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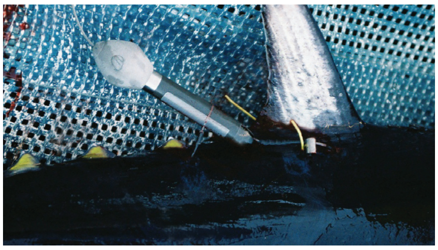
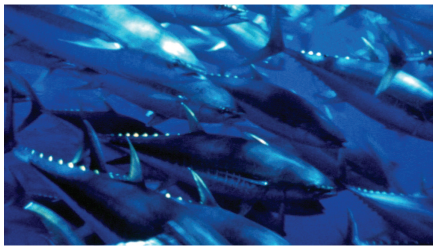

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Report on a geolocation methods workshop convened by the SCOR Panel on New Technologies for Observing Marine Life

5-6 October 2007, San Sebastián, Spain

Wealth from Oceans National Research Flagship

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EXECUTIVE SUMMARY

The last decade has seen many improvements in geolocating tag technology, position estimation and the development of useful models of movement for marine animals. Considerable effort has been invested in identifying factors that affect accuracy and precision of position estimates, quantifying the associated errors, deriving behavioural signals from resulting tracks and obtaining a better understanding of the spatial dynamics of tagged animals. However, positions estimated with geolocation techniques are still subject to significant errors and a number of problems remain relating to the identification and quantification of the factors affecting accuracy and precision of estimates. In response to concerns over the reliability and accuracy of underwater geolocation techniques and the ability to integrate oceanographic data with data from tagged animals, the Scientific Committee on Oceanic Research Panel on New Technologies for Observing Marine Life convened a workshop. The purposes of the workshop were to bring together scientists and engineers involved in all aspects of geolocation – from tag design to track interpretation – to identify key issues and possible solutions and to encourage further collaboration with users of the technology.

Detailed aims set out for the workshop were to:

- exchange results and outcomes of the latest work being conducted by participants;
- identify significant areas of common interest;
- arrange in-depth discussion by break-out groups and endeavour to resolve outstanding issues and scope future directions;
- develop co-operative and/or collaborative efforts for proposals to funding agencies at various levels;
- extend the results of the workshop to the broader electronic tagging community by presenting a report to the 2nd International Symposium on Tracking and Tagging Marine Fish with Electronic Devices, and publishing a summary account in the Symposium proceedings; and
- provide feedback to the SCOR Panel on New Technologies for Observing Marine Life and thence advice to the Scientific Steering Committee of the Census of Marine Life.

After reviewing progress made over the last decade, participants were assigned to two working groups, which met in parallel sessions and dealt separately with two primary areas of research: (1) the estimation of position (based on both light and other environmental variables) and (2) management and interpretation of position estimate data. The following key issues were identified as a result:

- a need for better sensor performance and the development of tags with wider capabilities, including new sensors;
- a need for complementary data that can be integrated with tag data: (i) to provide more accurate estimates of position; and (ii) to investigate population and ecosystem effects;
- a consequential need to improve interactions with groups associated with the collection, handling, analysis and distribution of complementary data;
- improved co-ordination in the development of analytical methods and the associated software required to improve position estimation and identify behavioural states of tagged animals;

- increased co-ordination to standardise quality control and achieve greater transparency in data handling and processing, particularly in relation to comparative studies; and

- sharing of data to specify and then collect an 'ideal' set of data with which to compare the performance of existing methods of geolocation and develop improvements.

After discussing these key issues and the actions required for resolution, the workshop agreed upon the following recommendations:

1. A working group should be established to focus on the advancement of analytical techniques and software needs in relation to geoposition estimation.

2. Existing datasets, which include data from individuals tagged with both archival (geolocating) and satellite tags, should be made available for a comparison of current analytical methods and to define ideal datasets and the experimental design required to acquire them.

3. Tag manufacturers should make available tags for the collection of ideal datasets to be used for comparing various methodologies and quantifying errors associated with different methods of geolocation.

4. Service Argos should provide an error field around each Argos position estimate and clear documentation on how each error field is calculated.

5. Tag manufacturers should make available information on how data are compressed and processed so that it is clear to users how the data have been treated prior to starting their own analyses.

6. The existing dialogue between scientists using data from tagged animals and those in the oceanographic, ecology and resource management communities should be expanded.

7. Sessions should be developed at appropriate conferences to focus on two areas: (i) the identification of fundamental ecological questions that can be answered with archival tag technology and (ii) the application of archival tag technology for informing resource management.

8. Data sharing and exchange should be facilitated through the development of a seamless interface between users and data via a data manager.

9. Interactions among other research groups studying the movements of marine animals should be encouraged as they develop data storage/management tools.

10. Data quality control functions already developed should be compiled and made available.

11. Dialogue among groups that have already developed or are developing data visualisation tools should be encouraged and avenues for possible development of such tools to suit archival tags should be investigated.

Keywords: SCOR Panel on New Technologies for Observing Marine Life, geolocation methods, electronic tags, marine predators

INTRODUCTION

Electronic tags have made a major contribution to marine ecology over the last four decades and have provided a great deal of information on the distributions, movements, physiology and foraging ecology of fish, reptiles, seabirds and marine mammals (Arnold and Dewar 2001, Kooyman 2004, Ropert-Coudert and Wilson 2005, Hooker et al. 2007). Of the range of electronic tags capable of estimating position, those suitable for fish and other marine animals that remain permanently below the surface or visit it only briefly at infrequent intervals, are somewhat restricted. Acoustic tags are limited by short transmission range and VHF telemetry by the opacity of seawater to radio waves. Satellite telemetry requires the animal to utilise surface waters so that the transmitter aerial is completely clear of the water for long enough for radio transmissions from the tag to be received by several satellites or for GPS signals to be received by the tag. Dead reckoning devices are limited by a requirement to accurately record speed or acceleration and heading, which is problematic in animals such as fish, resulting in the systematic introduction of errors in absolute positions. There is therefore considerable interest in deducing geographical location from environmental data that can be recorded underwater, such as hydrostatic pressure, temperature, salinity and irradiance.

The two most explored and developed approaches to estimating geographical location from environmental data are those associated with time series of hydrostatic pressure (the tidal method; Metcalfe and Arnold 1997, Hunter et al. 2003) and irradiance measurements (the light-based method; Smith and Goodman 1986, DeLong et al. 1992, Wilson et al. 1992, Gunn et al. 1994, Hill 1994).

The tidal method involves comparison of tidal range and time of high water recorded by the tag with those predicted by regional tidal models. Candidate position estimates are then refined by comparing sea bed depths and water temperatures recorded by the tag with independent data and a final position estimate determined (Metcalfe and Arnold 1997, Hunter et al. 2003). This method of determining position is theoretically applicable to any area where the appropriate tidal models exist. It is predominantly applied to marine animals that occupy shallow, turbid water on continental shelves and remain stationary on or close to the sea bed for at least 12 h each day. The tidal method has been utilised on a range of species including plaice (*Pleuronectes platessa*; Hunter at al. 2003, 2004), cod (*Gadus morhua*; Turner et al. 2002, Gröger et al. 2007, Righton and Mills 2008) and thornback rays (*Raja clavata*; Hunter et al. 2005).

The light-based method, in contrast, is largely applied to fast-moving pelagic species which move over large distances and generally occupy regions where transmission of light through the water column is not impeded by turbidity. Measures of irradiance are used to define particular times of day from which location can be derived. Traditionally, this has comprised the time of local noon, from which longitude can be derived, and the time of dawn and dusk, from which latitude can be derived (Smith and Goodman 1986, DeLong et al. 1992, Wilson et al. 1992, Gunn et al. 1994, Hill 1994). This method is applicable to any species that regularly occupies the photic zone (from the surface to approximately 300m) and has been used extensively to derive the movement paths of many pelagic species including tuna (Gunn et al. 1994, Lutcavage 1999, Block et al. 2001, Itoh et al. 2003, Musyl et al. 2003, Uosaki 2004; Schaefer et al. 2007), billfish (Sedberry and Loefer 2001, Gunn et al. 2003, Hoolihan 2005, Horodysky et al. 2007, Sippel et al. 2007), sharks (Gunn et al. 1999, Sims et al. 2003, Bonfil et al. 2005, Bruce et al. 2006, Wilson et al. 2006, Weng et al. 2007), turtles (Swimmer et al. 2006) marine mammals (DeLong et al. 1992, Beck et al. 2002, Hindell et al. 2003) and seabirds (Hull 1999, Tuck et al. 1999, Phillips et al. 2004, Shaffer et al. 2005).

The use of electronic tags with software capable of estimating geoposition, or simply recording the necessary data to calculate geoposition after the tag has been recovered, has expanded significantly over the last decade, resulting in an increased interest in both estimating and modelling useful interpretations of movement. Electronic tags now provide a primary source of data for several major research programs, including the Census of Marine Life and constituent programs such as TOPP and EUTOPIA (Block et al. 2003, Decker and O'Dor 2003,).

Concurrent with this expansion of tag use has been development of means by which the large datasets generated by significant deployments of tags under such programs are managed (Decker and O'Dor 2003, Ropert-Coudert and Wilson 2005, Halpin et al. 2006). Further, increasing interest from statisticians in both the position estimation problem and modelling useful interpretations of movement has advanced the field. However, positions estimated with geolocation techniques are subject to errors that are large in relation to those typically experienced when tracking animals using acoustic, satellite or GPS technology. They are also subject to a number of problems relating to the identification and quantification of the factors affecting accuracy and precision and, thereby, the deduction of behavioural signals from resulting tracks.

Concerns over the reliability and accuracy of underwater geolocation techniques and the ability to integrate oceanographic data with data from tagged animals led the Census of Marine Life's (CoML) Scientific Steering Committee to refer the subject to the SCOR Panel on New Technologies for Observing Marine Life for consideration. During their meeting in Kobe, Japan in 2006, SCOR Panel members agreed that these problems were of concern and suggested convening a workshop to help advance the subject by identifying critical challenges and discussing ways of improving existing technologies and methodologies.

This report provides an overview of the objectives of the ensuing workshop, a summary of the discussions and the recommendations agreed upon to be presented to the SCOR Panel and the Scientific Steering Committee of CoML. The workshop built upon discussions and actions agreed upon during two earlier workshops (Metcalfe 2001), which discussed the basic principles and some of the problems of estimating geoposition from measurements of underwater irradiance. The first was held at the Centre for Environment, Aquaculture and Fisheries Science (CEFAS), UK in 1999 and the second at the University of Hawaii, Hawaii, in conjunction with the First International Symposium on Tracking and Tagging Marine Fish with Electronic Devices in 2000. The present workshop was given wider terms of reference to encompass the advances made in deriving geoposition estimates in the intervening seven years. Participation in the workshop included researchers working on taxa other than fish in order to identify and exploit potential synergies.

Location and attendance

To make efficient use of time and travel budgets, the workshop was scheduled so that it was held immediately before the Second International Symposium on Tracking and Tagging Marine Fish with Electronic Devices, which was held in San Sebastián, Spain during 8-11 October 2007. Attendance and involvement in the workshop was by invitation, to bring together those working on issues relating to the determination, management and interpretation of geoposition estimates with those involved in the manufacture of tags. In this way, it was hoped to address the objectives of the workshop as directly as possible. The workshop was attended by 26 scientists from

15 institutions and manufacturing companies in seven countries. Full details of participants in the workshop are given in Appendix 1.

WORKSHOP SUMMARY

Aims and objectives of the workshop

The overall objectives of the workshop were to identify factors affecting the accuracy and precision of methods used to calculate geopositions; quantify the respective geolocation errors; review methods of reconstructing tracks from successive geoposition estimates; and consider how error limits associated with reconstructed tracks constrain deductions that can be made about the behaviour of tagged animals. The ultimate aim was to identify ways of improving methods so as to obtain a better understanding of the spatial dynamics of tagged animals.

