Application of photogrammetric methods for locating and tracking cetacean movements at sea

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ABSTRACT

Accurate measurements of the locations of surfacing cetaceans are important data for behavioural studies and sightings surveys. A system for tracking cetacean movements based on photogrammetric analysis of digital images has been developed and tested at sea. Radial distances from the ship to surfacing whales were calculated from video images by measuring the angle of dip between the whale and the horizon. Bearings were either measured from still images of reference points on the ship, from a magnetic bearing compass or from the bearing ring of stand-mounted binoculars. The system uses readily available equipment and can be operated by one person. Calibration tests were conducted to assess the accuracy of the system. Errors in distance measurement increased approximately linearly with distance. Under typical survey conditions, from a large vessel with an eye height of 18m, distances to whales could be measured with a root mean square error of 3.5%. A model was developed to enable corrections to be made for atmospheric refraction. This has implications for other studies using reticle binoculars. If refraction is not corrected then distance estimates will be negatively biased. Field trials of the system were conducted from several different types and sizes of vessel during studies of a number of different species. Results of these trials demonstrated that the system is a practical tool for fine-scale tracking of cetacean movements and could also be used on line transect surveys. The limitations of the system are the need for a clear horizon and difficulties, for some species, in obtaining suitable quality images of all surfacings. There is also a moderate overhead in increased analysis time. Advances in digital imaging technology are likely to solve many of the image quality problems in the future.

KEYWORDS: PHOTOGRAMMETRY; SURVEY-VESSEL; MOVEMENTS

INTRODUCTION

The aim of this work was to develop a practical system using readily available equipment that would enable the location of a surfacing cetacean to be accurately determined from a moving vessel. Determining locations has applications for both behavioural studies involving tracking of animal movements and also for line transect analyses that rely on knowing the location of sightings relative to the survey vessel. Tracking of whale movements close to shore is frequently achieved by using theodolites from fixed observation positions on land. This relies on the instrument being precisely aligned at a known fixed location, which is clearly impossible on a moving vessel. A commonly used alternative at sea is to use the horizon as a reference point enabling the distance to an object to be determined by the angle of dip from the horizon to the object, measured from a platform of known height. One way of measuring this angle is to use reticle binoculars that superimpose a visual scale on the image (e.g. Thompson and Hiby, 1985). However, accurate readings from reticle binoculars to a cetacean that only surfaces briefly are difficult to obtain and become increasingly so as vessel motion increases. Use of a video camera can overcome these problems by allowing measurements to be taken from still images captured at the optimum moment in the surfacing sequence. One of the difficulties in interpreting data from instantaneous measurements of distance in the field, whether made by eyeball or reticle binoculars, is that it is impossible to estimate the accuracy of the distances. Although calibration experiments can be performed on test targets where the distance can be measured by other means, these are not necessarily representative of the problems faced in estimating distance to a cetacean. An advantage of the video system is that measurements can be made to real targets which allows the accuracy of such a system to be reliably assessed.

Although photogrammetric methods have been used in several studies to measure distance (Gordon, 1990; 1994; 2001; Best *et al.*, 1996) and electronic instruments do exist for measuring bearing, these methods have not yet become a standard feature of general survey design. Routine use of such methods would enable a much more complete and accurate record of the raw data in line transect surveys to be collected, greatly increasing the precision and repeatability of possible analyses. In addition to accurate locations, video methods can provide precise timing of events such as blows or surfacings. Detailed behavioural observations can also be recorded as a verbal commentary. The combination of accurate time and position makes identification of duplicate sightings from independent observation platforms during line transect surveys more reliable. Accurate tracking during surveys may also allow factors such as animal movements in response to the survey vessel to be investigated.

Accurate measurement of location is also important for many behavioural studies. In particular, studies investigating response to disturbance often utilise data on swim speed and direction. Additional information can also be collected with video, including distribution of animals within pods (DeNardo *et al.*, 2001), body size (Gordon, 1990) and the properties of visual cues such as the height and duration of a blow.

