Locating Tuna in the Open Ocean

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ABSTRACT

Fisheries researchers are constantly faced with the challenge of tracking the long-term migration patterns of pelagic animals such as Tuna. This information is critical in understanding the life history and breeding conditions of the animals as well as to develop recommendations on fishing quotas. Unfortunately, Tuna do not spend any significant amount of time at the surface so conventional satellite (GPS or ARGOS) or radio tracking is not possible. A data collection and processing device has been developed by Lotek to determine daily Latitude and Longitude estimations based on observed sunlight levels from onboard a Tuna. This paper will describe the methodology, the device, and some data processing algorithms used to return daily position estimates.

1.0 Introduction

Quite often researchers would like to know where their subject animals have been traveling in the ocean. For animals that frequent the surface, radio and satellite tracking is readily available. However, there are animals such as Tuna that live in salt water and spend their lives beneath the surface. This annoying behavior precludes the use of real-time tracking systems that use electromagnetic signals, like GPS. Instead, some astronomy and an appropriate data collection platform worn by the animal can shed light on their whereabouts.

This paper will discuss the underlying principles of the LTD2000 family of Geolocation tags currently manufactured by Lotek Wireless Inc. in St. John's Newfoundland. These devices use a suite of sensors to measure temperature, pressure, and ambient light intensity, from which daily positions can be estimated. The estimates are on the scale of ± 1 degree of longitude or 60 nautical miles at the equator.

2.0 Methodology

This method of tracking a tuna requires that the subject animal be caught twice. The first time it is caught, the passive tracking device (tag) is either surgically implanted in the animal or attached externally using any number of accepted techniques. The technique used is usually a function of the species' and the researcher's preferences. The animal is then released, hopefully to be caught again sometime in the future. Recapture rates vary depending on the species but can be as high as 30%. When the animal is caught again, the tag is returned to the researcher, usually for a reward. The researcher interrogates the tag with a host computer and downloads a time series record of the logged sensor data as well as a daily record of latitude and longitude. The position estimates are derived each day on board the tag from the sensor data. The sensor data can be kept for further behavioral analysis such as dive profiling.

2.1 Geolocation Based on Light Levels

While radio signals do not penetrate salt water far enough to be useful to us, light does penetrate for several hundred meters in the open ocean. Sailors have for centuries observed the sky to learn where they are, and we continue that tradition. However all we can hope to observe from deep underwater is the sun, and since we can't see an image of it, all we can hope to learn about it is how bright its light is. What we really need to know is how bright it is at the surface. To learn that, we must first measure the light intensity at depth, then correct for the absorption of the water.

Assuming that we have found out how bright it is at the surface, we are still no better off than a hiker confined to a translucent tent. Day is very different from night and he can tell which it is just now, but how does he go from that knowledge to finding his location?

The simplest method begins by noting when it gets dark in the evening and then light again in the morning. If our hiker has with him a good clock that he happened to set to local time before he left England, and if he knows when sunrise and sunset are in England, he can learn a lot from the sunrise and sunset times he measures locally. If he is hiking in Newfoundland, in a time zone 3 ½ hours later than England, then he will find that the sun will rise and set about 3 ½ hours later.

Actually, it will be exactly 3 ½ hours only if he happens to be camping near Cape Spear, 52 ½ degrees west of the longitude zero point at Greenwich, England. If he is instead at the westernmost point on the island, at Cape Anguille, sunrise and sunset will be another 27 minutes later. Since the earth turns 15 degrees every hour, that delay tells us that Cape Anguille is 6 ¾ degrees of longitude West of Cape Spear. This added four-minute delay with every additional degree of longitude is our key to measuring longitude.

Similarly, since days are long in summer and short in winter, and since this effect is larger the farther we are from the equator, either our tent-bound hiker or our system riding onboard a fish can extract from day length a measure of his latitude. That is a more complicated problem than presented by longitude, and unfortunately the results one can obtain with a simple threshold-based approach are less satisfactory.