Most geolocation activities occur in clear, oceanic waters, utilising the light-based geolocation method. Because there are currently more unresolved problems with this method than there are with the tidal method, the workshop focused largely on light-based geolocation. However, discussions also encompassed the performance of active tracking systems, such as satellite and GPS telemetry, which are used in double-tagging experiments to estimate the errors of individual geopositions (Phillips et al. 2004, Teo et al. 2004, Shaffer et al. 2005) and more routinely to check the end points of tracks obtained with pop-up archival tags (Stokesbury et al. 2004, Wilson et al. 2006, Weng et al. 2007). Additionally, the workshop considered new technologies that may provide alternative means of obtaining high-resolution position data such as underwater transmission of GPS positions by sonar (www.star-oddi.com) and RAFOS tags that record and archive positions determined by triangulation of sound signal transmissions (Fischer et al. 2006, Recksiek et al. 2006).

The detailed aims set out for the workshop were to

- exchange results and outcomes of the latest work being conducted by participants;
- identify areas of common interest;
- arrange in-depth discussion by break-out groups and endeavour to resolve outstanding issues and scope future directions;
- develop co-operative and/or collaborative efforts for proposals to funding agencies at various levels;
- extend the results of the workshop to the broader electronic tagging community by presenting a report to the 2nd International Symposium on Tracking and Tagging Marine Fish with Electronic Devices, and publishing a summary account in the Symposium proceedings; and
- provide feedback to the SCOR Panel on New Technologies for Observing Marine Life and thence advice to the Scientific Steering Committee of the Census of Marine Life.

The format of the workshop involved an initial session within which participants presented the results of their most recent work. A working group session followed focussing on two areas: (1) estimation of position and (2) management and interpretation of position estimate data. Participants in each of the two groups set terms of reference within which they were to identify key issues and areas of future development and formulate realistic working proposals for addressing these. Finally, recommendations and actions were agreed upon in a concluding plenary session. Further details on the scheduling of the five sessions and abstracts associated with those presentations given during the workshop are presented in Appendix 1.

Estimation of position (Working Group 1)

Methods for estimation of geoposition

Two significant advances have been made in light-based methods of geoposition estimation since the previous workshop held in 2000. The first has involved the development of alternative models for estimating position from traditional threshold methods (DeLong et al. 1992, Wilson et al. 1992, Gunn et al. 1994, Hill 1994). These include utilising template-fit methods, state space models and twilight length.

Template fit methods for geolocation are based on comparisons of records of light as collected by a tag against a template for the variation of light with time during dawn and/or dusk (twilight) events (Hill and Braun 2001, Musyl et al. 2001, Ekstrom 2004, 2007). Recent work on template fit methods is based on a geophysical model which relates the variation of blue light (which may be less sensitive to weather conditions) throughout twilight to sun angle (see Ekstrom 2002, 2007 for further details). Derivatives of this template allow the estimation of two types of error associated with the accuracy of each day's geoposition estimate which are combined to produce a daily estimate of the standard deviation (Ekstrom 2007). Deployment of a single tag at a known location on land (48.6°N) during calibration trials produced median values of the estimated daily standard deviation of 0.42° in longitude and 0.95° in latitude. Further testing in field situations is continuing and suggests improved accuracy and precision of the template fit method over the threshold model across a number of species. Although the template method is still subject to similar errors as the threshold method during the period around the equinoxes (latitude estimates are subject to large errors at this time of year) and the diving behaviour of individuals (which can distort light data used within the model and result in poor definition of periods of sunrise and sunset), quantification of error estimates for each position estimate allows for the identification of outliers and resolution on the basis of track continuity.

The use of state-space models has largely been associated with the refinement of position estimates calculated using threshold or template fit methods (Sibert et al. 2003, Nielsen et al. 2006). Tracks were refined by matching light-based daily geolocations calculated using threshold or template fit methods with the underlying movement model assumed within the state-space model (Sibert et al. 2003). Later developments included sea surface temperatures to further improve the track (Nielsen et al. 2006). More recently state-space models have been utilised to estimate geopositions directly from light measurements recorded by a tag (Nielsen and Sibert 2007a). All parts of the movement model, covariance structure and the relationship between solar altitude and light measurements are estimated within the model and two estimates of geoposition associated with dawn and dusk events are calculated for each day. The model is structured in such a way to handle high correlations between light measurements and also allows for calculation of seasonal patterns in latitude precision. Sea surface temperatures can be included in the model to further improve track estimates. Tests of this model on simulated light data and light data collected from tags deployed on a drifter buoy (near Hawaii) and a mooring (near New Caedonia) demonstrated improved estimation of positions over those produced using threshold methods, with positions able to be estimated for those times when threshold based latitude estimates are difficult (Nielsen and Sibert 2007a). Latitudes were cacluated to be within 0.2° (near New Caledonia) to 1° or 2° (simulations) and longitudes within 0.5° (near New Caledonia) to 0.5° or 1° (simulations) of the true positions. Further testing of the method on light data collected from tags deployed on fish demonstrate similar improvements over threshold methods (Nielsen and Sibert 2007b).

The use of twilight length is based on the principle that the amount of time taken to pass through the area of twilight on the Earth (the width of which is defined by the eight degree range of sun angle between -5° to + 3°) is a function of latitude (Hill 2008). Passage time moves from a minimum at the equator to a maximum at the poles. Longitude is determined from the same, single twilight The twilight method is not subject to the same errors associated with the equinoxes that affect both the threshold and template fit methods. Additionally, because positions are estimated independently from twilight events, the method avoids some of the errors associated with movement of an animal between dawn and dusk. Preliminary testing of this method has begun and suggests improved resolution of position estimates from current methods utilised in light-based geolocating tags.

The second advance has involved the use of complementary environmental data to either refine position estimates calculated using light-based or tidal methods, or to calculate position estimates independently of these methods. Utilisation of these data has provided improvements on position estimates by either reducing errors associated with location estimates or providing estimates of position where light-based or tidal methods are not applicable.Water temperature (Beck et al. 2002, Hunter et al. 2004, Teo et al. 2004, Nielsen et al. 2006, Weng et al. 2007) and bathymetry (Metcalfe and Arnold 1997, West and Stevens 2001, Gröger et al. 2007) have most commonly been used in association with both light-based and tidal methods. More recently methods involving the matching of data from hydrodynamic models with depth, temperature or salinity data recorded by archival tags have been utilised in areas where tidal methods are not possible (Neat et al. 2006, Ådlandsvik et al. 2007, Andersen et al. 2007, Neuenfeldt et al. 2007, Righton and Mills 2008).

Error quantification

Considerable effort has been devoted to quantifying the uncertainty associated with geoposition estimates since the previous workshop in 2000. These efforts have largely involved two approaches, the first involving the utilisation of statistical models to calculate geoposition estimate errors and derive ‘best estimate’ or ‘corrected’ movement paths of individuals. Models utilised have predominantly been based on state-space methods (Patterson et al. 2008), including the Kalman filter (Sibert et al. 2003, Nielsen et al. 2006) and the particle filter (Royer et al. 2005, Andersen et al. 2007). Errors are calculated by comparing observations recorded by the tag with those estimated by the model. The second approach has involved the use of double tagging experiments where errors are quantified through the comparison of estimated positions with those considered to be more representative of the ‘true’ location of the animal. Comparisons have largely involved the use of Service Argos data collected either whilst the tag is attached to the animal or during pop-up end points after a tag has detached from the animal and surfaced (Hull 1999, Phillips et al. 2004, Teo et al. 2004, Shaffer et al. 2005, Tremblay et al. 2006). However, Argos locations are subject to varying degrees of error themselves (Hays et al. 2001, Vincent et al. 2002). Further, position estimates determined using light and water temperature collected at the water surface after a tag has surfaced cannot be considered to be typical of light and temperature collected by the animal. Quantification of geolocation errors in this manner are therefore likely to be compromised.

Bradshaw et al. (2007) recently provided a summary of error estimates associated with telemetry-derived position estimates. A broader summary of error estimates associated with position estimates derived from marine animals specifically and including those electronic tagging technologies currently used on marine animals are presented in Table 1. Note that this summary is not intended to be a comprehensive assessment of tag technologies and methods utilised on marine animals; rather it is intended to provide an indication of the range of scale of error estimates. The summary does, however, highlight that calculation of errors associated with position estimates is not entirely straightforward and can be affected by a number of factors, including the species on which the tag is deployed (due to species-specific behaviour effects on geoposition calculation); the area in which the tag is deployed; the conditions under which the tag is deployed and tag configuration (manufacturer). Further, error estimates are often presented as averages or ranges of the distance between estimated locations and known (often recapture) locations (e.g. Hunter et al. 2004, Gröger et al. 2007, Righton and Mills 2008), thereby limiting the ability to assess errors associated with latitude and longitude individually. As a result, comprehensive comparisons of the accuracy of differing technologies or methods are difficult.

Alternative technologies

Improvements in GPS technology and alternative technologies for estimating position, such as the RAFOS tag and GPS fish positioning systems have the potential to further expand the technological possibilities for determining the movements of marine animals.

The RAFOS tag, developed by the University of Rhode Island, is an acoustic receiving tag capable of calculating position by triangulation of measurements of the time of arrival of sound signals from three or more moored SOFAR (SOund Fixing And Ranging) transmitters to the tag (Fischer et al. 2006, Recksiek et al. 2006). The benefit of using a receiving RAFOS rather than a transmitting SOFAR tag is that the tag requires far less power, thereby reducing its size and increasing the life of the tag. In shallow seas (≤ 200m) the RAFOS tag is expected to have an operational range up to approximately 100km with an accuracy of 0.05–2km. In pelagic waters beyond the continental shelves, the operational range is estimated to be in excess of 1,000km, but only if the signal is confined to the deep-sound or SOFAR channel (~700–1000m depth).

Fish positioning systems developed by the data storage tag manufacturer Star-Oddi and the electronic fishery equipment manufacturer Simrad encode GPS position data from fishing vessels and transmit the position data via a sonar signal (www.star-oddi.com). If a fish tagged with an associated acoustic receiver is within one to seven kilometres of the fishing vessel (depending on the acoustic conditions of the area), it will receive a sonar signal containing the GPS position. The tag stores the encoded GPS position, together with a date/time stamp and sensor data. All the data collected are downloaded when the tag is retrieved. GPS units and smaller versions of the sonar transmitters with a transmitting range of several hundred metres can also be attached to fixed or drifting buoys for use in lakes, rivers or small ocean areas. The systems are fully operational and available for purchase from the manufacturer.

Table 1. A summary of current estimates of error associated with varying technologies and methods used to estimate position for marine species. Where errors have been presented in degrees in the original references, conversions to km are based on 1°= 111km for latitude and 1°= 111km x cos(longitude) for longitude.

