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COMMENTARY

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The value of using measurements of geomagnetic field in addition to irradiance and sea surface temperature to estimate geolocations of tagged aquatic animals

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Abstract

In this commentary, we describe how geomagnetic intensity can be used to estimate latitude, discuss its strengths and weaknesses, and argue for its potential use along with irradiance measurements for estimating the latitude of a migratory fish carrying an archival tag. We conclude this commentary by suggesting that researchers and tag manufacturers estimate positions using as many inputs as possible, environmental irradiance, sea surface temperature, and geomagnetic field. Each environmental property will provide a better estimate of position at different times of the year and locations on earth. We contend that one geolocation estimation approach is not better than another, as each functions optimally under different circumstances and thus should be used accordingly.

Keywords: Geolocation, Irradiance, Geomagnetic intensity, Archival tags

Background

As widely used in aquatic biotelemetry studies, the archival tag is a microprocessor-based recorder with sensors to measure behavioral properties of aquatic animals that can include heading, depth, and acceleration as well as environmental properties such as subsurface irradiance, water temperature, and geomagnetic field. These measurements, or a processed subset of them, are stored in electronic memory aboard the tag. A daily geographic position, termed a "geolocation," can be inferred for a tag holder from measurements of environmental properties, which to date have mainly been submarine illumination and sea surface water temperature (SST). In addition, depth measurements are taken commonly to ensure surface proximity when using maps of SST, to correct light curves, and to compare maximum observed diving depth to the bathymetry at a candidate position. The majority of geolocating archival tags have determined longitude using a method similar to that used by early mariners to navigate in the ocean. They found their longitude based on the difference between the "apparent" time, when they observed the sun was at its highest point in the sky at their current location, and the "true" time of noon, when the sun was at its highest point at a reference location (e.g., Greenwich, England). This time difference was recorded with an accurate clock, a chronometer. The archival tag similarly has a very accurate internal clock, which is initialized to universal time, yet is unable to find noon by the position of the disk of the sun because the fish tag is underwater and unable to distinguish celestial objects. Alternatively, the tag estimates the times of sunrise and sunset from rapid changes in the intensity of "irradiance" (energy in wavelengths near the visible region of the electromagnetic spectrum in contrast to "light" energy in the wavelengths visible to the human's eye) at dawn and dusk, respectively. Apparent noon, midway between the rapid increase in light at sunrise and the rapid decrease in light at sunset, can be compared to true noon to determine longitude—each hour difference between apparent and true noon equals an offset of

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ca. 15° from the prime meridian on the circumference of the earth. Latitude can also be estimated from irradiance measurements. Day length, or the time between sunrise and sunset (or conversely night length), varies with distance along a meridian on the earth's surface and thus is an indicator of latitude. The length of the day (or night) at the established longitude at the known time of the year is then entered into a mathematical algorithm that solves for latitude. The relative accuracy irradiance-based estimates of longitude are greater than similar estimates of latitude. To start with, latitudinal estimates are unreliable during the equinoxes, when the durations of daytime and nighttime area equal over the earth. They are most accurate during the solstices when the difference in the length of day varies greatest with latitude.

Furthermore, there are other sources of error in latitudinal estimates with biological causes. This is because of the necessity to correlate a point on the irradiance curve with a particular elevation of the sun. As an example, consider using 3.5×10^{-2} W/m^2 (~4 lx) as a threshold for the determination of latitude. Irradiance of this magnitude exists at the sea surface during civil twilight during sunrise when the sun is 6° below the horizon. The irradiance intensity recorded by the sensor will be lower than that present at the sea surface if it is covered sessile organisms such as algae or barnacles or if the fish is swimming at depths well below the sea surface. Consequently, the sensor will record that intensity later in the morning and an equal amount earlier in the evening. The measured day length is shortened, resulting in a latitude error. On the contrary, the time of apparent noon will not change, as it lies half way between the two points on the curve, and the estimate of longitude estimate will be comparatively unaffected by these conditions. The systematic improvements in light-based geolocation estimates are reviewed in the introduction to a description of the use of light measurements from moored tags to calibrate the curves recorded on the animal [1]. These permit them to be entered into a state-space model to increase the accuracy of geolocations.

Given the difficulty in estimating latitude from irradiance levels, researchers have estimated latitude by matching the temperature recorded by archival tags when the bearer swam near the surface to the sea surface temperature (SST) present at the longitude estimated based on irradiance. For example, the ARGOS-based positions of the endpoints of pop-up satellite archival tags and recapture locations of archival tags of salmon (*Lamna ditropis*) and blue sharks (*Prionace glauca*) in the North Pacific Ocean from 40 to 60°N were compared to the last geolocations of longitude based on irradiance and latitude based on sea surface temperature [2]. The root-mean-square errors of the irradiance-based longitude estimates were 0.89 and 0.55°, while for SST latitude estimates, the root-mean-square errors were 1.47 and 1.16° for salmon sharks and blue sharks, respectively. Simulations were carried out that indicated that difference between the SST measured by the electronic tag and the remotely sensed SST at a given location was the predominant influence on the accuracy of SST latitude estimates. Positional accuracy can be improved further by using a motion filter (e.g., Kalman, particle, and grid) within a state-space model to process longitude and latitude estimates based on measurements of both irradiance and SST [3]. This technique has been evaluated by comparing geolocations estimated by archival tags attached to thermistor-equipped drifting buoys located using the global positioning system (GPS). Hence, SST has been used in conjunction with irradiance and improved using state-space models, to increase the reliability of geolocation estimates of archival tags.

Estimating latitude geoposition with geomagnetic intensity

However, the earth's magnetic field intensity is another environmental property that can be used to estimate latitude, which for the most part has been largely overlooked in aquatic biotelemetry. Klimley and Mangan [4] first proposed that an electronic tag could infer the latitude at which a fish was swimming based upon the measurement of the intensity of the earth's magnetic field. They argued these estimates could be more accurate at certain times of the years (i.e., the equinoxes) and areas on the earth (i.e., near the equator). Furthermore, even during the solstices and in temperate and polar latitudes when and where day length changes along a north south gradient, there are both environmental and biological factors that can reduce the accuracy of latitude estimates based on irradiance.