2.1.1 Light Correction in more detail

Those of you who dive in the ocean know that you can see beams of light and shadows of floating objects near the surface but as you go down this softens into a diffuse glow, brighter above and dimmer below, that the oceanographers call downwelling light. Fortunately for us, if we choose to measure only the blue light that penetrates deepest, the intensity of that glow falls off in a simple way, exponentially with depth. To a good approximation the intensity I at any depth d is given by $I(d) = I(0) \exp(-d/L)$, where L is a characteristic depth scale that is worth a factor of e in intensity. Rewritten in terms of decades (factors of ten) the relation becomes $I(d) = I(0)10^{-d/2.303L}$. You divers also know that it gets dark pretty quickly as you go down. In the open ocean the water is clearer than near shore, but even in good tuna habitat L is near 22 meters and the light dims by a decade approximately every 2.303L = 50 meters.

Unfortunately, water properties vary from place to place in the ocean, so that our tag needs to look at its data and learn what the water is like today. Fortunately, tuna tend to swim up and down rapidly, sampling the water column during the bright part of the day. There are large changes in light due to diving that are faster than those due to weather, so we have a way to proceed. We can filter out the slow variations, fit our model to the rapid variation of light with the rapid depth changes, and extract the day's value of L.

When dealing with exponential processes, it is usually convenient to take the logarithm of the quantity that is varying exponentially, especially when the quantity is varying over a wide range. In our case that is the light, so we use a logarithmic light detector circuit. Extracting the opacity then amounts to fitting a straight line to the filtered data. That is a task within the capabilities of a small processor.

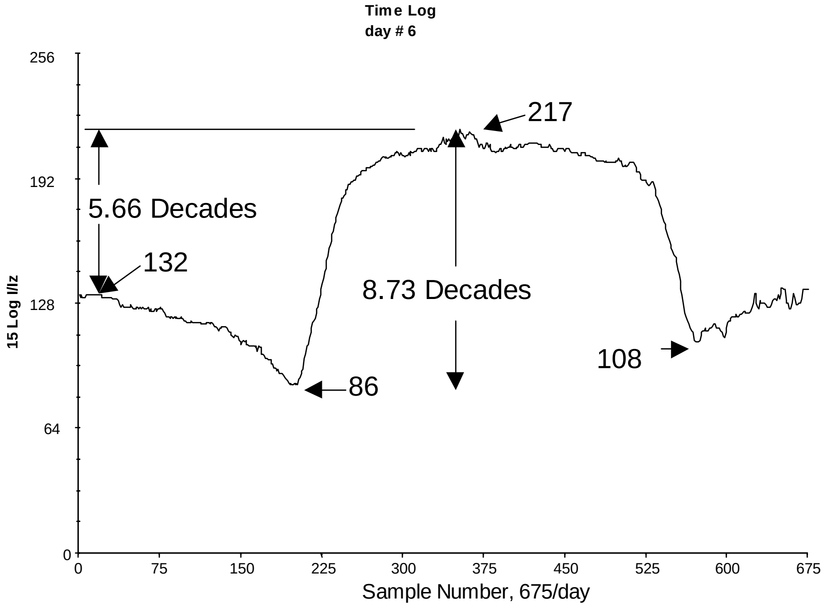
Then we can correct the light. By that I mean we take the measured values of d and I(d), and calculate I(0), our estimate for how bright it must have been at the surface to make it as bright as we found it to be at depth d. Again the calculation is easy: $\ln(I_0) = \ln(I) + d/L$. We don't even really care what the units of depth are; the value of L extracted as outlined above will always end up expressed in those same units.

First versions of the tags did exactly that. However there remains that awkward surface layer where the light has not settled down to its peaceful exponential behavior. Light near the surface is also roughly exponential in depth, but the exponent is larger. Current version tags extract separate opacities for the surface and for deeper layers, and correct the observed light with a two-layer model.

2.1.2 Sunset in more detail

What do we mean by sunset? When we can form an image of the sun and can see the horizon, the usual definition is the moment that the last of the sun's disk disappears. It is a dramatic event that can be timed precisely. In our situation aboard a fish, we can only infer a value for diffuse illumination, and it turns out that nothing special happens to diffuse illumination just at that moment. When the sun is low in the sky, most of the direct light from the sun is the color of a sunset – red. However the only light we can see very deep in the ocean is blue. At that time of day all the blue light we get is shining down on us from the blue sky, or is filtering down from the blue sky through a cloud layer. Nothing much happens to the sky just then. Only later in the evening does it begin to darken rapidly.