Species	Position estimation method	Error Longitude (km)	Error Latitude (km)	Error measurement/Reference
Acoustic telemetry				
Dogfish (*Scyliorhinus canicula*)	Three receiver triangulation	0.002	0.002	Maximum; Sims et al. 2001
Weddell seal (*Leptonychotes weddellii*)	Three receiver triangulation	0.001	0.001	Maximum; Hindell et al. 2002
GPS telemetry				
Wandering albatross (*Diomedea exulans*)	GPS-MS1 logger	0.004	0.004	CEP*; Weimerskirch et al. 2002
Loggerhead turtle (*Caretta caretta*)	TrackTag^{TM} GPS	0.009	0.011	Absolute value at 37°N; Schofield et al. 2007
Satellite telemetry				
Green turtle (*Chelonia mydas*)	ARGOS quality class 3	0.12	0.32	Variance; Hays et al. 2001
	ARGOS quality class 2	0.28	0.62	Variance; Hays et al. 2001
	ARGOS quality class 1	1.03	1.62	Variance; Hays et al. 2001
	ARGOS quality class 0	4.29	15.02	Variance; Hays et al. 2001
Gray seal (*Halichoerus grypus*)	ARGOS quality class 3	0.74	0.33	95th percentile of absolute error; Vincent et al. 2002
	ARGOS quality class 2	1.36	0.51	95th percentile of absolute error; Vincent et al. 2002
	ARGOS quality class 1	3.50	1.27	95th percentile of absolute error; Vincent et al. 2002
	ARGOS quality class 0	15.36	5.52	95th percentile of absolute error; Vincent et al. 2002
	ARGOS quality class A	10.39	5.37	95th percentile of absolute error; Vincent et al. 2002
	ARGOS quality class B	41.22	15.54	95th percentile of absolute error; Vincent et al. 2002

Species	Position estimation method	Error Longitude (km)	Error Latitude (km)	Error measurement/Reference
Hooded seal (*Cystophora cristata*)	Interpolation of ARGOS location data using a state space model	9.95–21.76	4.44–9.99	Variance; Jonsen et al. 2005
Tidal-based methods				
Fixed mooring	Integration of tag depth with tidal models	13.3±4.6 (4.4–22.2)	12.8±5.0 (2.2–21.8)	Mean±SD* (range), Hunter et al. 2003
Light-based methods – archival tags				
Rockhopper and royal penguins (*Eudyptes chrysocome, E. schlegelis*)	Light-based position estimation	189	383	Mean; Hull 1999
Pacific bluefin tuna (*Thunnus orientalis*)	Light-based position estimation	11.1±61.9	117.6±199.8	Mean±SD*; Itoh et al. 2003
Bigeye tuna (*Thunnus obsesus*)	Light-based position estimation with refinement using a Kalman filter (KF)	1.9–65.4	50.0–839.2	SD*; Sibert et al. 2003
Atlantic bluefin tuna (*Thunnus thynnus*)	Light-based longitude estimation and SST-based latitude estimation	61.6	99.9	RMSE*; Teo et al. 2004
Light-based methods – PSATs				
Blue shark (*Prionace glauca*)	Light-based position estimation with refinement using an extended Kalman filter incorporating SST	51.4–170.1	65.5–81.0	Mean variance; Nielsen et al. 2006
Atlantic bluefin tuna (*Thunnus thynnus*)	Light-based position estimation with refinement using a Kalman filter (KF)	0–62.3	28.9–1,665.0	SD*; Sibert et al. 2006

*CEP: circular error probability; RMSE: Root Mean Square Error; SD: standard deviation

The recent development of Fastloc™ technology allows GPS signals to be acquired by a receiver within less than a second (see www.wildtracker.com/fastloc for further details). Highly accurate locations can thus be calculated from receivers deployed on animals that surface only for brief intervals and that are not suitable for tagging with existing satellite tags. Current models of tags can be set to either transmit summaries of environmental data collected and a percentage of the GPS data via Service Argos during longer surface intervals by the animal, or simply store the recorded data for retrieval when the tag is recovered. Position estimates are calculated from the GPS data downloaded from the tag rather than on-board the tag itself, significantly reducing the time the GPS antenna is required to clear the ocean surface.

Terms of reference

Key questions identified by Working Group 1 for its terms of reference included the following:

1. What is the current scale of error associated with geoposition estimates and how does this compare to position estimates produced by other forms of electronic tags?
2. What science and management questions can be addressed with current geoposition estimates?
3. What scale of improvements in the accuracy of geoposition estimates can reasonably be expected in the next five to ten years?
4. What is required to achieve any identified improvements in the accuracy of geoposition estimates?
5. What science and management questions could be addressed given these improvements that we are unable to answer with existing technology?
6. Are there any important science and management questions that will never be able to be addressed given current and anticipated improvements in the accuracy of geoposition estimates?

In the time available, discussions in relation to question two were somewhat limited and those associated with questions five and six were not addressed.

Issues/limitations identified

The following key issues and limitations were identified by Working Group 1 in relation to its terms of reference.

1. Ultimate limitations: (a) physical (environment); (b) behavioural (animal).

Light data are impacted by environmental variables such as cloud cover and turbidity, both of which reduce light levels recorded by the tag and can thereby impact the accuracy and precision of estimated positions. Changing cloud cover during dawn or dusk, in particular, sets an ultimate physical limitation on the performance of the light-based method of geolocation. Whilst little can be done about the effects of cloud cover on light levels, tidal- and bathymetry-based position estimation techniques can be used to estimate position in highly turbid waters (Hunter et al. 2003, 2004, Gröger et al. 2007) to resolutions of 10-50km. Although also applicable to areas that are not affected by high turbidity, tidal methods are limited in their use to those areas where tidal models are available and to those species that remain stationary on (or very close to) the seabed for periods of greater than 12 hours, thereby reflecting the local tidal signal.

Light data collected by archival tags are further impacted by the diving behaviour of animals – often animals undertake dives beyond the photic zone where no light is available to be recorded by the tag. This becomes particularly problematic if deep diving behaviour occurs at sunrise and sunset, the time periods upon which light-based methods of geolocation are based. Similar problems occur when the diving behaviour of an animal is a reflection of that animal following a particular isolume. The resulting data demonstrate little variability in irradiance, resulting in poor definition of periods of sunrise and sunset. Although one study has found that sampling particular irradiance bands can assist in attaining higher levels of light at depth (Qayum et al. 2007), little can be improved in terms of light data collected if focal species spend substantial periods of time (particularly during sunrise and sunset) beyond the depth of light penetration.

2. Sensor performance.

Although it was noted that there is some potential to reduce their power requirements and response times, existing light sensors are considered to be near the practical limit of their sensitivity, with little scope for improvement. The maximum depth at which there is sufficient detectable daylight for geolocation, which is estimated to be approximately 300m in clear oceanic water, is thus not likely to increase in the foreseeable future.

3. Development of robust models for depth attenuation of light, which can then be applied to light-based geolocation data.

In order to estimate position from light-based methods of geolocation, estimates of light at the ocean surface are required. Most light collected from tags on marine animals is subsurface light because these animals remain permanently below the surface or visit the surface only briefly at infrequent intervals. As a result, light attenuation models must be used to estimate surface light irradiance from raw light data collected at depth. Current models are generally simple two-box models and may oversimplify the relationship between light at depth and surface light. Recent work on this issue by some of the larger programs utilising electronic tags (see J. Hartog et al. and Teo et al. in the abstracts of the workshop in Appendix 1) may provide more statistically robust models of light attenuation Manufacturers attending the workshop requested assistance from tag users in locating available light attenuation data and collecting data suitable for use in working on this problem. Of those data currently available, it was agreed that Jerlov (1976) still provided the best and most suitable body of work on optical oceanography.

4. Availability of ideal datasets for comparing various methodologies and quantifying errors associated with different methods of position estimation.

Numerous approaches to improving geoposition estimates and resolving the associated error distributions have been utilised and published on archival tag data (Metcalfe and Arnold 1997, Beck et al. 2002, Sibert et al. 2003, Teo et al. 2004, Royer et al. 2005, Nielsen et al 2006, Andersen et al. 2007, Righton and Mills 2008). Efforts to compare various analyses and methods, however, are compromised by the use of differing models and makes of tags, differing species on which tags have been deployed and differing temporal and spatial resolutions of the varying datasets. Comprehensive comparisons require the development of a suite of 'ideal' datasets in which these factors are standardised. It was agreed that data for comparisons should be collected and made available from double-tagging experiments in which archival tag data are coupled with GPS-quality data. These data should comprise a time series that includes at least one, but ideally two, equinoxes and a solstice, and a sampling interval of one minute or less. Species tagged should dive extensively but stay within detectable light levels and, if possible, cover a wide range of latitudes. Existing datasets (for several species of pinnipeds, several species of sharks and several fixed mooring deployments) meet some of these criteria and should provide a a reasonable starting point for such analyses.

5. Transparency of data processing and handling both on board tags and after download (i.e. data sampling, compression and processing).

At present, the various makes and models of tags have varying degrees of transparency of on-board data sampling, compression and processing methods. This is especially the case with pop-up satellite archival tags (PSATs), which need to compress data because of the bandwidth constraints of Service Argos. Similarly, the various software programs required to download and decode archival tag data and generate raw position estimates have varying degrees of transparency. Further information on how data are handled both on-board tags and during post-processing, and how certain parameters (especially SST) are estimated is required in order to better understand these process and reduce errors in light-based geolocation.

Service Argos is routinely used to relay data from satellite location and pop-up satellite archival tags and to assess the overall accuracy of track reconstruction, either by comparing the end point of the reconstructed track with the pop-up position of the tag, or by obtaining checks on intermediate way points if the animal surfaces during the track. Seven categories of location quality are provided by the Service Argos system (3, 2, 1, 0, A, B and Z), with precision ranging from 150m to tens of kilometres. However, little information is available on the methods used to calculate the quality of location and raw Doppler shift data are not provided. Whilst these data are unlikely to be made available due to the computing processes required to handle them, Service Argos is currently in the process of generating error ellipses for each position calculated. It is expected that these will be routinely provided with position data in the near future and it was proposed that a formal request should be made to Argos to expedite the process. It was noted that Service Argos does currently provide ancillary data in the DIAG format which can be used by experienced users to further assess position errors (e.g. the number of messages received, the pass duration, and the 2-digit IQ ‘quality indicator’, which provides information about the residual error on the frequency calculation and the drift in transmitter frequency between two satellite passes). However, these data are of little use to most users (not all of whom receive data in the DIAG format).

6. Error reduction.

At present, most light-based geolocation methods produce position estimates with a resolution of approximately 50-150km, with tidal or hydrodynamic model methods achieving resolutions of 5-50km (Table 1). Given that there are clearly still some improvements to be made, it is reasonable to expect light-based geolocation methods to approach resolutions closer to that of tidal-based geolocation. However, this improvement is unlikely to resolve anything other than medium- to large-scale movements. Errors associated with position estimation are affected by numerous factors, including species-specific behaviours, regional environmental conditions and tag configurations, to name just a few. Future improvements of geoposition estimates are likely to be similarly subject to such factors and, as a result, errors are not likely to be reduced to a common minimum standard.

Calculation of positions via Service Argos is significantly poorer than expected in a number of ocean regions, notably the Mediterranean (De Metrio et al. 2005), China and Japan. This is largely the result of poor reception of tag transmissions due to illegal or accidental transmissions in the animal telemetry frequency band that mask tag transmissions (Gaspar and Malardé 2007). Two approaches to reduced transmission success in these areas are being made by both Service Argos and tag manufacturers. Service Argos is endeavouring to have illegal sources of this 'noise' closed down in an attempt to reduce the masking of transmissions. The manufacturer Wildlife Computers is currently developing a pop-up satellite archival tag that will allow the user to vary power output between 0.25 and 1W, thereby permitting an increase in the transmitting power of tags released in areas of high radio interference.

7. Availability of other sensors, alternative methods and complementary data that may be integrated for better resolution of position estimates.

The potential to incorporate extra sensors into tags to allow the collection of complementary data (such as the angle of magnetic dip, salinity) that may then be used to improve light-based geolocation estimates in a similar way to sea surface temperature (SST) was identified. Conductivity sensors, geomagnetic compasses, accelerometers and digitial still cameras are currently utilised in a number of electronic tags (see Muramoto et al. 2004, http://biology.st-andrews.ac.uk/seaos/index.html, www.star-oddi.com). Sensor improvements, miniaturisation, reduced costs of manufacture and progress in the field of micro-machining and nano-technology are likely to result in incorporation of wider ranges of sensors into tags (Muramoto et al. 2004). Similarly, integration of complementary data such as ice cover in polar regions and temperature-at-depth models may also provide information that can be used to improve light-based geolocation estimates.

Development of Fastloc™ technology has the potential to expand the use of tags capable of collecting highly accurate locations to many species unsuitable for existing satellite tags (due to their short surface intervals). Tags that already incorporate Fastloc™ technology are still quite large, but future models are expected to get progressively smaller.

The GPS fish positioning system developed by Star-Oddi is a novel advance in technology and has the potential for widespread utilisation. However, application in studies on wide-ranging pelagic species will be limited (at least in the near future) by the number and distribution of sonar transmitters (i.e. instalment of systems on fishing vessels) and the number of receiving tags deployed on animals (and capable of being retrieved). Defining the exact position of the tagged individual will still not be possible as the distance of the tag to the vessel recording the GPS position is unknown (it can only be said to be within the range of the acoustic signal). The operating range of the acoustic signal will also vary depending on environmental conditions and the relationship of the receiver on the tag and the vessel.

