A note on a computer-based system for theodolite tracking of cetaceans

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ABSTRACT

Theodolites represent a non-invasive shore-based tool for obtaining data on cetacean movement patterns, habitat use and behavioural disturbance. Despite the common use of theodolites as research tools, relatively few computer-based systems exist to assist researchers with collection of theodolite derived data and the analysis of such information. A recently developed computer program named 'Pythagoras', provides an efficient and user-friendly tool for collecting, managing and subsequent analysis of data obtained with theodolites. *Pythagoras* provides location of user-defined fix types (e.g. whales, dolphins, boats, etc.) and has a dynamic interface, that can be customised to fit site-specific research needs. Additional information (behaviour, group size and environmental conditions) can be stored with each theodolite fix. Tracking data are immediately available in the form of a real-time graphic representation. All collected data are stored in *Microsoft Access* and can be exported as *Microsoft Excel*, *ArcInfo*, *Surfer*, *MATLAB*, or delimited text file formats. An analysis module is included to calculate linearity, reorientation rate and leg speed for each track, and distance and orientation between two or more tracklines. Behavioural data are analysed for frequency, time intervals (i.e. blow interval), duration (i.e. surface time) and rate (number per minute) of particular behaviours. Several other computer-based theodolite systems are reviewed here to evaluate their potential benefits and limitations as a means of providing a basis for future developments.

KEYWORDS: TECHNIQUE; MOVEMENTS; DISTRIBUTION; MANAGEMENT; SURVEY–SHORE-BASED; BEHAVIOUR

INTRODUCTION

A theodolite is a surveyor's instrument that measures horizontal and vertical angles with high precision and can be successfully used to determine the distance from the observation site to an object. When placed on an elevated shore-based vantage point, theodolites have been used as a research tool to obtain data on cetacean movement patterns, behaviour, distribution and habitat use (e.g. Würsig, 1978; Bejder, 1997; Ward, 1999; Yin, 1999; Brown, 2000). Theodolite derived data are collected in a completely non-invasive manner, as described by Würsig *et al.* (1991). Both cetaceans and other objects, for instance boats, can be tracked, and interactions between them can be continually and accurately monitored. This aspect makes a theodolite a useful tool for conservation and management research, especially in regard to monitoring potential human-related impacts on marine mammals.

Although this technique has been used for almost 30 years and despite the increase in digital theodolite use for cetacean studies, relatively few computer-based theodolite programs exist to assist researchers in collecting, managing and analysing theodolite data. One of the first theodolite programs for cetacean research was developed by Wolitzky to assist Würsig (1978) in analysing the associated data on dusky dolphins (*Lagenorhynchus obscurus*) off Argentina. Cipriano (1990) created a program called 'T-Trak' as a tool to help analyse data collected with a theodolite for dusky dolphins off New Zealand. In the early 1990s, a Macintosh program named 'Aardvark' was developed by Harold Mills to study humpback whales (*Megaptera novaeangliae*) off Hawaii. A recent program called 'Cyclops' was also created to study humpback whales off Australia (Kniest *et al.*, 2000).

A computer-based system benefits theodolite studies in many ways. For instance, angles can be recorded accurately and efficiently. In addition, real-time calculations of distance to the object and its geographic location can be performed, and trackline(s) can be visually displayed, allowing for rapid corrections of possible tracking errors. Moreover, once data are collected, a computer-based system reduces the time needed for further management and analysis.

This paper describes the fundamental components of a recent computer-based theodolite program, *Pythagoras*, and compares this system to other available theodolite programs.