To appreciate the potential of this environmental feature in geolocation positioning, one must have an understanding of the earth's geomagnetic field. The earth has a dipole magnetic field, which varies from 0.26 gauss (26,000 nT) at the equator to 0.66 gauss (66,000 nT) at the magnetic poles (Fig. 1). These are separated geographically from the north and south geographic poles, around which the earth rotates. This field is produced by the dynamo movement of molten iron in the outer core 2900 km from the earth's surface [5]. The distant subterranean origin of the main field accounts for its smooth and predictable structure near the surface and supports accurate latitude estimation. In addition, tiny particles of magnetite, a bipolar ferrous compound, embedded within the basaltic crust of the earth, usually a few km from the surface, generate a magnetic field. This added component distorts the main field with proximity to the

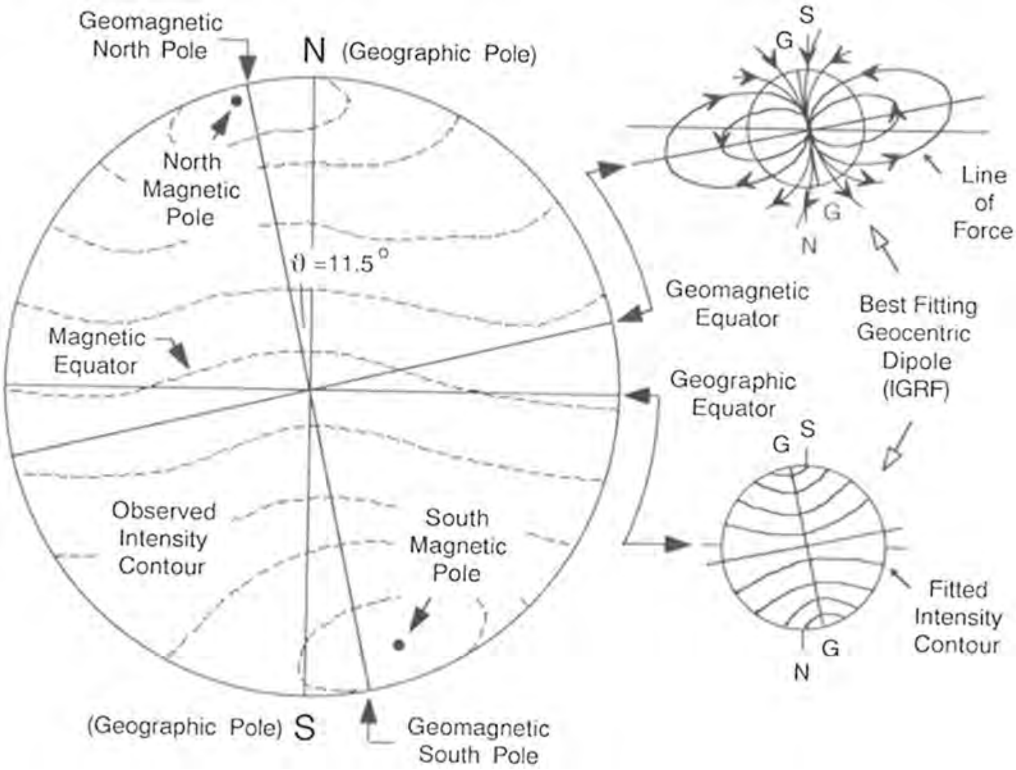

Fig. 1 Earth's main field showing the observed intensity contours, the magnetic and geomagnetic poles and the geographic pole, around which the earth rotates [7]. The *lines* of force are indicated on the above insert and the best-fitting geocentric dipole based on the International Geomagnetic Reference Field (IGRF) on the lower insert

magnetized body, but only exceptional anomalies distort the earth's main field by >1% of the field strength at the equator.

The earth's total field intensity is the sum of three orthogonal vectors, often described with a vertical, north–south, and east–west component. The intensity of the total field is measured throughout the year at magnetic observatories located over the entire surface of the earth. A series of spherical harmonics are used to determine Gauss coefficients to fit the thousands of magnetic measurements by the worldwide magnetic survey to a spherical dipole. The best fit is an inclined dipole with its axis passing through the center of the earth between north and south geomagnetic poles. This technique has been used to produce the International Geographical Reference Field (IGRF) [7] and the World Magnetic Model (WMM) [6] that map the earth's total field intensity in three dimensions. While IGRF and WMM model the main field only, the Enhanced Magnetic Model (EMM) [7, 8] also incorporates crustal magnetic anomalies with a minimal geographical extent of 56 km [9]. The modeled magnetic field can be visualized as a globe covered by isoclines, lines indicating similar magnetic strengths, looping around the earth. This feature, whose intensity varies largely along a north–south axis, is a prime candidate for estimating latitude. In this commentary, we describe how geomagnetic intensity can be used to estimate latitude, discuss its strengths and weaknesses for use in aquatic biotelemetry, and argue for its use along with irradiance measurements, sea surface temperature (SST) and other available gradients such as magnetic field inclination for estimating the latitude of a fish carrying an archival tag.