Application of the RAFOS tag has potential to substantially improve geoposition estimates in areas in which tidal-based methods are currently used or for non-demersal species for which tidal-based methods are unsuitable. Application in deep ocean pelagic regions is likely to be problematic because many of the pelagic animals of interest limit their vertical migrations to well above the SOFAR channel. As RAFOS tags rely primarily on acoustic signals received via the SOFAR channel this behaviour reduces the probability of tags deployed on such species detecting the signals from the acoustic transmitters. The moored SOFAR transmitters currently used to generate the sound signals used for triangulation by the tags cost in the vicinity of US$30K and these high costs are likely to limit the application of RAFOS tags on pelagic species, unless the cost can be shared with other oceanographic applications.

The Pacific Ocean Shelf Tracking (POST) project and the Ocean Tracking Network (OTN) are currently implementing extensive arrays of hydrophones at various locations around the world. Deployment of acoustic tags in marine animals will allow the determination of position of individuals within these array areas. Application in extensively ranging pelagic marine animals will be limited by the detection range (several hundred metres) of individual hydrophones and localised distributions of arrays, which are largely confined to shelf areas.

Argos 3 will soon provide two-way communication, a ten-fold increase in the rate of data transmission, more efficient data collection and remote control and programming of platforms. However, power requirements are likely to be too large for many animal telemetry applications in the immediate future.

Management and interpretation of position estimate data (Working Group 2)

Management of tagging data

As archival tag datsets have become larger in size (both in the number of tags and the complexity of the data), there has been an increasing need for the development of means by which data are managed and archived. Development of multi-relational databases has provided the ability to store and query large archival tag datasets, spanning multiple species and tag types (Hartog et al. 2007b; Lam et al. 2007). These databases have also provided the capability to integrate position estimates and behavioural data with multiple oceanographic and derived environmental products. Add-on products to these databases include automatic pre-processing of tag data, data visualisation and exploratory analysis tools (Halpin et al. 2006), enhancing the ability of researchers to provide both qualitative and quantitative assessments of movement and behaviour.

Interpretation of animal behaviour

Key to determining areas of importance to marine species is the ability to identify different types of behaviour in an animal. Behavioural events can be determined directly by recording physiological (e.g. rapid changes in internal temperature associated with feeding events; Gunn et al. 2001) or physical (e.g. opening of the mouth associated with feeding events; Wilson et al. 2002) changes in an animal. Behaviour can also be estimated indirectly via statistical methods used to relate changes in horizontal and vertical movement to environmental variables likely to drive changes in behaviour. Increasing utilisation of statistical methods for estimating behaviour has resulted from increases in personal computing power, greater interaction of researchers with statisticians and development of computer software, which has facilitated more complex statistical analyses. Analytical methods used to determine behavioural changes include the use of: generalised linear models (Bradshaw et al. 2004); generalised additive models (Bradshaw et al. 2004); spectral analysis (Newlands et al. 2004); generalised estimating equations (Wilson et al. 2005); generalised linear mixed models (Austin et al. 2006); state space models, including maximum likelihood methods and Bayesian simulation (Jonsen et al. 2003); and first passage time analysis (Pinaud and Weimerskirch 2005).

Access to larger datasets extending over larger areas and longer time scales, and the ability to integrate position data with associated behavioural and environmental data, has allowed the identification of features in the environment that are important to individuals and populations. These features include those that are static (e.g. bathymetric features) and ephemeral (e.g. frontal systems) in nature and have been used to define migratory and residential type behaviours (Bradshaw et al. 2004, Stokesbury et al. 2004, Wilson et al. 2005, Jonsen et al. 2005, Teo et al. 2007a, b). Larger datasets and the more extensive use of statistical tools have also enabled comparisons across species from defined areas, providing the ability to better understand potential overlap and niche separation within those areas (Perle et al. 2007). Integration of position estimates with complementary physiological data has allowed for a better understanding of where, when and how (Itoh et al 2003, Newlands et al. 2004, Jonsen et al 2007) animals forage and how foraging behaviour may vary through time (Kitagawa et al. 2006). This information has resulted in progress towards the development of dynamic foraging models and determination of behaviour in an evolutionary context. Better understanding of how individuals utilise their habitat has also allowed for assessments of the vertical and horizontal overlap of populations with fishery operations (Southall et al. 2006, Evans et al. In Press) and has permitted more informative use of spatial assessments and decisions in the management of exploited stocks (Hobday and Hartmann 2006).

Terms of reference

Key questions identified by Working Group 2 as terms of reference included the following:
1. What can be resolved in terms of the behaviour of marine animals from current technology?
2. What is limiting in resolving the behaviour of marine animals from current technology?
3. What is required to facilitate and increase the power of behavioural interpretation?
4. How can datasets from multiple species be combined to identify ecosystem effects?
5. How can tag datasets be integrated with independent datasets (otolith microchemistry, stable isotopes, genetics, prey fields, etc.) to identify population and ecosystem effects?
6. How can existing datasets be used to improve the experimental design of investigations utilising archival tag technology?

Issues/limitations identified

Key issues and limitations identified by Working Group 2 in relation to its terms of reference included the following:

1. sensor performance and availability of tags with expansive uses, including new sensors.

Current tag sensors lack the high accuracy and quick response times of the equivalent sensors routinely used for the collection of oceanographic data. If data from the two sources are to be integrated and comparisons made between data collected by electronic tags and those collected by oceanographic instruments, there is a need for the accuracy and response times of temperature and light sensors in tags to be improved. Data derived from additional sensors (such as oxygen and salinity) and devices (such as accelerometers) could provide additional information on the environmental conditions experienced by an animal and identify those to which it is responding. Sensors capable of collecting information on the physiological and hormonal state of an animal would serve to provide information on the energetic effect of the responses of an animal to its environment. Flexible programming of tags and flexible data sampling (for example, smarter controllers that recognise ‘interesting’ behaviour and respond by increasing the sampling rate during these events) would assist this process. Conductivity sensors, geomagnetic compasses, accelerometers and digital still cameras are currently utilised in a number of electronic tags (see Muramoto et al. 2004, http://biology.st-andrews.ac.uk/seaos/index.html, www.star-oddi.com). Availability of an increased range of sensors is likely to be possible following sensor improvements, miniaturisation, reduced costs of manufacture and progress in the field of micro-machining and nano-technology (Muramoto et al. 2004).

It was noted that while some improvement in sensor technology is possible, it is unlikely that any improvements will yield more than a 10-fold increase in sensitivity.

2. **an ability to further increase the size of datasets both numerically and temporally.**

Regardless of species or tag type, researchers commonly face the challenges of collecting datasets that are numerically adequate and comprise a time series of more than one year in length. Descriptions and models of ontogenic and environment-driven variability in the behaviour of individuals and populations are somewhat restricted as a result. Further, the ability to better understand multi-species use of the ocean is also constrained. The high cost of tags and tag performance, which were identified as major factors contributing to these challenges, are a consequence of existing technology. However, consideration is being given to the development of less expensive tags with simpler capabilities than current archival tags, with the aim of replicating observations more easily and generating longer time series of data. Examples are non-archival pop-up (or reporting) tags, which could provide conventional tag data without the requirement for the return of the tag, and light recording tags providing data for calculating positions only.

3. **availability of suitable independent datasets that can be integrated with tag data to investigate population and ecosystem effects and, in association with this, better interaction with researchers in other disciplines.**

In order to better understand aspects of the life history, energetics and foraging ecology of marine animals it would be useful to integrate archival tag data with other data types such as stable isotopes, genomics, body condition indices, otolith microchemistry, and datasets relating to the marine environment such as prey fields. Integration of tag data with higher resolution oceanographic data than those currently available, three-dimensional descriptions of the ocean, front finders and sea-ice cover would also be useful. These data, which need to be more readily available in a form that suits the needs of the tagging community, could be used to obtain a better understanding of interactions of individuals with their environment.

Some ongoing activities will contribute to improving existing datasets, particularly that associated with:

- GLOBEC (Global Ocean Ecosystem Dynamics) and CLIOTOP (CLimate Impacts on Oceanic TOp Predators) relating to prey field datasets (www. web.pml.ac.uk/globec/structure/regional/**cliotop/cliotop)**,
- the International Ocean-Colour Coordinating Group (IOCCG) relating to SST, ocean colour and altimetry products (www.ioccg.org),
- the ICES (International Council for the Exploration of the Sea) Working Group on Operational Oceanographic Products (WGOOP) relating to the generation of front indicators (ICES 2007); and
- those working on three-dimensional ocean models such as Simple Ocean Data Assimilation (SODA) analysis (Carton et al. 2000a, 2000b).

In light of the potential for these programs to generate useful data, establishing collaborations and interactions between those involved and tag users should be encouraged. Such interactions should also include consideration of what the archival tagging community can contribute to the broader scientific and resource management community. In doing so, the tagging community needs to be made more aware of the data requirements of such communities and develop better means by which such data can be made available. It was noted that some components of the tagging community were already taking part in workshops with the oceanographic community (e.g. SEals as Oceanographic Samplers (SEaOS), see http://biology.st-andrews.ac.uk/seaos/index.html) and that this interaction could be expanded to include those working with archival tags.

Similarly, there is a need for the archival tagging community to identify the fundamental ecological questions that can be answered with electronic tag technology and, in doing so, specify what the archival tagging community can contribute to broader ecological studies. Adopting this approach would have the benefit of opening access to long-term funding opportunities (e.g. Long Term Ecological Research grants) not currently available to the electronic tagging community.

The potential for integrating acoustic and archival tags was raised as something that should be considered, particularly in association with ground-truthing locations and collecting additional biological information. Development of tags capable of receiving GPS information from vessels (developed by Star-Oddi, as detailed above) was noted as a significant step forward in this area. Further developments that could be useful included, for example, archival tags capable of picking up signals from acoustic transmitters as well as ship-borne sonars and archival tags capable of detecting and recording proximity to another tag.

4. **an ability to quantitatively identify behavioural states in animals.**

Direct methods for determining foraging in marine animals are currently somewhat limited in their applicability and the robustness of data collected. Utilisation of telemetry devices capable of directly measuring foraging events can be restricted by the species and size ranges of animals on which they can be applied, either through the logistics of deployment or the capability of devices to record changes in behaviour across species and size groups.

Whilst indirect methods provide a means of assessing behaviour across different species, wide size ranges and multiple temporal and spatial scales, the proliferation of differing approaches has resulted in a real need for greater co-ordination in the development of methods. Methods need to be comprehensively documented and analytical tools made available to the broader community in user-friendly formats. Greater co-ordination would serve to identify the most appropriate and informative suite of methods for analyses, promote further development of these methods and provide a basis for greater collaboration on the development and testing of analytical techniques.

5. **availability of an efficient data-sharing facility.**

With the compilation of larger datasets and the collection of increasingly more complex data, many researchers and research institutions have developed specific means of managing their data. As a result, data are often stored, analysed and archived in differing formats, using differing methodologies and differing levels of integration of meta-data. If data sharing is to be promoted to permit comparisons of methodologies and datasets, an efficient and standardised means of facilitation is needed. This will require the implementation of data standards and formats for the data derived from electronic tags and the meta-data associated with each dataset. Data sharing mechanisms would need to take intellectual property, or confidentiality requirements, into account and include means by which individual researchers/institutions can identify requests for data and implement any restrictions associated with those data.

Considerable effort has been put into developing efficient means of managing tag data by a number of institutions to date (e.g. Pelagic Fisheries and Ecosystems Stream at CSIRO in Tasmania, Australia and the Pelagic Fisheries Research Program at the University of Hawaii in Hawaii, USA with similar efforts planned at additional institutions (e.g. the Ocean Tracking Network project at Dalhousie University in Nova Scotia, Canada). An assessment of these approaches should be encouraged as a first step in moving toward an efficient means by which data can be shared and a common way forward agreed. Given the investment put into developing institution-specific data management capabilities, it was noted that there may be some reluctance for those institutions to modify their systems to an identified common format. In light of this, in the longer term effort should be placed into facilitating a means by which data collected throughout the community and available for collaborative comparisons of methodologies and datasets can be submitted, documented and modified to a common format (e.g. through a centralised data manager).