DESCRIPTION

General

The program *Pythagoras* was designed to communicate with a digital theodolite and provide a dynamic and user-friendly interface. The system collects, manages and analyses theodolite data and calculates distance, bearing and geographic location information in real-time (Gailey and Ortega-Ortiz, 2000). *Pythagoras* was written in *Microsoft Visual Basic* with *Microsoft Access* as the database structure and management component of the program. The program stores specified theodolite station information, such as the observation platform height, geographical position and reference azimuth for multiple theodolite stations. A dynamic interface allows users to define 'fix type' objects, such as dolphins, whales and boats, and the behaviours associated with each defined object as well as environmental and other data not related to the fix itself (i.e. group size). Options for focal group or individual behavioural data collection (Martin and Bateson, 1993) are incorporated to provide detailed records of behavioural events of object(s) being tracked. Tide height can affect the accuracy of the distance estimations, and therefore is an important environmental variable to be considered. Tide height data can be imported *a priori* or *post hoc* to utilise predicted or real tide height values, respectively. Geographic information on the researcher's study area can be imported with geographic information system (GIS) digital vector line maps, such as *ArcInfo* ungenerated format, *Surfer*, *MapInfo* and *MATLAB*.

Data collection

Pythagoras uses the connected theodolite's horizontal and vertical angle readings, and the selected object type to perform calculations of distance, bearing and location upon each newly recorded entry. The recording of the theodolite's angles is subsequently referred to as a 'fix'. The distance calculation performed for each fixed object incorporates the station's geographic position (latitude, longitude), theodolite angle readings, observer's height above sea level and tide height. A modified version of the distance approximation proposed by Lerczak and Hobbs (1998) was used to calculate sighting distances from angular readings (in radians) of shore-based marine mammal surveys, which corrects for the curvature of the earth (Fig. 1).

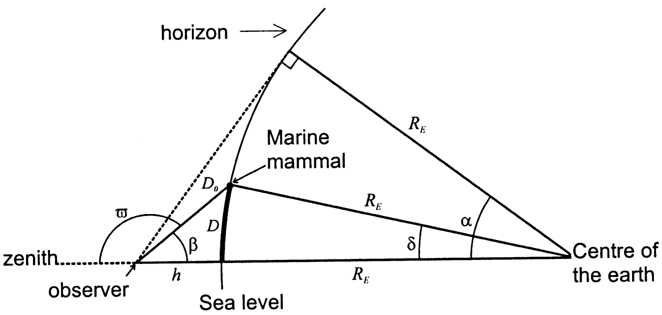

Fig. 1. Schematic showing distances and angles for distance measurements in which the angular drop from the zenith to an object at the sea surface (ϖ or theodolite vertical angle reading) is measured. α is the central arc angle from the horizon to the observation site; β is the angle from the object being fixed to the observation site; and δ is the central arc angle from the object being fixed to the observation site. R_E is the radius of the Earth. The parameter h is the observation site height above sea level. D_0 is the line-of-sight distance to the object and D is the distance to the object along the surface of the surface of the Earth (modified from Lerczak and Hobbs, 1998).

$$\beta = \pi - \varpi$$

$$D_0 = (R_E + h)\cdot\cos(\beta) - \sqrt{(R_E+h)^2\cdot\cos(\beta)^2 - (2hR_E + h^2)}$$

$$\delta = \arcsin\left(\sin(\beta)\frac{D_0}{R_E}\right)$$

$$D = \delta \cdot R_E$$

where:

α = central arc angle from horizon to station;
β = angle from object being fixed to station;
δ = central arc from object being fixed to station;
ϖ = vertical angle estimated with the theodolite (from zenith to object being fixed);
h = theodolite eyepiece height above sea level;
R_E = radius of the Earth (6.371×10^6 m);
D_0 = line-of-sight distance to object being fixed;
D = distance to object being fixed along the surface of the earth/ocean.