In order to estimate latitude based on magnetic field intensity, it is necessary to first estimate the longitude of the tag. This is determined using irradiance measurements. This technique has already been described in detail within the scientific literature [1]. However, latitude can now also be determined based on the measurement of the average magnetic field intensity. Magnetic field intensity can be measured using a 3-axis magnetometer aboard an archival tag. The intensities recorded on the three axes must be summed to provide an overall measurement of total field intensity. The component measurements can be made when the tag holder is at any depth because the strength of the main magnetic field varies only slightly as a function of depth. The difference in the intensity of field between that present at surface and at a depth of 2000 m, the typical maximum operating depth of most tags, is only roughly 0.1% of the magnitude of the earth's main field at the surface. This discrepancy is dwarfed by other sources of error such as the uncertainty of WMM measurements, which is roughly 0.3% of the strength of main field [8]. The measurement of the intensity of the earth's main field must then be paired with an estimate of longitude, derived from the daily series of irradiance measurements. These values are stored in memory aboard the tag and are available for removal upon recovery of the tag. If a fish carrying the tag swims at the surface, and the tag's antenna is out of water, the measurements can be transmitted via a radio frequency from a platform transmitting terminal (PTT) to the ARGOS satellite, given that it passes overhead when the fish (and tag) is at the sea surface. Archival tags that release from the fish and float to the surface can also transmit their stored information to the satellite. Given the longitude of the tagged animal, the latitude can be determined based upon the measurement of total field intensity. Software is available from the United State Geological Survey that will provide a user with total field intensity, given a longitude and latitude of any point on earth. An algorithm can be used to find the estimated latitude through an iterative examination, searching for the matching intensity along a series of modeled intensities along the estimated line of longitude until a match is found between measured and the modeled field intensity. The process is illustrated on a map of the earth's main field (Fig. 3). A meridian is drawn on the WMM map at the estimated longitude to isoclines with the measured geomagnetic intensity.

We demonstrate how the method works with an archival tag equipped with a magnetometer, irradiance, and temperature sensors on a tag drifting at the surface. It is our intention to provide error estimates independent of behavior, which varies with species, and thus our estimates would be of greater general value to the general tagging community working on a diversity of aquatic species. The drifting tag can be used to compare the positioning methods under a boundary condition of maximum accuracy. A tag on an animal would experience constantly changing depths and variable water conditions, and this would result in error estimates for the different methods unique to a particular species. An animal swimming at depth would experience greater magnetic anomalies in certain regions such as the Galapagos Islands or the Gulf of California, and this would add to (positive anomaly) or subtract from (negative anomaly) the total field, shifting the geoposition estimate to either a higher or lower latitude. The accuracy of the irradiance-based estimates of apparent noon or day length will be reduced due to an animal's behavior such as diving and the changing environmental conditions encountered that do not affect a drifter. For example, the deeper an animal goes and the greater the attenuation of irradiance, the later the threshold defining dawn will occur in the morning, and the earlier threshold defining dusk will happen in the evening.

The method by which geolocation is determined may vary between manufacturers. Hence, the method by which this Desert Star's SeaTag estimates longitude and latitude will be explained below. The explanation is general without some details because the information is proprietary. The tag's wrap-around solar power panel serves as the irradiance sensor. This 360° design provides near-equal response to illumination independent of tag orientation on the fish, thus improving the reliability of local apparent noon and apparent day length measurements. The magnetometer undergoes extensive factory calibrations to maximize the accuracy and reliability of magnetic field intensity measurements in order to accurately compare these measurements to values predicted by geomagnetic models. The irradiance measurements are based on timing the dawn and dusk illumination threshold crossing of an intensity of 1.4 Lux; a value above maximum expected surface moonlight but well below the nominal sunrise and sunset illumination of 400 Lux at the surface. This assures that for an animal located anywhere in the euphotic zone (light absorption $\leq$99%), dawn timing occurs before sunrise and dusk timing after sunset. Twilight is the period of the steepest irradiance gradient where measurements are least affected by disturbances such as varying turbidity, weather or animal diving behavior. The tag archives the determined local apparent noon, apparent day length, and a 24-h average magnetic field intensity that are used to estimate geolocation in a single daily observation summary packet. This is transmitted in a single ARGOS packet which maximizes the number of daily positions that will be available even if post pop-up transmissions should be interrupted.

Current measurements transmitted after pop-up by the tag in periodically transmitted engineering packets are compared to model predictions for the ARGSO-identified tag location and used to establish sensor biases for compensation. Sensor stability is verified by comparing sensor bias for the start and end of positions of the track. Conversion to geographical coordinates is accomplished by matching tag measurements to geomagnetic models and astronomical equations. If processed through CLS Track&Loc, these are improved based on information from sea surface temperature, bathymetry and coastal maps. The irradiance-based local apparent noon is converted to longitude, while latitude is identified by matching the observed and bias-compensated magnetic field intensity to the intensity at a point on the established line of longitude using the WMM geomagnetic model. The accuracy of the irradiance measurements for a given day, and thus the longitude component, is evaluated by comparing the apparent length of day, after bias compensation, to the length of day predicted for the magnetometer-identified latitude. If the observed day is much shorter than the predicted day, then the measurement of apparent noon may be unreliable due to turbidity, diving behavior, weather, or shading. Conversely, a matching or somewhat long apparent day indicates reliable longitude because the steep light gradient at dawn and dusk provides an upper bound to the observable day length and will only be observed if shading events have not unduly influenced the dawn or dusk irradiance measurements [10].

The tag was shed from a tiger shark (*Galeocerdo cuvier*) off the coast of Florida after traveling to the vicinity of Nova Scotia and back [11]. The buoyant tag drifted northwestward across the northern Atlantic Ocean from its release site from the shark on December 26, 2012, north of Grand Bahama Island off the southeastern coast of Florida for a period of 10 months until October 25, 2013, when the PTT was last detected off the coast Newfoundland, Canada. The PTT transmitted periodically to ARGOS over this period providing reference positions with a median error of 6.1 km. At this time, the solar cells charging the tag became covered with fouling organisms, and the tag did not generate enough power to transmit through the PTT to the ARGOS satellite. Shown in Fig. 2 are three tracks, which were computed using different positioning methods of the tag after it popped off the shark and was drifting for 10 months at the surface. The first track is composed of geolocations using magnetic measurements to estimate latitude (see red circles), the second track consists of geolocations using irradiance measurements for estimating latitude (yellow hexagons), and the third track is comprised of Doppler-derived ARGOS positions (white triangles and lines). Note that there was sufficient power received by its solar panel and stored in the tag for its logic circuit to continue to record and log irradiance and geomagnetic measurements in

