated with data messages, according to a user-selectable schedule. This results in a data transmission redundancy of around 1,000 for status messages, and between 1000 (after 1 year) and 100 (after 10 years), for each individual recorded data point of enhanced LHX tags.

## V. Testing and Simulating Multi-Year Deployments

The major challenges in the development of the LHX software were the need for a rapid development and testing of the basic software concepts, followed by the need to test the software under realistic conditions, in significantly less time than the planned ten-year deployment. The first part was accomplished by using a completely independent development and testing environment from the final deployment platform. We programmed a tag simulator in a Turbo-PASCAL (Borland, Scotts Valley, CA) environment. This Simulator included a keyboard-based input of ADC values for all available sensors, and a console (screen) based output of time and date, sensor ADC counts, tag state, error states, and the state of a number of auxiliary variables. The simulation program was built on the same mode-cycling architecture and sensor processing and HTST testing protocols as were intended for the actual tag software (Fig. 4). The Simulator was first run by entering one set of sensor ADC counts per 30-minute simulated time increment, via the keyboard. As the simulation proceeds, keyboard inputs, simulated time base, tag state variables, and all relevant parameters are logged to a text output file. A simulation is terminated when TST2 is declared. We used these simulations to test basic mode switching functionality, as well as the efficiency of fault tolerance, error-detection and the heuristic tag state determination algorithm via the HTST test protocol. Manual, keyboard input of ADC counts was soon replaced by automated generation of ADC counts from an input file created from likely behavior-based data sets. These files included ADC counts resulting from all possible combinations of faults and errors.

After completing development and testing of the operational software using the Simulator, the code was ported to C language for debugging on the deployment platform, using the PCWH PIC compatible C-compiler (CCS, Inc., Brookfield, WI). To facilitate code porting and debugging, we implemented a special debug mode for the LHX tag operational software by replacing the process elements labeled as **1**) in Fig. 4. In this debug mode, the tag used sensor ADC counts from previously generated simulation files in lieu of actual counts from the integral ADC. These external ADC counts were fed to the tag from a host PC via the active RS-232 serial interface. The time base for mode cycling was changed from an interrupt every 30 minutes, to an interrupt every second. In addition, the tag fed all variable states back to the host PC via the same serial interface. While the simulation was running on the LHX tag in debug mode, the host PC performed a comparison between the variable states listed in the TPS generated test file, and the variable states returned by the LHX tag. Any discrepancies between variable states, TST's, or the transmission modes terminated the simulation, and an alert was issued.

This combination of simulations on dual platforms, the Turbo-Pascal Simulator on a PC, and on-tag simulations in C using the debug mode, significantly enhanced our development and troubleshooting abilities. The most effective way to test software changes proved to be the initial debugging on the Simulator using a series of standardized test files, followed by a repeat of the identical test series on the deployment platform. Using the debug mode on the tag test-bed, we were able to simulate deployments lasting from a few days to multiple years in less than one week.

In addition to simulation testing, initial LHX tag prototypes and production tags are physically tested for pressure tolerance and proper data encoding and transmission using actual uplinks to the ARGOS system.

### *A. Initial Deployments and Implications of Tag Technology for Experimental Designs*

In 2004, LHX tags were implanted into four stranded and rehabilitated California sea lions (*Zalophus californianus*) at The Marine Mammal Center (TMMC) in Sausalito, CA. The tags were intraperitoneally implanted under gas anesthesia, following standard laboratory animal practices for such procedures. The animals were kept under observation at TMMC for 6 to 10 weeks following the procedure. This observation period was recommended by attending veterinarians to verify proper wound healing and the absence of complications from receiving implanted tags. All four animals were successfully released at the end of the captive observation period, without suffering any complications. Following their release, the animals were tracked through externally attached Satellite Data Transmitters (SDR-T16, Wildlife Computers, Redmond, WA), glued to the dorsal fur with marine epoxy (Fig. 5). This attachment method is standard practice for the tracking of diving marine mammals [18], [23]. The four animals were tracked for varying durations ranging from one to four weeks. The animals exhibited normal diving behavior during this period, and tracking was limited as a result of the external transmitters being shed during the annual molt. While this pilot study is continuing, these first four deployments provide an initial confirmation of the feasibility of implanting LHX tags into marine mammals. The short post-release tracking duration using conventional, external tracking devices illustrated the need for such novel tags.