The best simple thing we can do in the tag is to pick some particular intensity of illumination as a day-night threshold. We use it to define sunrise and sunset as the times when the inferred light intensity crosses that threshold. If we want those crossings to represent a precisely determined time, we should choose a part of the light curve that is steep. As we can see from the graph of light intensity vs. time of day shown at the right, the slope steepens for awhile as the light gets dimmer. As a practical matter, one chooses a threshold that is several decades below noon sun intensity.



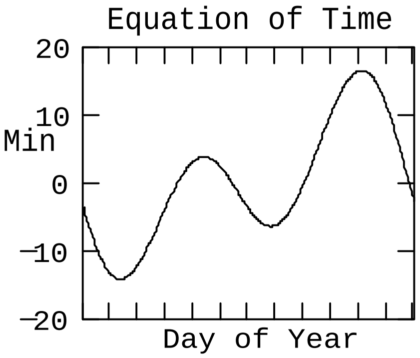
While that sunset time might be precisely determined, it may not be very accurately determined. The problem is the cloud layer we mentioned above. It can darken the day by a factor of ten, shifting our time by as much as ten minutes even on the steep part of the curve. The effect of this on our two position coordinates differs, and will be discussed below. However note that the two transients at sunrise and sunset look quite symmetric, and there are good reasons to expect that so long as the weather does not change during the day, they will be symmetric. We should expect to find the midpoint between them with considerable accuracy.

Actually there are situations where novel definitions of sunset can be very useful. The puffer fish, that dangerous culinary delicacy the Japanese call Fugu, has a habit of hiding in the sand during the day. Such behavior is very hard on most of the assumptions made above, and prevents us from getting any useful light record from the sand-covered detector. However the fugu can tell day from night, and after dark it wriggles out of the sand to swim around. The start of fugu swimming may not be the sunset criterion we would have chosen, but it is an example of another definition that we can use, at least for estimating longitude.

2.1.3 Longitude in more detail

It is useful to regard solar midnight as a line, a north-south line on the earth just opposite the sun. As the earth turns, that motion causes midnight to sweep across its surface. The arrival of midnight at any given location is the event we know by that same name. After passing Greenwich England, the zero point of longitude, midnight moves west across the Atlantic Ocean at 15 degrees of longitude per hour, reaching Cape Spear in Newfoundland about 3 ½ hours later. The longitude of any point is exactly 15 times the delay in hours between when midnight passes Greenwich and when it passes that point. If we can measure that time delay, we can learn the longitude.

To complicate matters a little, the orbit of the earth around the sun is not quite a circle, and the speed of the earth in its orbit is not quite constant. That and other astronomical effects turn out to mean that midnight does not usually pass Greenwich, England exactly at 00:00 hours Universal Time. The necessary correction is called the "Equation of Time" and varies throughout the year as shown at the right. For details, consult the Nautical or Astronomical Almanac. If we have a good clock that is set to UT, then this curve tells us just what it said when midnight passed Greenwich, England.



So now all we need to know is when midnight passed the location where we want to find the longitude. Of course nothing much happens to the ambient light intensity just at midnight, so we cannot sense that passage directly. However we can find midnight as the time midway between sunset and sunrise. If we incorrectly guess our threshold level and make it too low, we may move the apparent sunrise time early but we will at the same time move apparent sunset time late by the same amount. The two errors will largely cancel when we average the times to find midnight.

Now knowing the time when midnight passed the tag's location, and knowing the time when it passed Greenwich, we can subtract, convert from time to degrees of rotation, and obtain a value for longitude.

So what can go wrong with that? Mostly, the weather can change during the day, making the morning brighter or dimmer than the evening. If the weather goes from clear sky to heavy overcast, it can make a difference in intensity by a factor of 10, which will move the apparent sunrise time by perhaps 8 minutes, the apparent time of midnight by 4 minutes, and the longitude by one degree. Actually one does see errors of roughly that size, with a standard deviation somewhat less than a degree.