Once the distance to the object along the surface of the ocean (D) is known, the great circle equation is used to determine geographic position of the fixed object.

$$\tau = \eta - \rho$$

$$Lat_F = \sin^{-1}\left(\begin{array}{l}\cos(\tau)\cdot\sin(D/60/1852)\cdot\cos(Lat_S)+\\ \left[\sin(Lat_S)\cdot\cos(D/60/1852)\right]\end{array}\right)$$

$$Lon_F = \cos^{-1}\left(\frac{\cos(D/60/1852)-\left[\sin(Lat_S)\cdot\sin(Lat_F)\right]}{\cos(Lat_S)\cdot\cos(Lat_F)}\right)+Lon_S$$

where:

D = distance in meters between the two points along the surface of the Earth;
τ = bearing from station to object;
η = azimuth or horizontal angle estimated with the theodolite;
ρ = reference azimuth (bearing from station to reference point);
Lat_S = latitude of the station;
Lon_S = longitude of the station;
Lat_F = latitude of the fixed object;
Lon_F = longitude of the fixed object.

The great circumference equation is also used to determine distance between two geographic points along the surface of the Earth when the geographic coordinates (latitude and longitude) of both points are known.

$$D = \left(60\cdot\cos^{-1}\left[\begin{array}{l}\left(\sin(Lat_1)\cdot\sin(Lat_2)\right)+\\ \left(\cos(Lat_1)\cdot\cos(Lat_2)\right)\cdot\\ \cos(Lon_2 - Lon_1)\end{array}\right]\right)\cdot 1852$$

$$\varphi = \cos^{-1}\left[\frac{\sin(Lat_2)-\left[\sin(Lat_1)\cdot\cos(D/60)\right]}{\sin(D/60)\cdot\cos(Lat_1)}\right]$$

where:

D = distance in meters between the two points along the surface of the Earth;
φ = bearing from point 1 to point 2;
Lat_1 = latitude of point 1;
Lon_1 = longitude of point 1;
Lat_2 = latitude of point 2;
Lon_2 = longitude of point 2.

The algorithms were tested using the examples provided by Lerczak and Hobbs (1998) and during subsequent field tests. An example of the real-time distance output is given in Table 1.

Group dispersion data are collected with a series of four 'fixes' (i.e. right-left, front-back). The area of a group is estimated in the shape of a quadrilateral. Although the area occupied by cetacean groups is often other than a quadrilateral, estimating it with only four fixes saves valuable time in the field. This is an important aspect as theodolite fixes used to estimate group dispersion should be taken in the shortest possible time, especially for groups that move quickly.

Data management

Data collected by *Pythagoras* are stored in a *Microsoft Access* database. Each data type (i.e. fix, environmental, focal behaviour, etc.) contains separate tables with relevant data stored in columns within each table. These data are

Table 1

Pythagoras' output of objects fixed with a theodolite at a station (29°19'03.8"N, 94°45'04.8"W) with a station height of 43.189m, eyepiece height of 0.77m and reference azimuth of 79.88°.

Date	Time	Fix type	Group	Behaviour	Declination	Horizontal	Latitude	Longitude	Distance (m)	Bearing
3 June 2000	13:11:28	Vessel	3	Moving	91°40'50"	40°22'20"	29.31090N	94.73791W	1504.33	120.25
3 June 2000	13:13:00	Vessel	3	Moving	91°46'50"	51°40'20"	29.30925N	94.74036W	1419.17	131.55
3 June 2000	13:14:07	Vessel	3	Moving	91°50'20"	54°16'40"	29.30959N	94.74065W	1373.81	131.16
3 June 2000	13:15:10	Vessel	3	Moving	91°45'30"	61°24'50"	29.30763N	94.74205W	1437.25	141.29
3 June 2000	13:16:08	Vessel	3	Moving	91°45'40"	63°23'10"	29.30737N	94.74246W	1434.96	143.27
3 June 2000	13:17:16	Vessel	3	Moving	91°43'30"	67°23'40"	29.30663N	94.74315W	1465.25	147.27
3 June 2000	13:18:46	Vessel	3	Moving	91°46'00"	70°34'50"	29.30652N	94.74404W	1430.41	150.46
3 June 2000	13:20:06	Vessel	3	Moving	92°18'00"	74°11'50"	29.30885N	94.74637W	1096.83	154.08
3 June 2000	13:20:51	Vessel	3	Moving	93°20'40"	73°15'10"	29.31168N	94.74781W	753.00	153.13
3 June 2000	13:21:42	Vessel	3	Moving	95°52'40"	71°30'20"	29.31435N	94.74921W	427.14	151.39
3 June 2000	13:22:56	Vessel	3	Moving	98°07'40"	59°57'00"	29.31561N	94.74927W	307.85	139.83
3 June 2000	13:23:13	Vessel	3	Moving	98°17'40"	63°07'10"	29.31556N	94.74945W	301.58	143.00