Fig. 2 Path taken by the platform terminal transmitter (PTT) detached from a tiger shark (*Galeocerdo cuvier*) as it drifted across the North Atlantic Ocean, permitting the comparison of geomagnetic-based (*red circles*) and irradiance-based (*yellow circles*) to Doppler-based ARGOS positions (*white triangles*). The solar cell became fouled with sessile organisms as it drifted past 40°W depriving the transmitter with sufficient power to communicate with the ARGOS satellite. Note the less accurate irradiance-based estimates at the equinoxes, when day length is similar at latitudes and more accurate at the solstice when day length differs with latitude

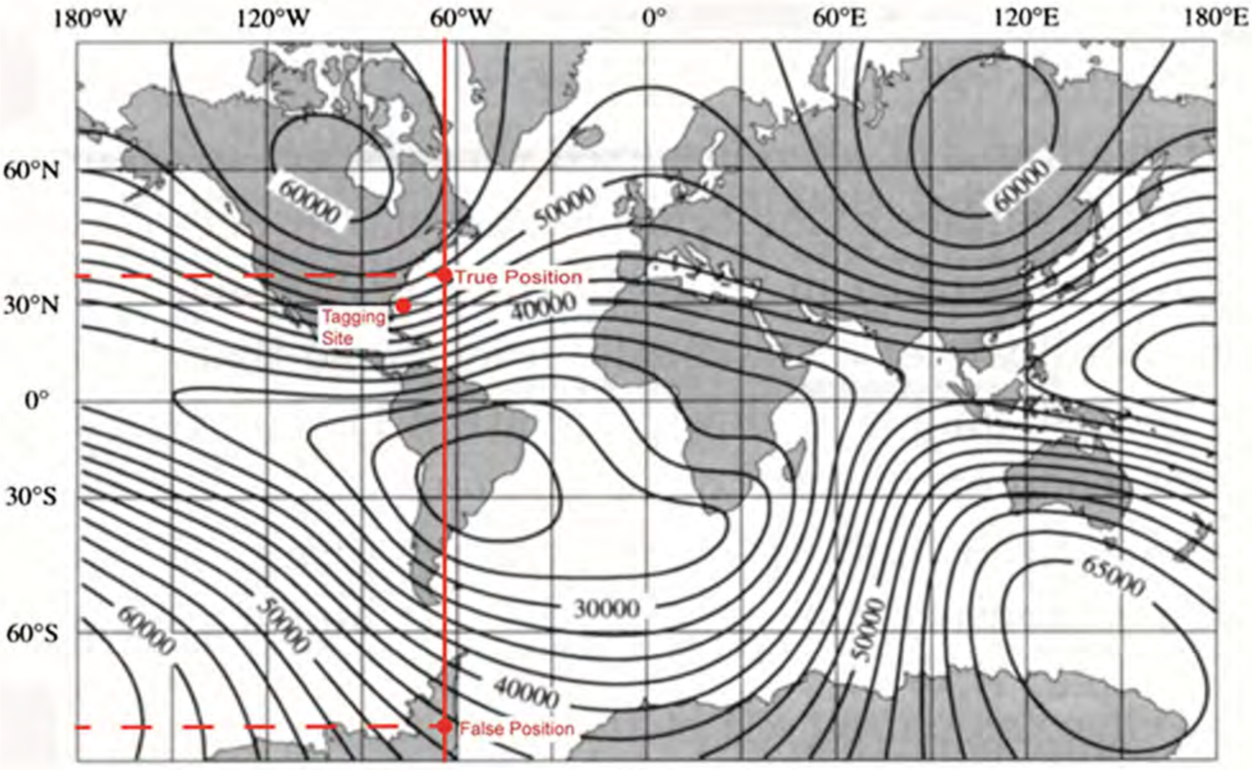

Fig. 3 Map of the reference field, which consists of magnetic isoclines fitted to the distribution of magnetic intensities measured by observatories located worldwide. Geomagnetic geolocations are most accurate in regions where the magnetic field intensity gradient is steep and runs north–south and thus where the *lines* of equal magnetic field intensity are dense and run approximately east–west. There are generally two locations (solutions) for each north–south line. In this case, the drifter is more likely to be at 38°N than 85°S, which is on the Antarctic Peninsula (see *dashed red lines* in Fig. 3). Note that the geolocation (*red circles*) for the drifter would be accurate because the dipole gradient is steep in the western North Atlantic Ocean

its memory until December 14, 2014, when the tag was recovered on a beach in South Wales, UK.

The geomagnetic geolocations for the drifting tag were determined with the use of a map of geomagnetic isoclines (Fig. 3). For example, analysis of the irradiance measurements indicated that the tag drifted across a longitude of 65°W during June 15, 2013 (see yellow rectangle in Fig. 2). The measurement of magnetic intensity by the tag for this day was 48,790 nT. A north–south trending line from the poles 65°N and 65°S through the 65°W meridian would intersect the isocline for 48,790 nT off the northeastern coast of North America at a latitude of 37.6°N. For geomagnetic estimates of latitude, there are generally two locations (solutions) for each north–south line. In most cases, they are widely separated, and one can be eliminated because it is considerably farther from the release location or not consistent with previous daily observations. In this case, the drifter was more likely to be at 37.6°N than 85°S, which is on the Antarctic Peninsula (see dashed red lines in Fig. 3). This estimate could further be validated, if the tag was also to provide an estimate of latitude based on day length and sea surface temperature.

Advantages and disadvantages of geomagnetic geolocation

For each method, the average expected error is a function of the following: (1) the steepness of the relevant field gradient over space, (2) the error inherent in the model of that field, and (3) the expected measurement error of the sensor aboard the electronic tag. For each approach estimating latitude, a small error can be expected when the gradient is steep as well as when the measurement and model errors are small. The expected error will be larger if the gradient is shallow and the model and measurement errors are large.