2.1.4 Latitude in less detail

The simple measure we have for latitude is day length, but the prospects for using it are far less favorable. Where the morning and evening errors in opposite directions tended to cancel when averaging times to find midnight, they tend to combine as badly as possible when subtracting to find day length. In addition, the dependence of day length on latitude and season is complex. Near the times of the spring and fall equinox the day lengths are nearly the same at all latitudes, so there is little latitude information to be had. Yes, one can learn something useful some of the time, but the situation is too complicated for this article.

What researchers usually do is to determine latitude from sea surface temperature, which also varies with latitude. The tag is programmed to notice when the fish is up into the surface mixed layer where temperature is nearly uniform with depth, and it measures the temperature then. The researcher compares that temperature measurement with sea-temperature maps measured by satellite radiometry. This is another complex topic, since the sea temperature varies also with longitude and time, and sometimes an eddy will cause two separated latitudes to have the same temperature. Again, we decline to pursue that topic here.

2.2 Data Requirements

To carry out the measurements discussed above, we first need to measure the intensity of blue light over a very broad intensity range. If we want to use a sunset threshold as much as three decades down from noon sun intensity, and have a nine-decade light detector, we have six decades of range left to handle water absorption. In water with a decade absorption of 50 meters, those six decades will let us see down to 300 meters depth. That is deep enough to deal with some tuna, such as yellowfin and juvenile bluefin, but will not always suffice for adult bluefin or bigeye tuna. We can accept a higher threshold on days or on missions when the alternative is no result at all, and some of the deep-living fish are kind enough to habitually hang out nearer the surface during twilight when the surface light is dim. Still we need the best light sensitivity that is practical within our space and power budgets. At present, that measurement floor is somewhere near nine decades below midday light intensity.

We must also measure depth, and the only simple way to do that is to measure pressure. Since some tunas routinely break pressure sensors tested to 1000 meters (1435psi) we have chosen a range of 2000 meters.

If we are to find longitude accurately over a multi-year mission, we need a good clock. Any clock error will translate into longitude error at the rate of ¼ degree of longitude for every minute of time error. A clock good to one part per million will accumulate an error of ½ minute per year, causing a longitude error of 1 degree after 8 years for that reason alone. The longest tuna track obtained to date spans 4 ½ years. When recovered, the animal was not yet a full-sized adult.

Finally, in order to support the determination of latitude from sea surface temperature, we must measure temperature. For this, we should measure to ±0.1°C. Amazingly enough, although they are true fish, tuna are at least partly warm-blooded! As a result, it is the external temperature that we need to measure for navigational purposes. Both we (for temperature compensation) and the researcher want to know the animal's internal temperature as well, so sensors are needed both inside and outside.

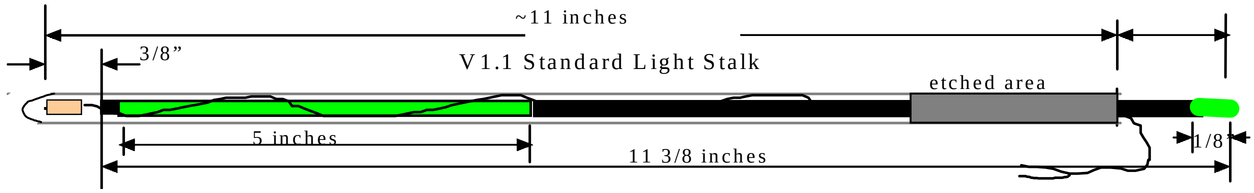
3.0 The Tag

All this background has been leading up to an electronic device, a field data acquisition system that is small enough to be implanted into the body of a fish. Every minute it makes the four measurements mentioned above then records them in both raw and processed form. We consider now its hardware and software.

3.1 On Board Sensors

Measurements of depth and internal temperature are made in conventional ways: a pressure sensor measures depth and a thermistor in the body of the tag measures the internal temperature of the fish.

However most fish are dark inside, and tuna are endothermic (warm-blooded) so the light sensor and a second thermistor must go outside. The tag does this with the patented sensor stalk diagrammed below. The dimensions shown are for the larger LTD2310.