visually displayed to the user with *Excel*-like spreadsheets. Search and sort functions further structure and manage the database and data partitioning functions separate records by day, fix type and group. Fix data can be recalculated *post hoc* with updated values in relation to distance and geographic location. Data can be exported to various GIS and database management type files. For further spatial analysis and graphical display, latitude and longitude trackline information can be exported to GIS related files such as *ArcInfo*, *MapInfo*, *Surfer* and *MATLAB*. For additional statistical analysis, data can be saved as *Microsoft Excel*, *Microsoft Access*, or delimited (ASCII) text files.

Analysis

An analysis module was developed to estimate trackline distance and bearing both within and between tracks. For a single trackline, the program calculates leg speed, linearity and reorientation rate per trackline. Leg speed is estimated by calculating the distance travelled between two sequential points within a trackline divided by the time interval between the two points. Linearity is the deviation of a trackline from that of a straight line and is calculated by dividing the net geographic distance between the first and last fix of a trackline by the cumulative distances along the track. Linearity values range between 0 and 1, where a linearity score close to one represents a straight trackline and a value close to zero represents a track with little or no observed directional movement (Batschelet, 1981). Reorientation rates represent a magnitude of bearing changes along a trackline. This rate is calculated as the summation of absolute values of all bearing changes along a trackline divided by the entire duration of the trackline in minutes (Smultea and Würsig, 1995).

Although leg speed, linearity and reorientation rates provide valuable information regarding movement patterns, each of these parameters are limited to information collected within a trackline. Often, theodolite studies that evaluate potential impacts of human-related activities on marine mammals are interested in how animals orient themselves in respect to boats or other moving objects. *Pythagoras* has distance and course estimation modules that determine relationships between tracklines or between a trackline and a fixed point. Comparing tracklines can be difficult due to temporal dependency and the logistic difficulty of fixing two objects at the same time. Algorithms were developed that calculate the distances between two or more tracklines within a defined critical time of actual fixed data or interpolated points. To temporally and spatially interpolate trackline data, the calculated speed and bearing between trackline points were used to estimate the geographic position of the object at specified time intervals within a trackline (Fig. 2). This assumes that objects travel at the same speed and direction between the fixed data points. Since this assumption is not always true for cetaceans, users must specify a critical time-interval (CTI) for interpolation between two consecutive fixes. If the time interval between two consecutive fixes is longer than the critical time, no interpolation will be performed. Defining a critical time interval should take into account the object/species being tracked, its behaviour and other factors that may affect movement. Cipriano (1992) used a 130 sec CTI and Barr (1997) a 240 sec CTI for dusky dolphin studies and Bejder (1997) used 60 sec CTI for research on Hector's dolphins (*Cephalorhynchus hectori*).

Relative orientation is estimated with the scheme devised by Bejder (1999) to interpret directional movements of one object in relation to another. This allows for a quantifiable description of approaches and avoidances between objects and can be used to access potential impacts of anthropogenic activity on marine mammals.

Pythagoras has a number of functions that allow for analysis of behavioural data. For each behavioural event recorded, the defined behaviour, fix type and associated group information are linked by date and time. The program analyses the frequency of behaviours, behavioural time intervals (i.e. blow interval), time between two behavioural events or duration of one event (i.e. the time of 'first surface' to the time of 'dive' = surface time) and rate of a specified behaviour (i.e. blows per minute).