Despite the efforts to increase tag reliability, several implications arise from the concept of delayed, end-of-life transmissions. To be able to use LHX tags for precise assessments of survival rates, the tag failure rate needs to be accurately determined. This should be done through appropriate experimental designs, since the actual failure rate may be influenced by location and species of deployment. For our initial target species, the Steller sea lion, we will pursue several approaches in order

Fig. 5. A California sea lion with an intraperitoneally implanted Life History Transmitter is released on a beach in Marin County, CA, in July 2004. The sea lion is also carrying an externally attached Satellite Data Transmitter for post-release tracking. (Color version available online at http://ieeexplore.ieee.org.)

to determine tag failure rate. A central element of our experimental design is the simultaneous deployment of dual tags, one standard and one enhanced tag, in each host animal. The ratio of single to dual data returns from these redundant tags is the most important measure required for the calculation of cumulative tag failure rates. While marine mammals are thought to be long lived, life table estimates for juvenile Steller sea lions predict high annual mortalities, with over 50% of weaned animals not surviving beyond six to seven years of age [55]. For our study of the Steller sea lion, a power analysis indicated the monitoring of 72 juvenile sea lions with dual LHX implants, for five years after implantation, will be sufficient to test the salient hypotheses advanced for the decline of this species. Twelve of these procedures will be conducted under controlled conditions following standard practices, on wild-captured sea lions temporarily held at a dedicated facility at the Alaska Sea Life Center (Seward, AK). Implant procedures will be conducted in a portable surgical container, and animals will be monitored for six to eight weeks in quarantined areas with independent pools, before being released and monitored using conventional external satellite data transmitters. The remaining 60 of the required 72 procedures will be performed on free-ranging animals using ship-based capture and surgical teams, in the same portable surgical container used for initial validation studies. These animals will be released within 24–48 hours. The sample size for this study is over one order of magnitude less than estimates for branding-based mark and recapture studies. In addition, the ship-based implant procedures can be conducted within a much smaller time frame than the required brandings. These changes result in a significant decrease in direct and incidental disturbances near sea lion rookeries through research activities.

## VI. Conclusion

We present the first telemetry transmitter specifically designed for collecting vital data from oceanic vertebrates over a time-period of a decade. The Life History Transmitter represents the first design to combine fault tolerance, real time sensor testing and use of an error-tolerant heuristic tag-state-determination algorithm as a means to increase tag reliability and data recovery likelihood. We used time-accelerated computer simulations in two distinct programming environments to test the functionality of fault tolerance and error detection protocols. While these reliability measures are particularly important for all-or-nothing applications as described here, conventional tags could also benefit from such design approaches. In conventional applications, data collection and/or transmission regimes are often determined based on sensor states. Error detection and fault tolerant designs will give users more control over backup data collection and transmission modes in case of failures, which could have important effects on experimental design and outcomes.

The new tag design permits the application of a new experimental paradigm, based on the survival of individual animals. Potential applications of this design include the assessment of threatened species stock, as well as the assessment of the efficacy of stranded animal rehabilitation programs. In addition, long-term telemetry transmitters should greatly facilitate the telemetry-based study of population dynamics and life histories of oceanic vertebrates. With mounting interest in using animal-borne telemeters as autonomous environmental samplers, the assessment of foraging and reproductive success of these animals over longer temporal and spatial scales will become important to address potential sampling biases. This new Life History Transmitter provides the researcher with new technology to facilitate such assessments.

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