The main limitation of these methods is the need for a clear horizon (or a shoreline at a known distance). This could present a problem in some areas. However, accurate distances to even a proportion of sightings would be of value in line transect surveys and use of the video system does not interfere with estimation of distance by other means. The other key limitation of the system is in the maximum

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distance at which cetaceans are detectable on video images due to image quality. The rapid pace of development of digital imaging technology makes it likely that digital devices will have a higher acuity than the human eye in the near future.

METHODS

To fix the target animal's location using these methods, three items of data are required: (1) the vessel's position at the time the image was taken; (2) the distance to the animal; and (3) its absolute bearing from the observer. The position of the vessel at the time an image was captured can be readily obtained by logging the ship's location from a Global Positioning System (GPS) at frequent (every few seconds) intervals.

Theoretical background to distance measurement

The general formulae for calculating distance between a vessel and an object at the sea surface, based on the angle of dip between the whale and the horizon, measured from a platform of known height, are given in Gordon (1990) and Lerczak and Hobbs (1998).

Suppose h is the observation height, is the angle between the horizontal (perpendicular to a line to the centre of the Earth) at the observer and the horizon, and θ is the observed angle between the whale and the horizon.

Let $\psi = \frac{\pi}{2} - \theta - \varphi$. Then the distance d to the object of interest is given by:

$$d = (R_E + h)Cos\psi - \sqrt{(R_E + h)^2 Cos^2\psi - (R_E + h)^2 + R_E{}^2} \quad (1)$$

where R_E is the radius of the Earth (6,356,766m).

This formula assumes that light travels in a straight line between the object and observer and ignores refraction. Light rays from objects at the sea surface pass through an atmosphere of decreasing density and are thus refracted downwards. This means that the observed angle of dip to the horizon (the angle between the horizontal and the horizon) is less than the true angle. The observed angle of dip to the object of interest will also be less than the true angle. However, the light from the horizon will be refracted more than the light from the object resulting in the measured angle between the object and the horizon being greater than the true angle. If this is not corrected, distance measurements will be negatively biased.

The standard correction used by mariners for the angle σ (in radians) between the horizontal and the horizon, for the height h measured in metres, is given by Burton (1974) as:

$$\sigma = 0.02933\frac{\pi}{180}\sqrt{h} \quad (2)$$

For the purposes of whale length measurement, Gordon (1990) used this standard correction for the effect of refraction between the horizon and the observer. A correction for refraction between the observer and whale was not necessary in that study because the distances to whales were only of the order of a few hundred metres.

Predicting the path of a light ray between an object at the sea surface and an observer at height h requires knowledge of the properties of the atmosphere through which the ray passes. For the purposes of estimating refraction, the atmosphere can be modelled as a set of fixed spherical shells concentric with the Earth. The temperature distribution can then be specified by values at the layer boundaries with a linear gradient in between. For shipboard observations of objects at the sea surface between the ship and the horizon, with an eye height of less than 30m, it is realistic to model the atmosphere as a single layer with a constant temperature gradient. The ray paths within a layer can be approximated by a parabolic arc using rectangular coordinates where x is tangential to the Earth's surface and z is perpendicular (Lehn, 1983). Using this coordinate system, the arc of a ray can be represented by:

$$z = \frac{-x^2}{2r} + x\tan\phi + h \quad (3)$$

where:

r is the radius of curvature of the ray;
ϕ is the ray-elevation angle (the angle between the ray direction and the horizontal) at its starting point;
h is the height of the observer's eye above sea level.

Rees (1990) demonstrates that for a horizontally stratified medium, the second derivative of the ray path d^2z/dx^2 is a function only of z and not of ϕ. Further, for rays from whales or the horizon which are close to horizontal (i.e. ϕ is very small) the radius of curvature can be expressed as $1/r \approx d^2z/dx^2$ and this will also be approximately independent of the ray parameter ϕ. Hence, if the radius of curvature can be estimated for the atmospheric conditions when an observation is made, this can be used to estimate the total angle through which light has been refracted between an object and the observer. A correction (α) to the angle measured between the horizon and the object can then be applied to compensate for refraction.