The heart of the stalk is a piece of plastic optical fiber doped with a fluorescent dye. The dye is chosen so that only blue light can make it fluoresce, and that provides our spectral filter. The dye can be excited by light striking it from any direction, and that provides our optical diffuser. The dye emits yellow-green light in all directions; a large fraction of it is emitted sideways and passes back out of the fiber, but some is emitted within the cone of 20° half angle that can propagate down the fiber. Ideally, only light originating inside the fiber can enter those propagating modes, so a photodiode coupled to the end of the fiber sees only light emitted by the dye, and that all comes from blue light shining on the fiber from outside.

The end of the fiber is painted black, as is the part not intended to be sensitive. To complete the stalk, the fiber and a miniature thermistor are enclosed in a fluorocarbon plastic sheath (Teflon™ FEP) filled with a silicone gel. The silicon photodiode operates directly into a logarithmic current-to-voltage converter.

One end of the plastic sheath is heat-sealed, and the other end is etched to permit bonding to it, then immersed in the epoxy potting compound that fills the tag package.

3.2 Packaging Issues

Since the completed tag is to be surgically implanted into a prime food fish, customers want it to be made of medical-grade materials. The LTD2310 tag case is 316 stainless steel, a tube 5/8” in diameter and 2.6” long. The steel case is very thin, really a potting shell, and depends for strength on the fact that it is filled with epoxy potting compound. The stalk, which must penetrate the animal’s skin and resist bio-fouling in the water, is made of an extremely inert plastic. The only other material contacting tissue is medical silicone resin used to cover the pressure sensor and optical communication devices, and as part of the bend relief for the stalk.

3.3 Sensor compensation

Each of the sensors requires some kind of compensation. The thermistors are nonlinear, the pressure sensor is temperature dependent and needs to have its scale factor set, and both the clock and the logging element in the light detector need temperature compensation. The thermistors are approximately linearized by choosing the optimum series resistor, but all other issues are handled algorithmically in the processor.

3.4 Memory Management

Limiting resources for a tag of this kind are volume, battery lifetime, and memory space, with trade-offs available among those resources. The first of this family of tags has 8MBytes of data memory, but a working lifetime exceeding ten years. If the tag makes measurements at its navigational interval of once/minute, and uses 6 bytes to record each measurement set, it will fill 8640 bytes per day, or 3.15 MB/year and will fill those 8 MBytes in 2 ½ years. In fact the tag is capable of making measurements 15 times as often as that, and might fill the log space even sooner. Memory has gotten small and cheap, but in this kind of application one can still not have all that would be useful.

The tag responds to this situation in two ways: first, it measures two streams of data, one at a fixed one-minute interval for geolocation, and a second stream at a user-specified rate. At midnight of each day, it processes its own private, temporary data record by correcting light for depth, extracting sunrise, sunset, and surface temperature along with other summary information for the day, and records that summary in a compact log that grows at a rate of only 29 bytes/day. It can afford to store that information for every day of a decade-long mission in a small fraction of its available memory. Once done with each day’s private data record, it overwrites that data with the next day’s navigational observations. In this way, the tag is guaranteed to bring home a geolocation track for every day of a long mission, even when it cannot afford to bring home all the raw data on which that track was based.

Meanwhile, the tag records the user-specified data stream as a time series, using for this purpose all the remaining space in data memory. If the mission continues long enough, that space will eventually fill up. When the log space does fill, the tag converts the time series memory into what we call a telescoping log. It declares the data for every odd-numbered day to be vulnerable, and begins replacing whole days' worth of data with data from subsequent even-numbered days. When the space originally used by odd-numbered days is all used up, the log then contains a record of data for all even-numbered days of the mission. If the mission continues, the tag declares the data from all days not exactly divisible by 4 to be vulnerable, switches to taking data only on days divisible by 4, and stores it replacing vulnerable data. The process continues for the duration of the mission, always maintaining data at constant time resolution for a selection of days that are spaced at approximately equal intervals throughout a mission of any length.

Actually the description above corresponds only to the simplest case of time series logging. The user also has options to delay the start of logging, to specify an initial non-telescoping section, and to designate day pairs or day quads as the unit to be replaced in the telescope.

4.0 Summary

We have developed a miniature electronic device that automatically practices the ancient art of celestial navigation while riding aboard a fish. It keeps a sailing log of its results, which can be read out by the researcher who put it aboard, once the fish is caught and the tag returned. It also measures and records as much of the raw data as it has memory for, in a manner that automatically deals with the problem of memory overflow.