The geomagnetic method works best in regions where the magnetic field intensity gradient is steep and runs north–south and thus where the lines of equal magnetic field intensity are dense and run approximately east–west. To understand where geomagnetic geolocations are best used, it is necessary to point out the irregular nature of the inclined dipole fitted to the earth's field. Strong north–south geomagnetic intensity gradients exist in a latitudinal band over the northern Pacific Ocean, Central America to Canada, northern Atlantic Ocean, northern Africa, and southern Asia (see Fig. 3). Similarly, steep gradients exist in the southern Pacific Ocean, the southern Atlantic Ocean, the extreme northern Indian Ocean, northeast Asia and across Australia. It is in these regions, where steep geomagnetic gradients exist, that geomagnetic latitudinal estimates will be most accurate. Hence, one would expect the accuracy of the positions of the drifter in the northern Atlantic, where magnetic field intensity gradient is steep to be high. This is where the accuracy of geomagnetic geolocations may be greater than those based on irradiance and sea surface temperature.

Let us return to the drifter's tracks in the northern Atlantic Ocean. This accuracy advantage is borne out when the accuracy of positions based on geomagnetic intensity is compared relative to the accuracies of positions derived from irradiance and sea surface measurements. At a longitude of 65°W and latitude of 38°N, there is a strong uniform gradient in the earth's main field. A 3-D plot shows the gradient in geomagnetic intensity at different longitudes and latitude (Fig. 4). Note the even slope to the surface of the plot over an oblique band stretching from 34°N–39°N to 77°W–54°W, including the area marked in Fig. 2. Day length is shown as a function of latitude over the course of a year (Fig. 5). The latitude limit of 56°S and 56°N was chosen because these are the extreme latitudes at which the sun still reaches civil dawn and dusk (i.e., 6° below horizon) during the summer solstice. The slope in day length on the 3-D plot is near its maximum on June 15, 2013, when we are comparing the accuracy of the different methods of geolocation. This day is within five days from the summer solstice and hence should provide more accurate positions than those earlier or later, near the vernal and autumnal equinoxes. Finally, sea surface temperature is plotted for the same day (Fig. 6.). It is apparent that the surface of the 3-D plot is flat at latitudes of at 36°N and 37°N, but further north there are steep SST gradients at 65°W.

The average expected error for estimating latitude is shown using geomagnetic, irradiance, or SST measurements for the 65°W meridian between 34°N and 39°N under conditions present on June 15, 2013, when the tag crossed this meridian (Fig. 7). The root-mean-square uncertainty (clear circles of the geomagnetic estimates) remain less than 1° over the latitudinal gradient. The uncertainty of the geopositions based on irradiance measurements remains at roughly 2° across latitude. Finally, the uncertainty of the geolocations based on

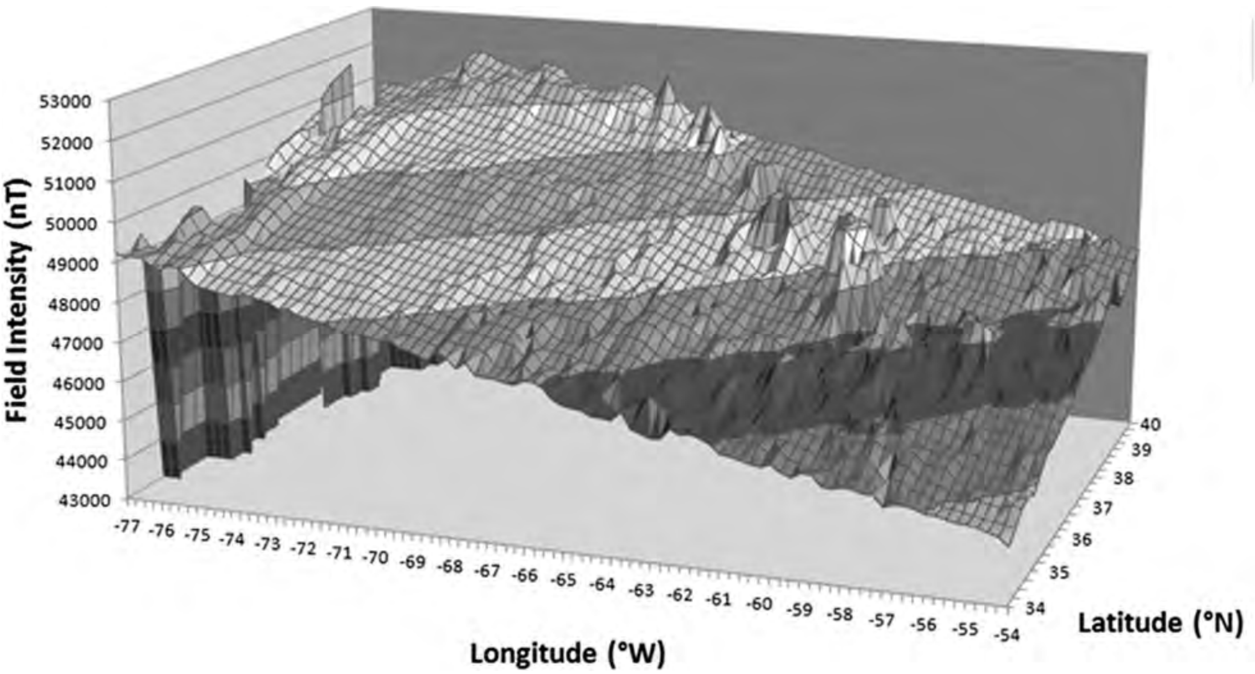

Fig. 4 Geomagnetic field intensities plotted as a function of longitude and latitude over the period of time the PTT was at the surface as it drifted across the western North Atlantic Ocean. The bands on the 3-D surface indicate iso-contours of 1000 nT. Note that even with the plotted crustal magnetic anomalies (from World Digital Magnetic Anomaly Map, WDMAM), the slope of the surface of the plot is relatively smooth and hence provides a good estimate of position