This simple model for calculating refraction is shown in Fig. 1. V represents the observer at height h above sea level and W represents the object of interest at the sea surface at a distance x_w from the observation position. The lower layer of the atmosphere including the observer is assumed to have a constant temperature gradient from T_0 to T_1. The path of the ray from W to V is represented by the circular arc of radius r, centre A, passing through W and V. The correction α, relative to the direct path WV is the angle $W\hat{V}B$ which is equal to $W\hat{A}V$ / 2. Now $W\hat{A}V \approx x_w / r$, giving:

$$\alpha \approx X_w / 2r \quad (4)$$

Lehn (1983) showed that the radius of curvature of the light rays can be derived from the temperature gradient by:

$$\frac{1}{r} = \frac{\varepsilon\rho}{(1+\varepsilon\rho)T}\left(\frac{dT}{dz} + g\beta\right) \quad (5)$$

where:
Atmospheric density ρ can be expressed in terms of pressure p and absolute temperature T by

$$\rho = \frac{p\beta}{T} \quad (6)$$

β = 0.00348 (the reciprocal of the specific gas constant);
ε = 0.000226 (from the refractive index of air);
g = 9.81 (the gravitational constant).

For the special case of a ray from the horizon, the angle of dip ϕ_h between the horizontal and the horizon at an observation height h is given by:

$$\phi_h = \tan^{-1}\left(\sqrt{2h(\frac{1}{R_E} - \frac{1}{r})}\right) \quad (7)$$

where R_E is the radius of the Earth.

In some instances (e.g. to check if the true horizon is visible when land can be seen in the background) it is also