Comparison of theodolite computer systems

To evaluate the benefit that various theodolite programs contribute to cetacean research and to give a basis for future developments, several different systems available for cetacean theodolite tracking were compared. The programs evaluated here are Wolitzky's program (Würsig, 1978), *T-Trak* (Cipriano, 1990), *Aardvark*, *Cyclops* (Kniest *et al.*, 2000) and *Pythagoras* (Gailey and Ortega-Ortiz, 2000). The functionality of each program is presented in four basic categories: (1) general system design; (2) data collection; (3) data management; and (4) analysis (Table 2).

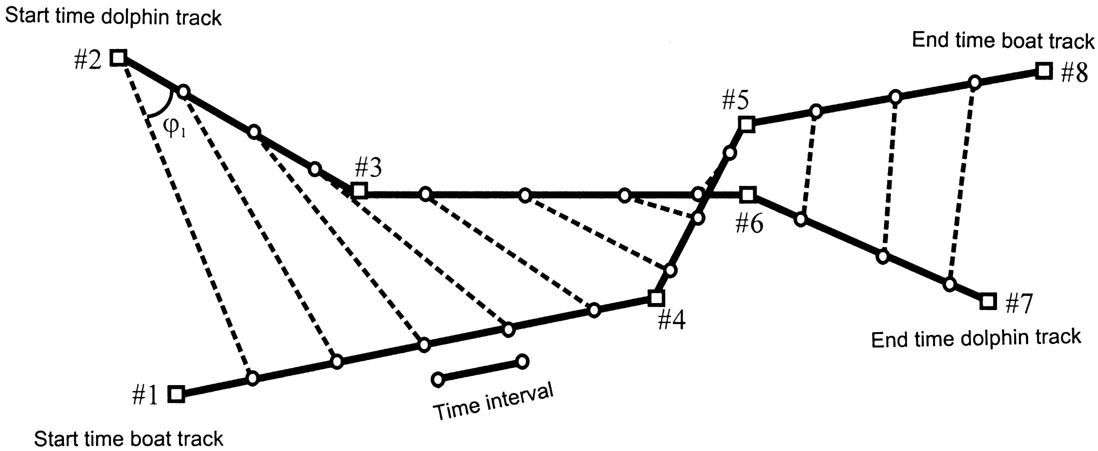

Fig. 2. Positions used to estimate distance between a dolphin trackline and a boat trackline. Location is estimated by interpolating position at specified time intervals. Numbers indicate the sequence of actual fixes. The angle φ indicates the relative orientation of reference trackline (dolphin) to trackline selected for comparison (boat) at time interval one.

Table 2

Comparison of five different theodolite programs. An × indicates the programs ability to perform a function.

Function/feature	Wolitzky's Program	T-Trak	Aardvark	Cyclops	Pythagoras
General					
Operating system	HP Desk Calculator	MS-Dos	Mac	Windows	Windows
Program language	Basic	C		Fortran	Visual Basic
User manual		×		×	×
Supported theodolites			Topcon, Sokkia	Leica, Sokkia, Nikon, Topcon	Topcon, Sokkia
Coordinate system	Cartesian	Cartesian	Cartesian or Lat./Long.	UTM or Lat./Long.	Lat./Long.
Program's database			Text	Binary	Microsoft Access
Data collection					
Data collection program			×	×	×
Environmental			×	×	×
Non-fix data			×		×
Focal behaviour			×		×
Observer data			×		×
Group dispersion				×	×
Real-time display				×	×
GIS maps				Raster	Vector
Real-time calculations				×	×
Data management					
Sorting		×			×
Searching					×
Data partitioning					×
Recalculation		×		×	×
Post-hoc visualisations			×	×	×
Import formats		Text		Text	Excel, Access, Text
Export formats		Text	Text		Excel, Access, Text, ArcInfo, MATLAB, MapInfo, Surfer
Analysis					
Distance calculation	×	×	×	×	×
Leg speed	×	×	×	×	×
Linearity			×		×
Reorientation rate			×		×
Interpolated tracklines			×		×
Relative orientation			×		×
Behaviour					×