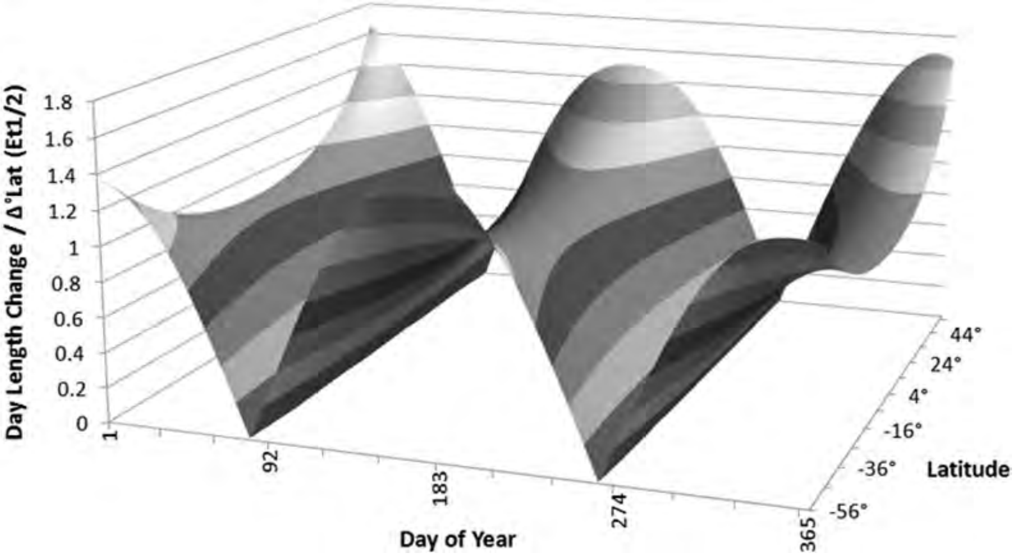

Fig. 5 Three-dimensional plot of day of day length as a function of time of year and latitudes from 56°S to 56°N. Daylight change is expressed in irradiance half-life periods ($E_{t1/2}$) per Δ° of latitude. An irradiance half-life period is the time it takes for irradiance levels to double during dawn and halve during dusk. While day length around the solstices changes dramatically in the high latitudes per degree latitude travelled north or south, the dawn and dusk light gradient is also less pronounced at these latitudes. Nonetheless, day length measurement-based latitude estimates can be expected to be about 1.7 times more accurate at 56°N as compared to the equator at solstice. In conclusion, the gradients in day length are greatest during the summer and winter solstices, when the days are longest and shortest in the northern and southern hemispheres; the gradients are weakest during the fall and spring equinoxes

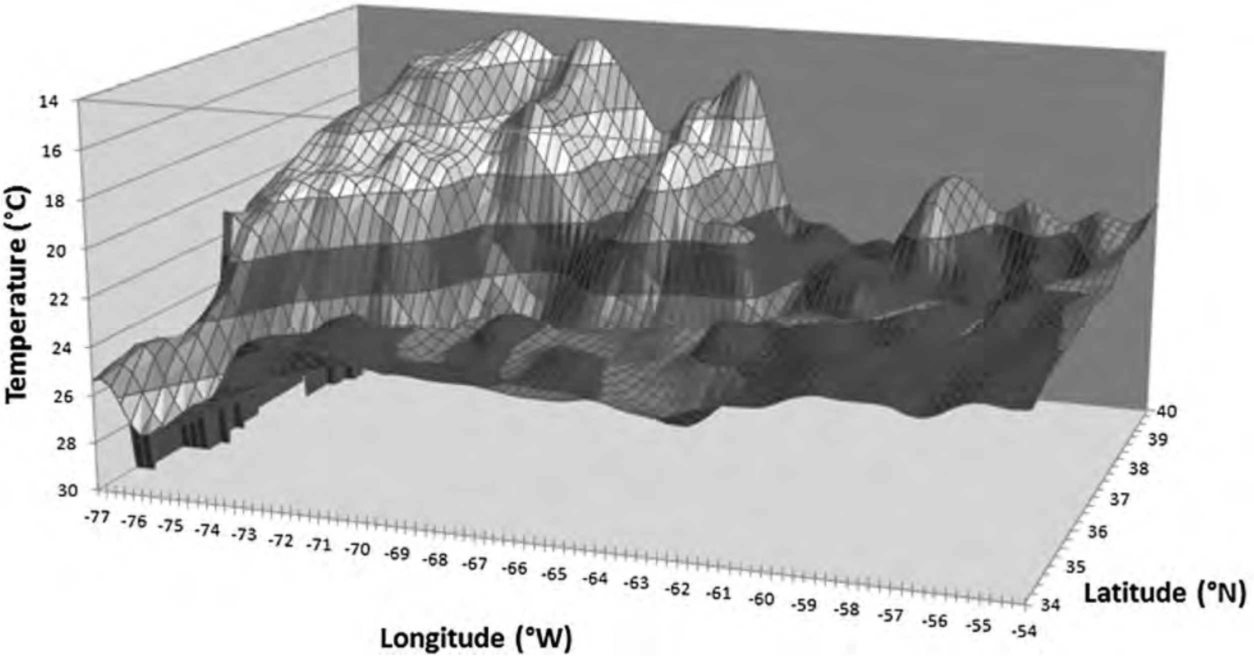

Fig. 6 Three-dimensional plot of these surface temperatures (SST) at different longitudes and latitudes when the PTT crossed the 65° meridian on June 15, 2013. The shaded bands are at 2 °C intervals. The SST gradient is location specific and highly variable, meaning that north–south positioning accuracy and confidence can be expected to vary accordingly

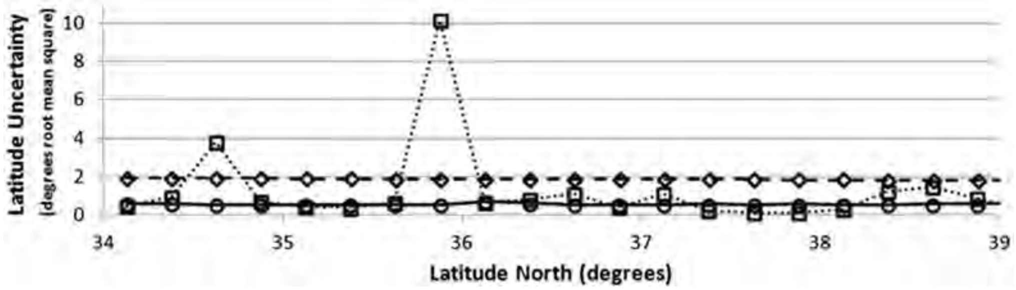

Fig. 7 Expected uncertainty of latitudinal estimates (root-mean-square) at 65°W on June 15, 2013. The geomagnetic field-based estimates are indicated by *clear circles*, irradiance-based determinations by *clear diamonds*, and surface temperature-based estimates as *clear squares*. A relatively steep gradient in magnetic field intensity with only minimal disturbances provides an estimated north–south accuracy of 0.5°–0.7° throughout the region. Irradiance measurements are generally a less accurate predictor of latitude in this case, but are useful to constrain the search area in the case of an uneven SST field or strong, local magnetic anomalies not captured by available models. The north–south accuracy available through SST measurements fluctuates, inversely proportional to the fluctuating SST gradient. Southern and northern regions show similar SST and magnetic performance, while in the center region, magnetic measurements can be expected to yield substantially better accuracy