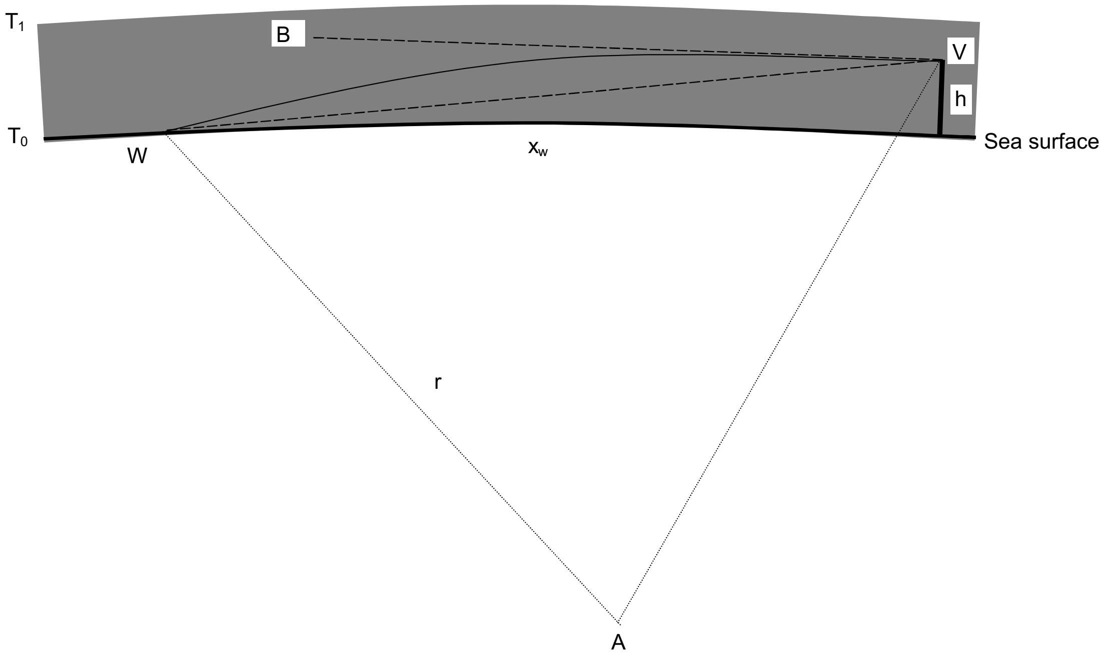

Fig. 1. Cross-section view of surface layer of atmosphere, showing path of light from object to observer (see text). Shaded area represents the lower layer of atmosphere assumed to have a constant temperature gradient from T_0 to T_1. *V* is the location of the observer's eye; W is the object of interest at the sea surface; *A* is the centre of the arc of radius *r* passing through *W* and *V*; *VB* is the tangent to the Earth's surface at *V*; h = height of observer above sea level; x_w = distance to whale along Earth's surface; r = radius of curvature of light ray.

useful to know the distance to the horizon x_h from a particular observation height. Lehn (1983) gives this as:

$$x_h = \left(\frac{1}{R_E} - \frac{1}{r}\right)^{-1} \tan\phi_h \tag{8}$$

For an atmospheric pressure of 1,000mB, a surface temperature of 289.6K (16.4 °C) and a temperature gradient of –6.5K/km, values of ϕ_h calculated using Equation (7) are equivalent to the standard correction given in nautical tables (Equation 2). For the US standard atmosphere (Fleagle and Businger, 1980) with a pressure of 1,013mB, a temperature of 288.15K and a temperature gradient of –6.5K/km, values of ϕ_h calculated using Equation (7) are within 0.02% those calculated using Equation (2).

The differences using formulae such as given by Lerczak and Hobbs (1998) which ignore refraction are shown in Fig. 2 for three different air temperatures (curves A-C). In all cases, distances calculated ignoring refraction are negatively biased. Although it is straightforward to measure both the temperature and the atmospheric pressure, the temperature gradient may need to be assumed. Within the range of the majority of conditions encountered at sea, the effects of changes in atmospheric temperature profiles on the correction needed to account for refraction are relatively minor compared to ignoring refraction completely. An extreme condition, which is sometimes observed at sea, is when the images of objects such as ships or distant land appear inverted above the horizon. This is known as 'superior mirage' and occurs when there is a strong temperature inversion at 10m or so above a roughly isothermal layer at sea level. The effect of refraction may be more difficult to predict under these conditions but the error caused by using the standard atmosphere model are nevertheless likely to be relatively small compared to ignoring refraction completely. This is illustrated by curve 'D' of Fig. 2.

For the purposes of the calibration tests, calculations were performed using this model for refraction with measured temperature and pressure values but assuming a standard temperature gradient of −6.5K/km. Distances were also calculated for comparison purposes making no correction for refraction.

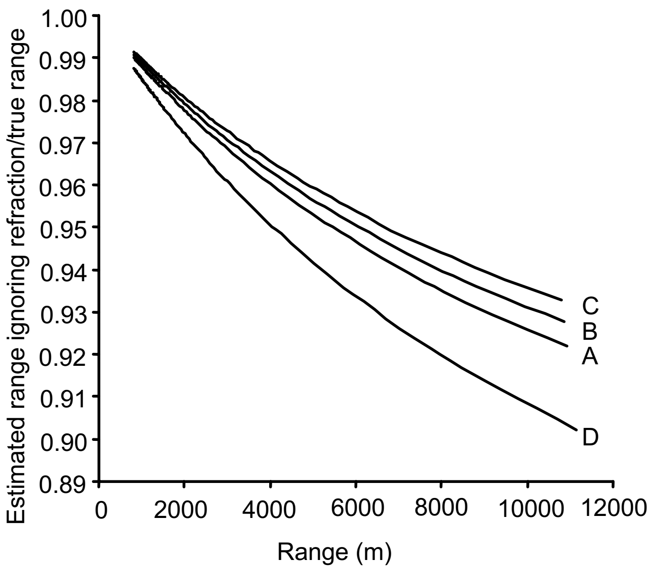

Fig. 2. Ratio of estimated distance ignoring refraction to true distance for three atmospheric profiles. A = Air temp. 0ºC, Surface pressure 1,000mB, Temperature gradient −6.5ºC/km. B = Air temp. 10ºC, Surface pressure 1,000mB, Temperature gradient −6.5ºC/km. C = Air temp. 20ºC, Surface pressure 1,000mB, Temperature gradient −6.5ºC/km. D = Air temp. 0ºC, Surface pressure 1,000mB, Temperature gradient 0ºC/km.