6. **standardised means by which quality control inputs can be implemented on data.**

Data derived from electronic tags are invariably less than perfect. Sensors may malfunction, drift may occur in sensor readings, or data may be corrupted for a variety of reasons. Without quality control measures in place, the resulting gaps in datasets make analyses challenging. In implementing efficient management measures, there have been several approaches to developing diagnostic tools for data quality control. To facilitate increased data sharing and comparisons of methodologies and datasets, there is a need to identify the functions already available to address data quality control issues and then to derive and implement a standard methodology for data quality control.

7. **availability of suitable data visualisation tools.**

Although some effort has been invested in visualising tag data, most specific tools readily available to the tagging community (e.g. proprietary software developed by tag manufacturers) have limited capabilities. Data visualisation using such tools is largely two-dimensional and has primarily been developed with quality control measures, rather than data integration, in mind. The ability to visualise where an animal is, what it is experiencing in its immediate environment and what relationship it may have with other conditions in space and time is largely restricted to software routines written by individuals for specific datasets and analyses. These routines, as a result, may not necessarily be readily available or user friendly.

Some software that allows for the overlaying of data collected by tags onto three dimensional maps of the ocean (e.g. MAMVIS – see http://biology.st-andrews.ac.uk/seaos/technology.htm) and integration with oceanographic variables (Hartog et al. 2007a) has been developed in user-friendly formats. A higher level of interaction with groups producing these types of software is needed and the development of such tools with the potential for wider use throughout the tagging community should be investigated.

Recommendations and agreed actions in relation to identified limitations

The working groups identified a need for improved sensor performance and wider tag capability plus more complementary data to improve the resolution of position estimates and investigate population and ecosystem effects. They also noted a need for better interactions with groups responsible for collecting, handling, analysing and distributing such data. The discussions highlighted the need for better co-ordination in the development of analytical methods (and the associated software) required to improve position estimation and identify specific behavioural activities of tagged animals. They also recognised the need for standardised quality control and greater transparency in data handling and processing. Both working groups also concluded that there was a need to specify and collect a suite of 'ideal datasets', which could be used to compare the performance of existing methods of geolocation and provide a foundation from which to develop future improvements.

In response to the limitations identified by the two groups and the actions required to address them, the workshop agreed upon the following recommendations:

1. That a working group be established to focus on the advancement of analytical techniques and software needs. *Contact for facilitation: Uffe Hogsbro Thygesen, Anders Nielsen.*

2. That the Tagging of Pacific Predators (TOPP) programme make available existing data from individuals tagged with both archival (geolocating) and satellite tags in order to define an 'ideal' dataset with which to compare the performance of current geolocation methods and test new methods. *Contact for facilitation: Barbara Block/TOPP.*

3. That tag manufacturers make available tags for the collection of ideal datasets to be used for comparing various methodologies and quantifying errors associated with different methods of position estimation. *Contact for facilitation: Roger Hill/Wildlife Computers, Phil Ekstrom/Lotek.*

4. That Service Argos provide an error field around each Argos position estimate and clear documentation on how each error field is calculated. *Contact for facilitation: Philippe Gaspar/CLS Argos.*

5. That tag manufacturers make available information on data compression and processing, so that it is clear to users how the data have been treated prior to analyses. *Contact for facilitation: Roger Hill/Wildlife Computers, Phil Ekstrom/Lotek.*

6. That existing dialogue with oceanographers, ecologists and resource managers is expanded. *Contact for facilitation: Mark Hindell (oceanographic communities), Julian Metcalfe, David Righton and Graeme Hays (ecology communities and resource managers).*

7. That sessions at appropriate conferences are established to focus on: (i) the identification of fundamental ecological questions that archival tag technology can contribute to and (ii) the application of archival tag technology for informing resource management. *Contact for facilitation: Barbara Block/TOPP. Conference identified for implementation: Biologging III.*

8. That data sharing/exchange is facilitated through the development of a seamless interface between users and data via a data manager. *Contact for facilitation: data managers at the CSIRO (Jason Hartog), University of Hawaii (John Sibert) and the Ocean Tracking Network (Mike Stokesbury).*

9. That interaction with other research groups studying marine animal movement is encouraged as they develop data storage/management tools. *Contact for facilitation: Barbara Block.*

10. That existing data quality control functions are compiled and made available (possibly through the development of a wiki). *Contact for facilitation: John Sibert.*

11. That dialogue with groups developing data visualisation tools is encouraged and possibilities for developing such tools to suit archival tags are investigated. *Contact for facilitations: data visualisation developers at the CSIRO (Jason Hartog) and Duke University (Pat Halpin) and Mark Hindell (for contact with MAMVIS developers).*

In relation to the recommendations made, two further points were noted.

1. The University of Hawaii currently holds archival tag data from a number of tags including those deployed on moorings in the North Pacific and published in Musyl et al 2001. This mooring deployments dataset is currently being expanded and can be accessed at http://www.soest.hawaii.edu/tag-data/. It was recommended that such datasets should be utilised when developing and comparing geolocation methods.

2. The University of Hawaii has been developing a website aimed to facilitate the exchange of software that might be used on electronic tagging data. While still under development, an initial version can be accessed at http://www.soest.hawaii.edu/data/software/data-analysis-code.

3. The CoML is convening a workshop on data visualisation tools and the SCOR Panel on New Technologies for Observing Marine Life is assisting in the planning for this workshop. It was recommended that this workshop should include key attendees also currently working on data visualisation tools to ensure that such a workshop benefits from multiple contributions including that of the archival tagging community.

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REFERENCES

Ådlandsvik B, Huse G and Michalsen K. 2007. Introducing a method for extracting horizontal migration patterns from data storage tags. Hydrobiologia 582: 187-197.
Andersen KH, Nielsen A, Thygesen UH, Hinrichsen H-H and Neuenfeldt S. 2007. Using the particle filter to geolocate Atlantic cod (*Gadus morhua*) in the Baltic Sea, with special emphasis on determining uncertainty. Canadian Journal of Fisheries and Aquatic Sciences 64: 618-627
Arnold G and Dewar H. 2001. Electronic tags in marine fisheries research: a 30-year perspective. Pages 7-64 in Sibert JR and Nielsen JL (eds). Electronic tagging and tracking in marine fisheries. Kluwer Academic Publishers Dordrecht.
Austin D, Bowen WD, McMillan JI and Iverson SJ. 2006. Linking movement, diving and habitat to foraging success in a large marine predator. Ecology 87: 3095-3108.
Beck CA, McMillan JI and Bowen WD. 2002. An algorithm to improve geolocation positions using sea surface temperature and diving depth. Marine Mammal Science 18: 940-951.
Block BA, Costa DP, Boehlert GW and Kochevar RE. 2003. Revealing pelagic habitat use: the tagging of Pacific pelagics program. Oceanologia Acta 25: 255-266.
Block BA, Dewar H, Blackwell SB, Williams TD, Prince ED, Farwell CJ, Boustany A, Teo SLH, Seitz A, Walli A and Fudge D. 2001. Migratory movements, depth preferences, and thermal biology of Atlantic bluefin tuna. Science 293: 1310-1314.
Bonfil R, Meÿer M, Scholl MC, Johnson R, O'Brien S, Oosthuizen H, Swanson S, Kotze D and Paterson M. 2005. Transoceanic migration, spatial dynamics, and population linkages of white sharks. Science 310: 100-103.
Bradshaw CJA, Higgins J, Michael KJ, Wotherspoon SJ and Hindell MA. 2004. At-sea distribution of female southern elephant seals relative to variation in ocean surface properties. ICES Journal of Marine Science 61: 1014-1027.
Bradshaw CJA, Sims DW and Hays GC. 2007. Measurement error causes scale-dependent threshold erosion of biological signals in animal movement data. Ecological Applications 17: 628-638.
Bruce BD, Stevens JD and Malcolm H. 2006. Movements and swimming behaviour of white sharks (*Carcharodon carcharias*) in Australian waters. Marine Biology 150: 161-172.
Carton JA, Chepurin G and Xao C. 2000. A simple ocean data assimilation analysis of the global upper ocean 1950-95. Part II: results. Journal of Physical Oceanography 30: 311-326.
Carton JA, Chepurin G, Xao C and Giese BS. 2000. A simple ocean data assimilation analysis of the global upper ocean 1950-95. Part I: methods. Journal of Physical Oceanography 30: 294-309.
Decker CJ and O'Dor R. 2003. A census of marine life: unknowable or just unknown? Oceanologica Acta 25: 179-186.
DeLong RL, Stewart BS and Hill RD. 1992. Documenting migrations of northern elephant seals using day length. Marine Mammal Science 8: 155-159.
De Metrio G, Arnold GP, de la Serna JM, Block B, Megalofonou P, Lutcavage M, Oray I and Deflorio M. 2005. Movements of bluefin tuna (*Thunnus thynnus* L.) tagged in the Mediterranean Sea with pop-up satellite tags. Collective Volume of Scientific Papers ICCAT 58: 1337-1340.
Ekstrom P. 2007. Error measures for template-fit geolocation based on light. Deep-Sea Research II 54: 392-403.
Ekstrom PA. 2002. Blue twilight in a simple atmosphere. Pages 73-81 in Shaw JA (ed). Proceedings of SPIE annual meeting 2002: Atmospheric radiation measurements and applications in climate. SPIE Bellingham, WA.

Ekstrom PA. 2004. An advance in geolocation by light. Memoirs of the National Institute of Polar Research. Special issue 58: 210-226.

Evans K, Langley A, Clear NP, Williams P, Patterson T, Sibert J, Hampton J and Gunn JS. In Press. Behaviour and habitat preferences of bigeye tuna (*Thunnus obesus*) and their influence on longline fishery catches in the western Coral Sea. Canadian Journal of Fisheries and Aquatic Sciences.

Fischer G, Lee S, Obara M, Kasturi P, Rossby HT and Recksiek C. 2006. Tracking fishes with a microwatt acoustical receiver – an archival tag development. IEEE Journal of Oceanic Engineering 31: 975-985.

Gaspar P and Malarde JP. 2007. Analysis of Argos system performance in the Mediterranean area for transmitters with weak output power such as pop-up tags. Second International Symposium on Tagging and Tracking Marine Fish with Electronic Devices Abstracts, pp 99. Available at: http://unh.edu/taggingsymposium/abstracts.html.

Gröger JP, Rountree RA, Thygesen UH, Jones D, Martins D, Xu Q and Rothschild BJ. 2007. Geolocation of Atlantic cod (*Gadus morhua*) movements in the Gulf of Maine using tidal information. Fisheries Oceanography 16: 317-335.

Gunn J, Hartog J and Rough K. 2001. The relationship between food intake and visceral warming in southern bluefin tuna (*Thunnus maccoyii*). Pages 109-130 in Sibert JR and Nielsen JL (eds). Electronic tagging and tracking in marine fisheries. Kluwer Academic Publishers Dordrecht.

Gunn J, Polacheck T, Davis T, Sherlock M and Betlehem A. 1994. The development and use of archival tags for studying the migration, behaviour and physiology of southern bluefin tuna, with an assessment of the potential for transfer of the technology to groundfish research. Proceedings of the ICES Mini Symposium on Fish Migration, 21, 23pp.

Gunn JS, Patterson TA and Pepperell JG. 2003. Short-term movement and behaviour of black marlin *Makaira indica* in the Coral Sea as determined through a pop-up satellite archival tagging experiment. Marine and Freshwater Research 54: 515-525.

Gunn JS, Stevens JD, Davis TLO and Norman BM. 1999. Observations on the short-term movements of whale sharks (*Rhincodon typus*) at Ningaloo Reef, Western Australia. Marine Biology 135: 553-559.

Halpin PN, Read AJ, Best BD, Hyrenback KD, Fujioka E, Coyne MS, Crowder LB, Freeman SA and Spoerri C. 2006. OBIS-SEAMAP: developing a biogeographic data commons for the ecological studies of marine mammals, seabirds and sea turtles. Marine Ecology Progress Series 316: 239-246.

Hartog J, Hartmann K, Cooper S, Patterson T, Jumppanen P, Bradford R, Stanley C and West G. 2007. An integrated system for storage and access to large volumes of electronic data. Second International Symposium on Tagging and Tracking Marine Fish with Electronic Devices Abstracts, pp 99. Available at: http://unh.edu/taggingsymposium/abstracts.html.