temperature measurements, although less than 1° over most of the latitudinal range, increases to 4°–10° at 34.6° and 35.8°.

Following is a detailed description of how the geopositions were determined using the three different inputs for the drifting electronic tag (SeaTag-MOD; Desert Star Systems) [see summary in Table 1]. Note that geolocations are derived with a method particular to this manufacturer and may not represent the accuracies determined using other algorithms by the other manufacturers of archival tags. The tag's temperature sensor has a typical accuracy of ±0.1 °C, and its magnetometer has a typical residual error of 300 nT. Its light intensity measurement repeatability error is assumed to be negligible. The geomagnetic and irradiance model error assumptions in Fig. 7 reflect typical use for SeaTag. For the geomagnetic measurements, we used site-specific anomaly amplitude values per World Digital Magnetic Anomaly Map (WDMAM) as the model error. For day length measurement by irradiance, we assumed that any starting bias (such as due to solar panel sensitivity or tag fouling) is in situ compensated by comparing day length observations for the pop-up point to predicted day length at the ARGOS-determined location and that equivalent points on the undisturbed sunrise and sunset irradiance curves are measured with a four-minute typical error, equivalent to fluctuating irradiance disturbances such as due to weather, turbidity or depth changes of −50/+100% of the nominal irradiance value. This is a value that in combination with the typical steepness of the twilight irradiance curve at mid-latitudes gives rise to 0.5° typical longitude error observed for the tag. Figure 7 also assumes that the SST model error is ±0.6 °C typical, the stated accuracy of the foundation SST of the OSTIA model. OSTIA is the SST model used by the CLS Track&Loc service (a state-space model), which supports the processing of SeaTag data.

It is noticeable that the line indicating magnetic field latitude uncertainty remains at a typical value of roughly a half of a degree of latitude from 34°N to 39°N in the northwestern Atlantic Ocean. The line denoting irradiance geolocation uncertainty indicates roughly 2.0° of latitudinal uncertainty. Note that it decreases slightly with increasing latitude, as the difference in day length with latitude increases toward the poles. Finally, the sea surface temperature curve has two peaks, corresponding with high uncertainty at latitudes where there was little spatial gradient in temperature. However, the curve slopes downward at higher latitudes, where a greater temperature gradient manifests. The steep slopes in the 3-D plot of sea surface temperature exist at these highest latitudes between 38.3° and 39.0°N (see Fig. 6). Figure 7 does not imply that the stated typical or root-mean-square (RMS) latitude uncertainty necessarily produces a latitude error of that amount, but rather indicates the error potential or north–south extent of the 50% confidence interval resulting from the combination of the local field gradient, the measurement uncertainty and the model uncertainty.

Although magnetic geolocations are relatively more accurate in certain areas on the earth's surface, they are less so in other regions. Weak meridian gradients are present from Canada northward in northern America, over the equatorial Pacific Ocean, much of Brazil and the equatorial Atlantic Ocean, and south of Australia (see Fig. 3). In these regions of the globe, the geomagnetic intensity gradient is minimal and thus geomagnetic geolocations will not be accurate. Furthermore, in the southern Indian Ocean geomagnetic field intensity-based latitude estimation will be inaccurate because the lines of

Table 1 Comparison of geolocations based on irradiance, magnetic intensity, and sea surface temperature

	Irradiance (day length)	Magnetic field intensity	Sea surface temperature
Sensor cost	Low	Medium–high	Low–medium
Sensor calibration	Available from the factory	Requires special equipment and magnetically undisturbed site or facility	Available from the factory
Field characteristics	Naturally smooth, varies with time of year, less of gradient with latitude at equinox than solstice	Smooth main field changes slowly over years (intensity, inclination, and declination) with overlaid crustal and man-made anomalies	Highly dynamic over time. High gradients in mid-latitudes, low gradients near equator and high latitudes.
Main disturbance	Tag fouling, water clarity, diving depth, sea state, tag orientation if directional; cosine correction or wrap-around collector avoids directionality	Crustal anomalies associated with magnetic lineations and volcanic seamounts and islands, man-made anomalies of wrecks, rare solar storms	Diurnal variations and vertical stratification. Errors arising from small, hot or cold regions or uncertain depth profiles not captured by the model but influencing the tag measurement
Availability at depth	Within the euphotic zone, <200 of meters depending on water clarity	Present at all depths. Main field uniform at surface, anomalies increase with depth or in proximity to magnetized bodies	Mixed layer to a depth captured by model
Typical model error	Civil day length computed using astronomical equations. Negligible modeling error	Mean error of 152 nT for WMM model. This paper uses site-specific maximum anomaly in 0.25° × 0.25° cells per WDMAM	Error of 0.6 °C mean for OSTIA foundation Sea surface (temperature at the indeterminate depth free of diurnal variations)
Typical measurement error	±4 min typical error for measuring equivalent points on the sunrise and sunset irradiance curve. This corresponds to approx. +100/−50% irradiance disturbance due to factors such as weather changes, turbidity changes, animal depth changes and in situ bias compensation	A 300-nT residual error after in situ bias compensation	0.1 °C after in situ bias compensation

equal magnetic field intensity run approximately north–south, thus producing an east–west gradient rather than the desired north–south gradient. However, here measurements of the inclination of the earth's magnetic field could be used, rather than its intensity, as the proxy for latitude, as the inclination gradient is steep and runs north–south [12].