Practical techniques for obtaining images for distance measurement

The utility of the video system is clearly dependent on the practicalities of obtaining suitable images from which the appropriate measurements can be taken. It will usually be easier to see an animal than to film it, and so an important consideration in designing the system was to maximise the likelihood of obtaining images once an animal had been sighted. The probability of obtaining a distance and bearing will vary with species, distance and the method being used to detect the animals. The standard line transect assumption is that the perpendicular distances of the locations where animals or groups are first seen are used to model the detection function. Hence, it is also important to be able to locate a whale as soon as it is detected.

The situation is most straightforward in cases where observers exclusively use binoculars to search for animals, either to make primary sightings (e.g. IDCR/SOWER surveys) or to sight animals well ahead of the survey vessel and track them through the field of view of the primary observers (e.g. Borchers *et al.*, 1998). In these cases, it is likely that, with a good commentary to help interpretation, most animals that are seen for more than one surfacing will be detectable on video. There will always be some delay in starting the video recorder, especially if tape has to be wound around recording heads. One solution would be to video continuously and then analyse the sections of tape when sightings were made. Another option currently being developed is to use a computer-based recording system incorporating a buffer. This would enable video to be stored for a set time period prior to the observer pressing a button.

Observers scanning with binoculars need to be able to operate the video camera without taking their eyes off the sighting. This requires the camera to be mounted so that it is always aligned with the field of view of the binoculars. Separate systems were developed for hand-held 7×50 and for tripod-mounted 25×150 binoculars[1]. A *CANON MV1* digital camcorder was used in both cases. The main feature of the *MV1* which made it suitable for this work was the progressive scan facility, which allowed both interlaced fields (essentially alternate lines of data which make up the video image) to be captured simultaneously. This effectively doubled the vertical resolution of the camera compared to capturing each interleaved field 1/50s apart. The focus was set to infinity for all measurements. This ensures a fixed focal length of lens and also prevents problems encountered with most auto-focus systems that do not focus efficiently on images at sea because of the lack of contrast. Shutter speeds were set as fast as conditions would allow, and were typically less than 1/1,000s.

Design of hand-held frame

A rigid frame was built to hold 7×50 binoculars, video camera and digital still camera (Fig. 3). The frame was designed to allow scanning with binoculars for long periods of time with minimum fatigue but also to allow complete freedom of movement. The centre of gravity of the frame was centred over the observer's shoulder so that the weight was borne on the shoulder and hands were used for steadying purposes and operating the controls. A monopod attached to the frame by a thick rubber universal joint was also used under certain conditions to take some of the weight. A digital still camera was mounted on a strut projecting forwards under the binoculars and pointed vertically downwards at reference lines marked on the deck that were used for the measurement of bearings (see below). A microphone input to allow a verbal commentary on the video sound track was mounted on the frame beneath the binoculars such that it was close to the observer's mouth and also protected from wind noise. The timing of events was recorded to the nearest second by the built-in clock in the video.

Variants of the frame described have been tested at sea from a number of vessels during studies of several different cetacean species. The final version of the system described here has been used to track the movements of right whales in the Bay of Fundy from *Song of the Whale*, a 14m research vessel, during the past three field seasons. It was also used from the British Antarctic Survey vessel *James Clark Ross* during a survey around South Georgia in 1999/2000 and during the IWC/CCAMLR survey in 2000, both as a survey tool and for tracking whale movements during a small-scale study.