Hartog J, Hobday A, Hartmann K and Patterson T. 2007. Linking electronic data, primary environmental data and derived environmental products to aid fisheries oceanographers. Second International Symposium on Tagging and Tracking Marine Fish with Electronic Devices Abstracts, pp 99. Available at: http://unh.edu/taggingsymposium/abstracts.html.

Hays GC, Åkesson S, Godley BJ, Luschi P and Santidrian P. 2001. The implications of location accuracy for the interpretation of satellite-tracking data. Animal Behaviour 61: 1035-1040.

Hill RD. 1994. Theory of geolocation by light levels. Pages 227-236 in Le Boeuf BJ and Laws RM (eds). Elephant seals: population ecology, behaviour and physiology. University of California Press, Berkeley.

Hill RD. 2008. Crossing the twilight zone: estimating a location from an observation of dawn or dusk. Advances in fish tagging and marking technology international symposium abstracts, pp 82. Available at: http://www.fisheries.org/units/tag2008/FishTagging_abstracts.pdf.

Hill RD and Braun MJ. 2001. Geolocation by light level. The next step: latitude. Pages 315-330 in Sibert JR and Nielsen JL (eds). Electronic tagging and tracking in marine fisheries. Kluwer Academic Publishers Dordrecht.

Hindell MA, Bradshaw CJA, Sumner MD, Michael KJ and Burton HR. 2003. Dispersal of female southern elephant seals and their prey consumption during the austral summer: relevance to management and oceanographic zones. Journal of Applied Ecology: 40: 703-715.

Hindell MA, Harcourt R, Waas JR and Thompson D. 2002. Fine-scale three dimensional spatial use by diving, lactating, female Weddell seals, *Leptonychotes weddellii*. Marine Ecology Progress Series 242: 275-284.

Hobday AJ and Hartmann K. 2006. Near real-time spatial management based on habitat predictions for a longline bycatch species. Fisheries Management and Ecology 13: 365-380.

Hooker S, Biuw M, McConnell BM, Miller PJO and Sparling CE. 2007. Biologging science: logging and relaying physical and biological data using animal attached tags. Deep-Sea Research Pt. II 54: 177-182.

Hoolihan JP. 2005. Horizontal and vertical movements of sailfish (*Istiophorus platypterus*) in the Arabian Gulf, determined by ultrasonic and pop-up satellite tagging. Marine Biology 146: 115-129.

Horodysky AZ, Kerstetter DW, Latour RJ and Graves JE. 2007. Habitat utilization and vertical movement of white marlin (*Tetrapturus albidus*) released from commercial and recreational fishing gears in the western North Atlantic Ocean: inferences from short duration pop-up archival satellite tags. Fisheries Oceanography 16: 240-256.

Hull CL. 1999. The foraging zones of breeding royal (*Eudyptes schlegeli*) and rockhopper (*E. chrysoscome*) penguins: an assessment of techniques and species comparison. Wildlife Research 26: 789-803.

Hunter E, Aldridge JN, Metcalfe JD and Arnold GP. 2003. Geolocation of free-ranging fish on the European continental shelf as determined from environmental variables. I. Tidal location method. Marine Biology 142: 601-609.

Hunter E, Metcalfe JD, Holford PH and Arnold GP. 2004. Geolocation of free-ranging fish on the European continental shelf as determined from environmental variables. II. Reconstruction of plaice ground tracks. Marine Biology 144: 787-798.

Hunter E, Buckley AA, Stewart C and Metcalfe JD. 2005. Migratory behaviour of the thornback ray, *Raja clavata* L., in the southern North Sea. Journal of the Marine Biological Association of the UK 85: 1095-1105.

International Council for the Exploration of the Sea. 2007. Report of the planning group on operational oceanographic products (PGOOP). ICES CM 2007/OCC:02.

Itoh T, Tsuji S and Nitta A. 2003. Migration patterns of young Pacific bluefin tuna (*Thunnus orientalis*) determined with archival tags. Fisheries Bulletin 101: 514-534.

Jerlov NG. 1976. Marine optics. Elsevier Press, Amsterdam.

Jonsen ID, Flemming JM and Myers RA. 2005. Robust state-space modelling of animal movement data. Ecology 86: 2874-2880.

Jonsen ID, Myers RA and Flemming JM. 2003. Meta-analysis of animal movement using state-space models. Ecology 84: 3055-3063.

Jonsen ID, Myers RA and James MC. 2007. Identifying leatherback turtle foraging behaviour from satellite telemetry using a switching state-space model. Marine Ecology Progress Series 337: 255-264.

Kitagawa T, Kimura S, Nakata H and Yamada H. 2006. Thermal adaptation of Pacific bluefin tuna *Thunnus orientalis* to temperate waters. Fisheries Science 72: 149-156.

Kooyman GL. 2004. Genesis and evolution of biologging devices 1963-2002. Memoirs of the National Institute of Polar Research Special Issue 58: 15-22.

Lam C, Tsontos V, O'Brien F, Domeier M and Kiefer D. 2007. TagBase and FishTracker – informatics tools for data management, analysis and visualization. Second International Symposium on Tagging and Tracking Marine Fish with Electronic Devices Abstracts, pp 99. Available at: http://unh.edu/taggingsymposium/abstracts.html.

Lutcavage ME, Brill RW, Skomal GB, Chase BC and Howey PW. 1999. Results of pop-up satellite tagging of spawning size class fish in the Gulf of Maine: do North Atlantic bluefin tuna spawn in the mid-Atlantic? Canadian Journal of Fisheries and Aquatic Sciences 56: 173-177.

Metcalfe JD. 2001. Summary report of the workshop on daylight measurements for geolocation in animal telemetry. Pages 331-342 in Sibert JR and Nielsen JL (eds). Electronic tagging and tracking in marine fisheries. Kluwer Academic Publishers Dordrecht.

Metcalfe JD and Arnold GP. 1997. Tracking fish with electronic tags. Nature 387: 665-666.

Muramoto H, Ogawa M, Suzuki M and Naito Y. 2004. Little Leonardo digitial data logger: its past, present and future role in bio-logging science. Memoirs of the National Institute of Polar Research. Special issue 58: 196-202.

Musyl MK, Brill RW, Boggs CH, Curran DS, Kazama TK and Seki MP. 2003. Vertical movements of bigeye tuna (*Thunnus obesus*) associated with islands, buoys and seamounts near the main Hawaiian Islands from archival tagging data. Fisheries Oceanography. 12: 1-18.

Musyl MK, Brill RW, Curran DS, Gunn JS, Hartog JR, Hill RD, Welch DW, Eveson JP, Boggs CH and Brainard RE. 2001. Ability of archival tags to provide estimates of geographical position based on light intensity. Pages 343–368 in Sibert JR and Nielsen JL (eds). Electronic tagging and tracking in marine fisheries. Kluwer Academic Publishers Dordrecht.

Neat FC, Wright PJ, Zuur AF, Gibb IM, Gibb FM, Tulett D, Righton DA and Turner RJ. 2006. Residency and depth movements of a coastal group of Atlantic cod (*Gadus morhua* L.). Marine Biology 148: 643-654.

Nielsen A, Bigelow KA, Musyl MK and Sibert JR. 2006. Improving light-based geolocation by including sea surface temperature. Fisheries Oceanography 15: 314-325.

Nielsen A and Sibert JR. 2007a. State-space model for light-based tracking of marine animals. Canadian Journal of Fisheries and Aquatic Sciences 64: 1055-1068.

Nielsen A and Sibert JR. 2007b. A holistic approach to light based geolocation. Second International Symposium on Tagging and Tracking Marine Fish with Electronic Devices Abstracts, pp 99. Available at: http://unh.edu/taggingsymposium/abstracts.html.

Neuenfeldt S, Hinrichsen H-H, Nielsen A and Andersen KH. 2007. Reconstructing migrations of individual cod (*Gadus morhua* L.) in the Baltic Sea by using electronic data storage tags. Fisheries Oceanography 16: 526-535.

Newlands NK, Lutcavage ME and Pitcher TJ. 2004. Analysis of foraging movements of Atlantic bluefin tuna (*Thunnus thynnus*): individuals switch between two modes of search behaviour. Population Ecology 46: 39-53.

Patterson TA, Thomas L, Wilcox C, Ovaskainen O and Matthiopoulos J. 2008. State-space models of individual animal movement. Trends in Ecology and Evolution 23: 87-94.

Perle C, Jorgensen S, Weng K, Dewar H, Kohin S, Sosa-Niskizaki O, Schaefer K and Block B. 2007. Tagging of Pacific Pelagics: ecological niche partitioning in the *Thunnus* and Lamnid guilds in the eastern North Pacific ocean. Second

International Symposium on Tagging and Tracking Marine Fish with Electronic Devices Abstracts, pp 99. Available at: http://unh.edu/taggingsymposium/abstracts.html.

Phillips RA, Silk JRD, Croxall JP. Afanaseyev V and Briggs DR. 2004. Accuracy of geolocation estimates for flying seabirds. Marine Ecology Progress Series 266: 265-272.

Pinaud D and Weimerskirch H. 2005. Scale-dependent habitat use in a long-ranging central place predator. Journal of Animal Ecology 74: 852-863.

Qayum HA, Klimley AP, Newton R, Richert JE. 2007. Broad-band versus narrow-band irradiance for estimating latitude by archival tags. Marine Biology 151: 467-481.

Recksiek CW, Fischer G, Rossby HT, Cadrin SX and Kasturi P. 2006. Development and application of 'RAFOS Fish Tags' for studying fish movement. ICES CM 2006/Q:16: 1-13.

Righton D and Mills CM. 2008. Reconstructing the movements of free-ranging demersal fish in the North Sea: a data matching and simulation method. Marine Biology 153: 507-521.

Ropert-Coudert Y and Wilson RP. 2005. Trends and perspectives in animal-attached remote sensing. Frontiers in Ecology and Environment 3: 437-444.

Royer F, Fromentin J-M and Gaspar P. 2005. A state-space model to derive bluefin movement and habitat from archival tags. Oikos 109: 473-484.

Schaefer KM, Fuller DW and Block BA. 2007. Movements, behaviour and habitat utilization of yellowfin tuna (*Thunnus albacares*) in the northeastern Pacific Ocean, ascertained through archival tag data. Marine Biology 152: 503-525.

Schofield G, Bishop CM, MacLean G, Brown P, Baker M, Katseledis KA, Dimopoulos P, Pantis JD and Hays GC. 2007. Novel GPS tracking of sea turtles as a tool for conservation management. Journal of Experimental Marine Biology and Ecology: 347: 58-68.

Sedberry GR and Loefer JK. 2001. Satellite telemetry tracking of swordfish, *Xiphias gladias*, off the eastern United States. Marine Biology 139: 355-360.

Shaffer SA, Tremblay Y, Awkerman JA, Henry RW, Teo SLH, Anderson DJ, Croll DA, Block BA and Costa DP. 2005. Comparison of light- and SST-based geolocation with satellite telemetry in free-ranging albatrosses. Marine Biology 147: 833-843.

Sibert JR, Lutcavage ME, Nielsen A, Brill RW and Wilson SG. 2006. Interannual variation in large-scale movement of Atlantic bluefin (*Thunnus thynnus*) determined from pop-up satellite archival tags. Canadian Journal of Fisheries and Aquatic Sciences 63: 2154-2166.

Sibert JR, Musyl MK and Brill RW. 2003. Horizontal movements of bigeye tuna (*Thunnus obesus*) near Hawaii determined by Kalman filter analysis of archival tagging data. Fisheries Oceanography 12: 1-11.

Sims DW, Nash JP and Morritt D. 2001. Movements and activity of male and female dogfish in a tidal sea lough: alternative behavioural strategies and apparent sexual segregation. Marine Biology 139: 1165-1175.

Sims DW, Southall EJ, Richardson AJ, Reid PC and Metcalfe JD. 2003. Seasonal movements and behaviour of basking sharks from archival tagging: no evidence of winter hibernation. Marine Ecology Progress Series 248: 187-196.