The common component of all the programs is the ability to use the required station parameters to convert theodolite vertical and horizontal angles into Cartesian (x-y) coordinates and/or geographic positions. Although such information is the primary goal of using a theodolite as a research tool, it demonstrates the main benefits of using computer programs to perform calculations based on multiple variables that are constantly changing. Of the five programs, three (*Aardvark*, *Cyclops* and *Pythagoras*) provide a means of collecting data from a computer-connected theodolite in the field. This allows for both accurate and rapid recording of the angles measured by the instrument and increases the number of fixes per trackline. By decreasing the time needed to record each fix, the resolution of the data is increased, not only for the current cetacean of interest, but also for the multitude of other objects (e.g. boats, swimmers, oil platforms, sources of underwater noise, etc.) that might be relevant to a particular study.

Cyclops and *Pythagoras*, the two most recently developed programs, provide the ability of real-time calculations and trackline display. This is mainly due to the improvement of computer systems and the increased availability of data from GIS databases. Displaying the fixed object position in real-time allows for rapid detection and correction to errors that may occur during a session.

All programs, with the exception of Wolitzky's program, manage data in some form or another. However, *Pythagoras* alone dedicates a separate module designed specifically for database management. *Pythagoras* also has the ability to interact with *Microsoft Access* and *Excel*, two programs commonly used for database management.

Aardvark and *Pythagoras* provide the most detailed analysis routines of the five programs evaluated here. Both programs can calculate leg speed, linearity and reorientation rates within a trackline and distance and relative orientation between two or more tracklines. Behavioural data analysis is only available in *Pythagoras*.

DISCUSSION

Although theodolites are highly accurate in determining geographic locations of fixed objects, errors can always present a problem in calculations. Würsig *et al.* (1991) described asymmetrical errors caused by inaccurate estimates of observation platform height. The estimated error decreases with increasing elevation of the observation height, and increases with increasing distance of the object from the theodolite. Swell height produces errors due to the change in height of an object being fixed at the crest or trough of a swell. As object distances increase with respect to the station, refraction of light affects line of sight estimation.

The analysis of movement patterns presented here can be improved by incorporating algorithms to evaluate tracklines in terms of correlated random walks (CRW) as suggested by Turchin (1998). The use of CRW models can provide estimates of diffusion rates of individuals and the system can evaluate the appropriateness of CRW models with net squared displacement plots (Turchin, 1998). Other analytical considerations for future system developments should include distance-to-shore, depth profile, and habitat use analysis, which can increase the efficiency in analysing theodolite data.

As computers increase in computational power, increasingly sophisticate software programs are being developed for cetacean research, and often target a specific species, type of data to be collected and analytical approach. Individual photographic identification, for instance, has been aided by the development of computer-assisted recognition systems (Hiby and Lovell, 1990; Mizroch *et al.*, 1990; Whitehead, 1990; Gailey, 2001). Similarly, population estimates and analysis of social patterns have benefited greatly from other programs (Menkens and Anderson, 1988; Whitehead, 1999).

Relatively few such programs exist for theodolite-based research. The system described here provides researchers with a tool to efficiently collect, manage and analyse theodolite-obtained cetacean movement and behaviour data in the field. It also provides functions that can benefit cetacean studies and allow easier integration of data to and from other tools (e.g. database management, GIS, GPS). With the increasing concern of human-related impact on marine mammal populations, quick, efficient and accurate processing of theodolite-based data may allow for rapid assessment of potential impacts, and timely responses to possible management issues.

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