For the IWC/CCAMLR survey, the camera was operated on full zoom with a 72.8mm focal length giving an image size of 3.76° horizontally and 2.70° vertically. Although this is considerably less than the horizontal field of view of 7° of the Fujinon 7×50 binoculars, this was not a problem in practice, due to the natural tendency of the observer to place the object of interest in the centre of the image. The choice of field of view also depends on the minimum distance at which measurements are likely to be required. For a given

[1] After completion of this paper the authors were made aware that Tim Gerrodette (Southwest Fisheries Science Center, La Jolla, California, US) had attempted a similar video system for range finding in 1992. *Cohu* monochrome video cameras with telephoto lenses were mounted on top of 25x binoculars with the fields of view aligned, and observers captured individual frames by pushing a button when the animals were in view. However, the researchers concluded that the acuity of the video equipment available at that time was not adequate to make the technique practical.

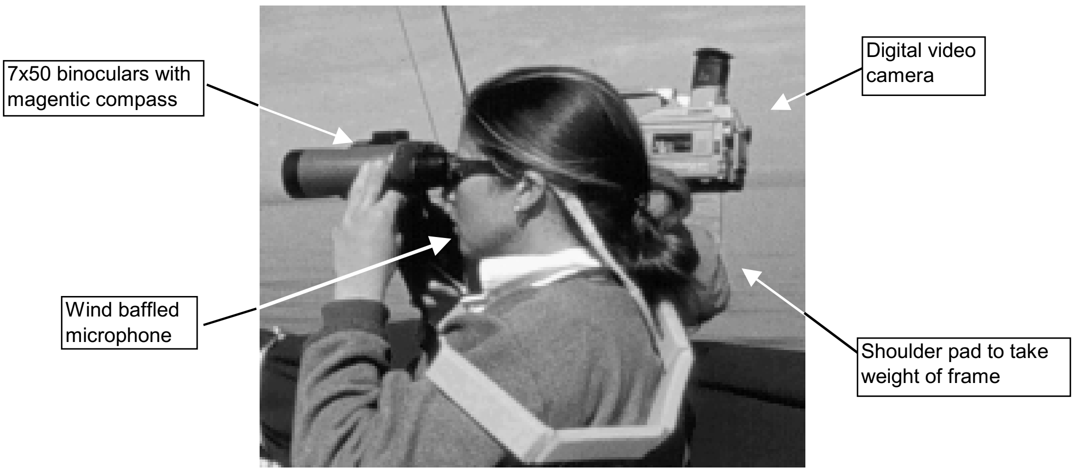

Fig. 3. Use of rigid frame to hold video camera and 7×50 binoculars. A downward pointing digital still camera (not shown here) was also attached below the binoculars for taking bearings relative to reference points on deck.

field of view this minimum distance will be approximately proportional to the observation height. For example, the 2.70° vertical field of view limited the closest range at which distances could be measured to around 400m from an 18.3m high platform.

During right whale (*Eubalaena australis*) tracking studies, the vessel followed the subjects, so maximising the range of detection was not an important consideration. The focal length of the lens was set to give a vertical field of view equivalent to the 7×50 binoculars (7°). Increasing the field of view allows distances to be measured to closer whales but limits the maximum range of detection and could result in some loss of accuracy at greater distances. It is quite possible to change the focal length of the lens during a tracking sequence provided that images of a calibration object at known distance are obtained each time it is changed.