Sippel TJ, Davie PS, Holdsworth JC and Block BA. 2007. Striped marlin (*Tetrapturus audax*) movements and habitat utilization during a summer and autumn in the southwest Pacific Ocean. Fisheries Oceanography 16: 459-472.

Smith P, Goodman D. 1986. Determining fish movements from an 'archival' tag: precision of geographical positions made from a time series of swimming temperature and depth. NOAA Technical Memorandum NOAA-TM-NMFS-SWFC-60. 13pp.

Southall EJ, Sims DW, Witt MJ, Metcalfe JD. 2006. Seasonal state-space estimates of basking sharks in relation to protection and political-economic zones in the north-east Atlantic. Biological Conservation 132: 33-39.

Stokesbury MJW, Teo SLH, Seitz A, O'Dor RK and Block BA. 2004. Movement of Atlantic bluefin tuna (*Thunnus thynnus*) as determined from satellite tagging experiments initiated off New England. Canadian Journal of Fisheries and Aquatic Sciences 61: 1976-1987.

Swimmer Y, Arauz R, McCracken M, McNaughton L, Ballestero J, Musyl M, Bigelow K and Brill R. 2006. Diving behaviour and delayed mortality of olive ridley sea turtles *Lepidochelys olivacea* after their release from longline fishing gear. Marine Ecology Progress Series 323: 253-261.

Teo SLH, Boustany A, Blackwell S, Walli A, Weng KC and Block BA. 2004. Validation of geolocation estimates based on light level and sea surface temperature from electronic tags. Marine Ecology Progress Series 283: 81-98.

Teo SLH, Boustany A and Block BA. 2007. Oceanographic preferences of Atlantic bluefin tuna, *Thunnus thynnus*, on their Gulf of Mexico breeding grounds. Marine Biology 152: 1105-1119.

Teo SLH Boustany A, Dewar H, Stokesbury MJW, Weng KC, Beemer S, Seitz AC, Farwell CJ, Prince ED and Block BA. 2007. Annual migrations, diving behaviour and thermal biology of Atlantic bluefin tuna, *Thunnus thynnus*, on their Gulf of Mexico breeding grounds. Marine Biology 151: 1-18.

Tremblay Y, Shaffer SA, Fowler SL, Kuhn CE, McDonald BI, Weise MJ, Bost C-A, Weimerskirch H, Crocker DA, Goebel ME and Costa DP. 2006. Interpolation of animal tracking data in a fluid environment. The Journal of Experimental Biology 209: 128-140.

Tuck GN, Polacheck T, Croxall JP, Weimerskirch H, Prince PA and Wotherspoon S. 1999. The potential of archival tags to provide long-term movement and behaviour data for seabirds: first results from wandering albatross *Diomedea exulans* of South Georgia and the Crozet Islands. Emu 99: 60-68.

Turner K, Righton DR and Metcalfe JD. 2002. The dispersal patterns and behaviour of North Sea cod (*Gadus morhua*) studied using electronic data storage tags. Hydrobiologica 483: 201- 208.

Uosaki K. 2004. Preliminary results obtained from tagging of North Pacific albacore with archival tag. Collective Volume of Scientific Papers ICCAT 56: 1496-1503.

Vincent C, McConnell BJ, Fedak A and Ridoux V. 2002. Assessment of ARGOS location accuracy from satellite tags deployed on captive gray seals. Marine Mammal Science18: 301-322.

Weimerskirch H, Bonnadonna F, Bailleul F, Mabille G, Dell'Omo, G and Lipp H-P. 2002. GPS tracking of foraging albatrosses. Science 295: 1259.

Weng KC, O'Sullivan JB, Lowe CG, Winkler CE, Dewar H and Block BA. 2007. Movements, behaviour and habitat preferences of juvenile white sharks, *Carcharodon carcharias* in the eastern Pacific. Marine Ecology Progress Series 338: 211-224.

West GJ and Stevens JD. 2001. Archival tagging of school shark, *Galeorhinus galeus*, in Australia: initial results. Environmental Biology of Fishes 60: 283-298.

Wilson RP, Duchamp J-J, Rees WG, Culik BM and Niekamp K. 1992. Estimation of location: global coverage using light intensity. Pages 131-134 in Priede IG and Swift S (eds). Wildlife Telemetry. Ellis Horwood, New York.

Wilson RP, Steinfurth A, Ropert-Coudert Y, Kato A and Kurita M. 2002. Lip reading in remote subjects: an attempt to quantify and separate ingestion, breathing and vocalisation in free-living animals using penguins as a model. Marine Biology 140: 17-27.

Wilson SG, Lutcavage ME, Brill RW, Genovese MP, Cooper AB and Everly AW. 2005. Movements of bluefin tuna (*Thunnus thynnus*) in the northwestern Atlantic Ocean recorded by pop-up satellite archival tags. Marine Biology 146: 409-423.

Wilson SG, Polavina JJ, Stewart BS and Meekan MG. 2006. Movements of whale sharks *Rhincodon typus* tagged at Ningaloo Reef, Western Australia. Marine Biology 148: 1157-1166.

APPENDICES

Appendix 1: Workshop program and associated abstracts

GEOLOCATION METHODS WORKSHOP

5-6 October 2007

San Sebastián, Spain

organised by the

SCOR PANEL ON NEW TECHNOLOGIES FOR OBSERVING MARINE LIFE

on behalf of the

CENSUS OF MARINE LIFE

held in conjunction with the

2ND INTERNATIONAL SYMPOSIUM ON TRACKING AND TAGGING MARINE FISH WITH ELECTRONIC DEVICES

(8-11 October 2007)

PROGRAM AND ABSTRACTS

Contents

International Council for Science

Scientific Committee on Oceanic Research

CENSUS OF MARINE LIFE

Day One: Friday 5 October 2007		
09:00-09:30		**Registration**
Session A: Introduction		
09:30-09:35	Karen Evans	Welcome and house-keeping
09:35-10:05	Geoff Arnold	Where have we been? A review of previous workshops in series Where are we now? What level of scientific question can be asked of today's technology? Where do we want to go? What level of scientific question do we need to ask in the future and what new technologies/analytical techniques are required to get there? Relationship of workshop to SCOR and CoML Objectives of workshop
Session B: Short presentations: deriving movement from tag-based estimates of position. Chair: Karen Evans		
10:05-10:20	Graham Hays	Tracking turtles using satellite telemetry and GPS loggers
10:20-10:35	David Sims	The accuracy of fish tracks and the extraction of behavioural signals
10:35-10:50	Julian Metcalfe	Geolocation without light
10:50-11:05	Chris Perle	Understanding the influence of geography and oceanography on the accuracy and variability of geolocation estimates
11:05-11:30		**Morning tea**
Session B continued: Short presentations: deriving movement from tag-based estimates of position. Chair: Geoff Arnold		
11:30-11:45	Mark Hindell	A generic, Bayesian approach to quantifying location position and precision from tag data.
11:45-12:00	Michael Sumner	Estimation of position based on recorded light levels: an integrated approach.
12:00-12:15	Roger Hill	Crossing the twilight zone – or – estimating a location from an observation of dusk (or dawn), but not both.
12:15-12:30	John Sibert	Potential relief from light-based geolocation problems
12:30-12:45	Phil Ekstrom	Current state of the template fit method
12:45-13:00	Barbara Block	Validation of template-fit geolocation with GPS double tagging experiments using free swimming sea-lions and bluefin tuna in farm pens
13:00-14:00		**Lunch**

Day One: Friday 5 October 2007		
Session B continued: Short presentations: deriving movement from tag-based estimates of position. Chair: Karen Evans		
14:00-14:15	Steven Teo	Influence of light attenuation models on geolocation error
14:15-14:30	Francois Royer	Sunset/sunrise-based geolocation in pop-up tags
14:30-14:45	Uffe Høgsbro Thygesen	Geolocation by direct numerical filtering and Hidden Markov Models
14:45-15:00	Jason Hartog	Depth attenuation – a new approach
Session C: Short presentations: hardware and software improvements and new developments Chair: Karen Evans		
15:00-15:15	Conrad Recksiek	Development of the 'RAFOS Fish Tag' for studying movements of demersal species on the continental shelf
15:15-15:30	Phil Ekstrom	Road map for the Lotek LAT tag family
15:30-15:45	Francois Royer	The definition and specification of an "open, self-described file format for tagging data dissemination"
15:45-16:15		**Afternoon tea**
Session D: Working groups: discussion of problems/areas of required development and identification of solutions		
16:15-18:30	Chair: Geoff Arnold Rapporteur: Mike Sumner	Working groups I: Estimation of position: identification of key problems. How can we improve current methods used (both on-board and post download)? How can we improve and to what extent can we improve current light attenuation algorithms? How best can we quantify and to what extent can we quantify error? What tools are required? How far will these improvements/quantifying of error move us toward resolving some of the science/management questions/hypotheses needed to be resolved?
16:15-18:30	Chair: Mark Hindell Rapporteur: Chris Perle	Working groups II: Interpretation and management of position data: identification of key problems and limitations. How do we derive inferences about behaviour and how can we improve these? What problems require resolution? What tools are required? How far will these improvements move us toward resolving some of the science/management questions/hypotheses needed to be resolved? How do we best handle data for archival and exchange?
18:30		**End Day One**

Day Two: Saturday 6 October 2007		
Welcome and house-keeping		
09:00-09:05	Karen Evans	Welcome and house-keeping
Session D continued: Working groups continued: discussion of problems/areas of required development and identification of solutions		
09:05-10:30	Chair: Julian Metcalfe Rapporteur: Toby Patterson	Working groups I Estimation of position
09:05-10:30	Chair: Barbara Block Rapporteur: Ben Galuardi	Working groups II Interpretation and management of position data
11:00-11:30		**Morning tea**
Session D continued: Working groups continued: discussion of problems/areas of required development and identification of solutions		
11:30-13:00	Chair: Julian Metcalfe Rapporteur: Geoff Arnold	Working groups I Estimation of position
11:30-13:00	Chair: Barbara Block Rapporteur: Karen Evans	Working groups II Interpretation and management of position data
13:00-14:00		**Lunch**
Session E: Conclusions		
14:00-14:45	Chair: Geoff Arnold Rapporteur: Karen Evans	Summation of the outputs of working group I back in plenary
14:45-15:30	Chair: Geoff Arnold Rapporteur: Karen Evans	Summation of the outputs of working group II back in plenary
15:30-16:00		**Afternoon tea**
Session E continued: Conclusions		
16:00-18:30	Chair: Geoff Arnold Rapporteur: Karen Evans	Resolution of future directions and identification of potential collaborative projects Formulation of an outline of a workshop report to be submitted to SCOR and CoML
18:30		**End Day Two and End Workshop**
18:30-20:30		**Workshop Cocktail Function**

ABSTRACTS

Tracking turtles using satellite telemetry and GPS loggers

G. Hays

Biological Sciences
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I will review our work over the last few years to track a range of turtle species with both Argos transmitters and GPS loggers and linking patterns of movement to diving behaviour at a range of spatial and temporal scales.

The accuracy of fish tracks and the extraction of behavioural signals

D. Sims

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The electronic tag type chosen to record or estimate movements of a marine fish is dependant, at least in part, on the scale of movements a species is likely to undertake. Hence, the geolocation method and its accuracy usually scales with such displacements; small moves require greater accuracy than do large moves for the behaviour present to be resolved. However, what are the likely error thresholds for resolving behavioural signals in animal tracks where different methods confer different error fields? This overview will use empirical and simulation studies to investigate the effects of geolocation method and movement scales on the detection of behavioural signals in animal movement data.

Geolocation without light

J. Metcalfe

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In the turbid waters of the European continental shelf, light-based geolocation methods are often not appropriate. Also, the scale of spatial movement of fish inhabiting shelf seas is often smaller (10s or 100s of km) than that of open-ocean species, so light-based methods are not usually accurate enough to be of great utility. For a decade or so, we have been developing methods based on other environmental variables, principally tidal data; that vary systematically and predictably and provide geolocation at a finer resolution than light-based methods. This presentation will provide an update on methods and results.