There are disturbances in the earth's main field both in time and in space, and these can affect the accuracy of geomagnetic geolocations. WMM models the long-wave or smooth components of the earth's magnetic field, which originates within the earth's fluid outer core [3]. While the field is disturbed by external fields such as from solar storms, these are too infrequent to be of much consequence for position estimation. For example, from 2010 to 2015, the United States Geological Survey lists ten significant magnetic disturbance events with total observed field disturbances up to around 500 nT with durations of from 1 to 6 days. With regard to space, man-made anomalies can be very strong, and we have observed disturbances up to 2500 nT during a boat-based magnetometer survey along the length of the lower Niagara River (Marco Flagg, pers. commun.). However, they are small in size and their association with human activities provides a basis to consider or ignore their impact based on the likelihood of sustained animal presence around such structures. Crustal magnetic anomalies are produced by basalt extruded from the earth's mantle that contains tiny particles of magnetite. The seafloor is composed of bands of crust with alternating strong and weak magnetization, created by the periodic reversal of the earth's dipole field. These disturbances are evident as sharp peaks and troughs oriented usually in a north–south direction. Islands and seamounts, which are produced by volcanic activity, have a dipole field associated with the crater and peaks and troughs leading away from them produced by the lava flows. The crustal anomalies create a total error of the WMM of 152 nT typical, which is <1% of the main field [3].

One must therefore be careful of estimating geolocations using latitude estimates from magnetic field intensity in areas characterized by unusually large crustal anomalies. The WDMAM [7] identifies the area around the Galapagos Islands as a region of major crustal magnetic anomalies, produced by the Galapagos spreading center. The anomalies captured in the WDMAM data set in this area, range from −1163 to +1060 nT. These anomalies caused a prominent north–south displacement of the geomagnetic track of a whale shark carrying a SeaTag (Desert Star Systems), with intensities up to 1200 nT per day producing a displacement of 250 n.m. along the north–south gradient of the WMM. This produced large latitudinal departures from the track of a whale shark tracked off the Galapagos Islands (Alex Hearn, pers. commun.). These errors diminished as the shark approached the coast of Colombia where large anomalies were not present.

Using multiple inputs for geolocation estimation

The track of an animal will be more accurate and robust if multiple environmental features are used in position determination. Notice in the track of the drifting transmitter that during spring 2013 equinox, irradiance-based geopositions (yellow circles) are far north of the Doppler-based ARGOS positions (white triangles). This is also characteristic around the fall 2013 equinox. During these times, geomagnetic-based geolocations (red circles) are closer to satellite-based geopositions (white triangles). However, during the summer equinox of 2013, both the yellow and red circles are close to the triangles, indicating that both the irradiance and geomagnetic position determinations were accurate, with the latter being slightly more accurate than the former. The actual track of the drifter is most closely approximated when the geolocations are based on geomagnetic field as well as the SST and irradiance measurements processed through a state-space model (Fig. 8). The three position determinations using the three methods are indicated by green circles connected by solid green lines and the ARGOS positions by white triangles. Note the close correspondence of the two curves off the coast of Florida and from 55°W to 40°W. The discrepancies between the geolocation-based positions occur most often where ARGOS positions are absent, and the lines are drawn between far removed positions. They would likely to be closer concordance in the tracks, given that there were more intervening positions. The errors when both techniques are used are now often only ±0.13° to ±0.25° latitude, considerably better the ±1° of accuracy estimated on the basis of irradiance measurements for latitude determinations [13].

We would like to conclude this commentary by suggesting researchers and tag manufacturers to consider estimating positions from archival tags using as many inputs as possible, environmental irradiance, sea surface temperature, and geomagnetic field. We are not advocating using one sensor over another, as each functions better than the other under different circumstances. These should be considered when estimating latitude using either irradiance, SST, or geomagnetic approaches. Using measurements from all sensors in tandem will likely produce the most accurate and robust tracks. Ideally, in the future more experiments will be carried out, in which drifters are deployed at different times and locations with ARGOS transmitters that provide a reference to compare the three methods. Similarly, insights will be gained from aquatic animals dual tagged with multi-sensor archival

Fig. 8 Path taken by the PTT as it drifted across the North Atlantic Ocean with the geomagnetic-irradiance-SST-derived positions indicated by *solid green diamonds* and the Doppler-derived positions by *solid white triangles*. Note that the track based on the use of three inputs and processed through a state-space model is closer to the ARGOS-determined track than the two tracks shown in Fig. 2

tags and ARGOS satellite tags serving as a reference for comparison of geoposition estimates. In the case of tags with a sufficiently long post pop-up reporting period for drift observations, such experiments might be incidental to animal tagging while providing a baseline estimate for the track accuracy available with a given complement of inputs in a given area and season. Using this approach, archival tags will likely to provide more accurate and more reliable position determinations in the future. It is ironic that with regard to the orientation of animals, magnetic cues were first shown to perceive latitude based upon the obvious north–south gradients and only later to be used to estimate longitude based on properties of the earth's magnetic field [14].

Authors' contributions

APK conceived of the idea for the commentary, provided guidance in the plotting and presentation of data, and wrote the article. MF estimated the positions of the drifting transmitter based on geomagnetic, irradiance, and SST measurements and edited the manuscript. NH provided the files of sensor measurements and ARGOS-determined positions from the drifter in the North Pacific and edited the manuscript. AH provided the file of measurements of geomagnetic field intensity measured by a transmitter tracked at the Galapagos Islands in the Tropical Eastern Pacific and edited the manuscript. All authors read and approved the final manuscript.

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None.

Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The dataset used during thing the current study are available from the corresponding author, APK. The position determinations of the drifting electronic tag are present in an archive maintained by NH and AH; the analyses and data, with which the graphs were plotted, are in archive maintained by MF. The contributing author will obtain the data, with which the plots were made, from these two sources, given that there is interest in re-analyzing them.

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