Mounting video on 25 × 150 'Big Eye' binoculars

The large size and solid support stands of these binoculars make it relatively easy to attach a camcorder to them without affecting their normal functionality. A robust pan and tilt tripod head was bolted to a rigid support and this was attached to the lens barrels using hose clips. A quick release shoe in the tripod head, which allows cameras to be removed and replaced without needing realignment, was useful. A 72.8mm lens and 2x tele-converter was used. This gave a field of view of 2.66° horizontally and 1.91° vertically. Mounted on top of big-eye binoculars, the video camera was some 25cm above the observer's height of eye and quite inaccessible. This resulted in some practical difficulties in assuring that the camera was aligned and was correctly configured and functioning. A useful addition, which was available on one cruise, was a video monitor allowing the operator to check camera alignment. A system with a separate video camera on top of the binoculars and a video recorder or computer capture device at deck level would be advantageous. 'Big eye' stand-mounted video was used by JG on three days during a NMFS Gulf of Maine/Bay of Fundy harbour porpoise abundance survey, Cruise No. AJ 99-02, in July 1999. This survey was conducted from the 30m research vessel *Abel-J* with a lens height of 8.4m above sea level. The system was also used from the NOAA ship *Gordon Gunter* (length 68m, camera height 14.2m) during an inter-agency cruise in July 2000 to study sperm whales in the Gulf of Mexico.

Measurement of bearings

If the vessel is constructed from non-magnetic material then a magnetic sighting compass can provide bearings directly with a good level of accuracy. These are built-in to some suitable models of binoculars. Steel vessels distort the earth's magnetic field to an extent that varies with location on the boat, and also with the vessel's heading. This makes the use of magnetic sightings compasses unreliable on such platforms so that indirect methods of determining bearing are needed. Two pieces of information are required: (1) the vessel's heading; and (2) the bearing to the target relative to the ship. Vessel heading will be provided (usually in computer readable format) by a gyro-compass on most large vessels. On smaller boats the net movement over ground of the vessel provided by a GPS navigator may have to be used. However, there are two potential sources of error. In a cross-current, the vessel's heading through the water will be different from the direction of movement over the ground provided by the GPS. Secondly, the 'heading' provided by a GPS represents the net movements between fixes and small heading changes in between these will not be represented. For a vessel attempting to steer a straight course, variation in heading will tend to be greater the smaller the vessel. A high quality gyro-compass attached to the camera and binoculars could give the best results but these tend to be heavy and expensive and we have not attempted to incorporate these into hand-held equipment.

Powerful binoculars, such as 'Big Eyes' need to be supported and they are usually firmly mounted in a good viewing position on an adjustable stand incorporating some degree of vibration isolation. 'Big Eye' stands also incorporate a ring showing relative bearing. When using video techniques with 'Big Eyes', relative bearings were read, to the nearest degree, from the bearing ring on the stand and this was spoken onto the voice track of the tape. It should be relatively easy to improve this system by measuring and recording bearing automatically (a wind direction sensor with computer readable output could be adapted for this purpose for example). The continuous stream of bearing data that this would provide could also be used to investigate observer scanning patterns.

There are disadvantages to using smaller binoculars on rigid stands. The human body is very efficient at motion compensation and a rigid stand does not allow flexible movement to compensate for the pitch and roll of the vessel. In addition, the observer is also unable to move position to get a better view of a sighting or move around to reduce fatigue. Thus, a system that allowed as much freedom of movement as possible was developed. This involved putting reference marks on the deck in the form of lines running fore and aft and taking a photograph using a downward-pointing digital still camera every time a bearing was required. The camera also recorded the time to the nearest second. The reference marks should extend over a sufficiently large area of deck to provide coverage wherever the observer is likely to stand.

Analysis to obtain distances and bearings

The first stage of analysis was usually to view the video sequences and use simple event recording software to log events from the verbal commentary. Individual frames or sequences of video were then captured using commercially available digital video capture cards and software, and stored on the computer so that the best quality image in any surfacing sequence could be selected. A dedicated software program written in *Microsoft* Visual Basic was used to analyse these images. The software was designed to reduce the number of keystrokes required in processing each image and to write the data to a database. For each sequence this involved making the appropriate measurements of the size of the calibration target then using the mouse to click on the sea surface at the object of interest and two points on the horizon. Analysis of digital still images to determine relative bearing was performed using another Visual Basic program. Bearing and ship's heading data were related to distance measurements by their time stamp.