Understanding the influence of geography and oceanography on the accuracy and variability of geolocation estimates

C. Perle

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Correlating horizontal movements with oceanic habitat characteristics has become common practice for researchers interested in understanding the influence of environment on the behaviours of marine animals. Positions are often based on threshold light level techniques for longitude and sea surface temperature measurements for latitude. The accuracy and precision of geolocation estimates can be influenced by environmental parameters such as the strength of sea surface temperature gradients or geographic factors such as islands and or nearby land masses. Understanding how geolocation error varies along an animal track in space and time is vital to correctly extracting oceanographic data before correlations can be tested. Validation of algorithms can be performed when free-swimming animals are double tagged with ARGOS satellite-based tags. In the Tagging of Pacific Pelagics program we've generated a large double tag data set of Wildlife Computers Spot versus PAT tag data sets. We present data from sets of multiple runs of our SST based geolocation algorithm to examine variability in both accuracy and precision with changing latitude. High quality ARGOS satellite-based positions are used when available to assess the accuracy of the algorithm in a variety of search settings, sea surface temperature fields and geographies. Since the algorithm uses a stochastic model to estimate positions, precision is analyzed by measuring the variability of multiple runs of the same data.

A generic, Bayesian approach to quantifying location position and precision from tag data

M. Hindell

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We present a Bayesian approach to the problem of estimating location from archival (and other electronic) tags that builds on the relationship between solar elevation and recorded light level during twilight. The method applies a movement model to constrain the set of location estimates and can also incorporate any available auxiliary data (such as SST, depth, etc.). This provides a framework that allows the seamless inclusion of any data source which may be specified in an appropriate way. The movement model unifies the method for archival tags in a way that can be used for satellite and other location methods. Estimates may be queried directly for spatial measures with confidence intervals including likely paths and spatial usage maps, and estimates from different animals may be combined arbitrarily.

Estimation of position based on recorded light levels: an integrated approach

M. Sumner

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Hobart, Tasmania, 7001, Australia

We describe a Bayesian approach to location estimation that has four main categories of data available: (i) the Prior consisting of the known range of the population, (ii) the primary data, consisting of the recorded light levels, (iii) the auxiliary data, for example SST, depth, coastline, ocean height, ice cover, and (iv) the movement model which enables direct and intermediate estimates constrained by likely movement of the animal. Using the twilight periods independently helps avoid issues of rapid animal movement and equinoxes, as well as providing two primary locations per day. SST and other auxiliary data may be used conservatively as "masks", or more directly with likelihood models comparing in-situ measures to environmental databases. Estimation is carried out using MCMC, by direct application of the Metropolis-Hastings algorithm. The sampling code is written to be generic and is publicly available, with model objects specified for solar or Argos data, with inclusions or other modifications as required.

Crossing the twilight zone – or – estimating a location from an observation of dusk (or dawn), but not both.

R. D. Hill

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Current light-based geolocation techniques rely on the measurement of dawn and dusk events. Longitude is estimated by determining the midpoint between these events (noon or midnight), and latitude is usually estimated by determining the time between these events (day or night length). The trouble with forming an estimate of position using both dawn and dusk measurements is that animal movement during the day can add a significant undetermined error to the estimated position. A fast eastward migration in the northern hemisphere in summer will shorten the observed day and bias the latitude estimate to the south. By moving north in the northern hemisphere in winter, the apparent day length is shortened shifting the longitude estimate west.

Can we estimate position from twilight alone? If we define twilight as the transition from +3 to -5 degrees sun elevation (Ekstrom recommendation), a virtual band is created around the earth. This generally runs north-south (but tilted by the tilt of the earth for a given day) and has a width defined by the 8 degree sun angle range of twilight. Because the Earth is a spinning ball, the amount of time taken to pass through the band is a function of latitude and is a minimum at the equator and gets longer as one moves towards the poles. Thus a measurement of time to pass through this twilight zone gives a direct measurement of latitude. Longitude can then be determined from the same, single twilight event, since it is a function of the GMT time at which the twilight crossing occurred at the already determined latitude.

Potential relief from light-based geolocation problems

J. Sibert

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Light-based geographic position estimates are often wildly inaccurate near the equinoxes and severely biased during the remainder of the year. These errors are caused by the geometry of the solar system and the mathematical transformation from astronomical to terrestrial coordinate systems. In some cases, it is possible to apply state-space models to "correct" these errors. A more satisfactory approach is to reanalyze the original solar irradiance time series with appropriate, completely coherent, statistical models. Such models enable the simultaneous estimation of a track, a statistical confidence region around the track, and a set of movement parameters that can be applied to populations as well as to individuals.

Current state of the template fit method

P. Ekstrom

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Beginning with a geophysical model of twilight, the Template fit method constructs a template of light: variation with sun elevation angle during twilight. Since sun elevation depends on latitude, longitude and season, the template can be re-expressed in those terms and fit to depth-corrected irradiance data, yielding direct estimates of latitude and longitude which appear largely unbiased.

A covariance matrix for each day's parameter estimates is available, reflecting both the individual day's weather and the seasonal variation in accuracy of the latitude estimate that occurs in any light-based method. The method can be fully automated and executed unattended in a tag, providing both drastic data compression and informative input for a track reconstruction filter.

Validation of template-fit geolocation with GPS double tagging experiments using free swimming sea lions and bluefin tuna in farm pens

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Template fit geolocation potentially provides a more precise algorithm for positioning animals that remain submerged. In addition to more accurate positions, the method provides an estimation of the geolocation error. We validated the output of this algorithm and error estimates against GPS locations. Three Californian sea lions were simultaneously tagged and tracked with the Wildlife Computers MK10AF Argos linked Fastlok GPS tags and Lotek 2310 archival tags off the southern Californian coast. We compared the daily mean GPS positions (mean daily variance of longitude: 0.04 degrees and latitude: 0.08 degrees) with the geolocation estimates from threshold methods, light level longitude and SST based latitude estimates and template fit algorithms. The template fit methodology showed a significant reduction of the mean error for both longitude (0.56±0.06 degrees) and latitude (1.37±0.14 degrees) compared to threshold light methods. However, the threshold light algorithm combined with SST based latitude geolocations provided the lowest latitudinal error. Similarly we collected 954 days of Pacific bluefin tuna (n=8) archival tag geolocation estimates in a farm pen with known GPS position. Unfiltered template fit methods provided an improved longitude (0.43±0.03 degrees) and a much improved latitude (2.77±0.15 degrees) estimate in comparison to the threshold light methods (longitude: 0.65±0.02 degrees; latitude: 12.8±0.74 degrees). The results indicate that template fit techniques have significant promise for improving light derived tracks and should increase our confidence in ecological outcomes from the data. *Supported by TOPP*

Influence of light attenuation models on geolocation error

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Electronic tags deployed on diving animals record the light levels at depth as the animals dive through the water column. In order to make geolocation estimates, the light level at depth needs to be converted into light level at surface using light attenuation algorithms. As light moves through the water column, it is scattered and absorbed by the water and particles in the water, leading to attenuation of the light. To my knowledge, the light attenuation algorithms currently used by electronic tag manufacturers are relatively simple. For example, Lotek uses a 2-bin light attenuation model to correct the light at depth to the surface. However, the actual light attenuation in the water column is likely to be more complex. For example, light attenuation in the open ocean is dominated by the phytoplankton concentration. An over-simplified light attenuation model leads to a distorted light curve and increased geolocation error. This is especially important for tags like pop-up tags, which perform onboard light attenuation correction. However, the geolocation error from over-simplified light attenuation models has not been modelled and studied in detail. It will also be important to determine the optimal light attenuation model given the constraints of the electronics.

Sunset/sunrise-based geolocation in pop-up tags (in contrast to irradiance-based geolocation)

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To save bandwidth and memory space, an option for geolocation-able tags is to detect, store and/or transmit the timing of sunrise and sunset everyday, instead of light levels. The user can then infer the location of the fish from these two measures. However, depth behavior and water clarity tend to produce asymmetric, heavy-tailed errors that are propagated through the astronomical equations in a non-trivial way, further biasing movement estimates. I present here a model to correct for these errors and infer the movement patterns from the time series of sunset/sunrise timings.

Geolocation by direct numerical filtering and Hidden Markov Models

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In this talk I will discuss an alternative to the Kalman filter and the particle filter. The idea is to discrete 2-D space into cells and compute the probability that the fish is in each cell, given all data. Once we have discretised, the problem is a Hidden Markov Model, but with a special structure. Compared to a Kalman filter, our approach is better at handling non-linearities e.g. from bathymetry, and we can and do find multimodal posterior distributions. Compared to a particle filter, our approach handles the "smoothing" step more easily, as well as finding the Most Probable Track. Our method requires about the same computer power as a particle filter. I will present the technique and if time permits also some results from North Sea cod. The work is joint with Martin Wæver Pedersen, Ken Haste Andersen, Henrik Madsen, and David Righton.

Depth attenuation – a new approach

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In the realm of geo-location problems and challenges, depth attenuation – how light levels decrease as the depth increases – has often been overlooked or dealt with in a rudimentary manner. Determining a uniform correction (via depth casts) and applying to all tags fails to take into account the variation between the sensitivity of light sensors on individual tags. A depth cast could be performed for each tag prior to deployment, but this becomes problematic in large archival tag studies and doesn't account for drift in tag sensors. Another approach is to use the deployment data and determine a correction after tag recovery. This may be better, but fails to account for the effect of turbidity on light-at-depth, e.g. as fish move from oceanic water to coastal waters and back over time. We have implemented a generic method, using a HMM that incorporates a simple movement model to filter tag data and predict day and night. This allows us to extract only daytime data for depth attenuation. This enables us to investigate a variety of other techniques in order to determine a tag dependant attenuation correction.

Development of the 'RAFOS Fish Tag' for studying movements of demersal species on the continental shelf

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We report progress in developing the 'RAFOS fish tag' which reverses the tracking process of conventional acoustic tags by receiving acoustic signals from moored sound sources, allowing triangulation of geographic position during deployment on fish. This archival tag would be used for geolocation of demersal shelf fishes. The tag and navigation system are similar in concept to those of isopycnal RAFOS floats, in which arrival times of low frequency tones broadcast from anchored sources are archived and later retrieved for retrospective positioning. The principal differences between the RAFOS fish tag and RAFOS floats is that the tag is small enough to be attached to or implanted in fish about 50 cm or larger, and the tags must be recovered from the tagged fish to download data. Deployment of sound sources would be on or along the edge of the continental shelf where detection ranges appear to be on the order of 100 to 120 km for sources generating a sound pressure of 180 dB re 1 μP. The size of the prototype is governed by dimensions of a cylindrical housing which functions as the hydrophone. Within this is a full-custom 0.5-μm feature size receiver chip, memory chip, timing crystal, two batteries, and pressure sensor (temperature sensor is on-chip). The receiver chip is designed to consume 36 μW at 3 V with an expected data storage life of several months to two years. In the past year the functionality of the tag has been expanded so that pressure and temperature can be measured frequently while geolocation takes place once or twice per day. We encountered some difficulties with power drain due to overly tight packing of circuitry, but these issues have been resolved. The next receiver chip, to be delivered later this coming fall, should be ready for a first major field program. The acoustic navigation capability, i.e., the sound source component of the system, is ready for operation.

Introduction to and overview of the new Lotek LAT series of geolocating tags

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The LAT series of archival tags is a replacement for the LTD series, that will include both tags that are smaller physically and those that are larger in data capacity and longer in operating lifetime. They will be supported by enhanced desktop software. This presentation will briefly cover those models available at the time of the workshop, and those to be released soon after.

The definition and specification of an "open, self-described file format for tagging data dissemination"

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Several manufacturers are now offering a number of tag models, with different applications and scopes. This has lead to a growing number of computer file formats, which mostly consist of the original records and/or the result of intermediate processing. Extra information (tagging location, fish condition at release, tag setup and duty cycle etc...) are often stored separately. There may be a need for a self-described file format, similar to open-source formats developed for GPS applications (e.g. leading to the sharing of tracks, waypoints, bearings and altitudes...). An XML based format could be adopted, along with a stylesheet specifying the fields that could contain the various information coming from the tag. The building blocks of such files can be discussed during the meeting.

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