Calibration tests

A number of different calibration tests have been performed to investigate the accuracy of the system from different platform heights under different conditions. The tests reported here are from a 14m auxiliary powered sailing vessel, *Song of the Whale*, in coastal waters (Bay of Fundy, Canada) giving an eye height of 4m, and from a 99m long oceanographic vessel (*James Clark Ross*) in the Southern Ocean with an eye height of 18.3m. Bearings from the *Song of the Whale* which is constructed of fibreglass, could be measured using the magnetic compass, whereas on *James Clark Ross* bearings were measured relative to the ship using the digital still camera.

Tracking from small vessel using magnetic bearings
The calibration tests from *Song of the Whale* were performed with either a buoy in the water or a small inflatable boat with a radar reflector. Distances were obtained using LEICA GEOVID 7 × 42 BD infrared binoculars which have a specified accuracy of ±2m, or by radar. Distances using the infrared binoculars could be obtained easily up to 2-300m. At distances of 3-600m it became more difficult to get a good reflection from the target resulting in fewer data points. The radar was used for all distances greater than 600m. Observations using the radar involved the boat approaching the target at a steady rate. A simple linear regression of distance against time was applied to the individual radar distance measurements. This reduced the effects of errors in individual measurements and allowed interpolation between measurements.

No systematic tests were conducted to assess the accuracy of bearings derived from compass binoculars in the field but this is a system that has been used for many years for navigation of small craft. From a steady platform it is reasonable to expect such bearings to be within ±1° and from small craft under moderate conditions bearings within ±3° are usually achieved. For this analysis, bearing errors were assumed to be normally distributed with a mean of 0 and a standard deviation of 2°. Over the distances at which right whales were observed (mean of 360m) this contributed to a root mean square (RMS) error of 13m in distance from true position. This makes errors in bearing a relatively minor component of location error compared to errors in distance from a small vessel with a low observation height.

The accuracy of the positions obtained from the GPS receiver was assessed from position readings at a fixed location close to the study area. The overall RMS error in distance from true position was 31.2m. The RMS error in distance between pairs of locations taken five minutes apart was 41.0m. These GPS positions were obtained at a time when the accuracy of the system had been deliberately down-graded. The removal of selected availability will improve the accuracy of standard GPS receivers considerably. Accuracy of within a few metres would be possible using a differential GPS system in areas where this is available.

During the study of whale response to vessels, it was sometimes possible to use a combination of the video system and laser range-finding binoculars to continue data collection even when no horizon was visible. This was achieved by using the range-finding binoculars to obtain distances to vessels which were close enough to the whale that both were in the field of view of the camera. The vessel at known distance could then be used as a reference for analysis of video images (e.g. DeNardo *et al.*, 2001). The range-finding binoculars could be used to obtain distances to vessels, which presented a large reflective target, at up to 1,000m. However, distances to right whales could only be obtained using the laser binoculars when the whales were closer than 2-300m.

Tracking from large vessel using photogrammetric bearing
In order to test the accuracy of positions derived from the *James Clark Ross* using photogrammetric measurements of both distance and bearing, small icebergs or 'growlers' were tracked from ahead of the vessel until the closest point of approach when they came abeam. Using the position measured at the closest point of approach as the estimate of true location, the errors for the positions measured at greater distances were estimated. This effectively gives an upper bound on the error since any motion of the ice due to wind or currents would be counted as measurement error. In some cases when the ship was in areas with large amounts of ice, frequent course changes were required. Although the reading from the gyro-compass was recorded every time a bearing was taken, it was found that the errors on the bearing measurements were rather greater when the ship did not steam a straight track for the duration of the tracking experiment. The ship's position was recorded to a high degree of accuracy using multiple differential GPS receivers.

RESULTS

Accuracy of distances

Distance measurements from large oceanographic vessel
Fig. 4 shows the overall distribution of errors in distance measured from the *James Clark Ross* including the corrections for refraction. These are approximately normal with mean of –3m ($\sigma^2 = 11$). Thus, the mean was not significantly different from 0, suggesting no evidence of overall bias in the distance measurements.

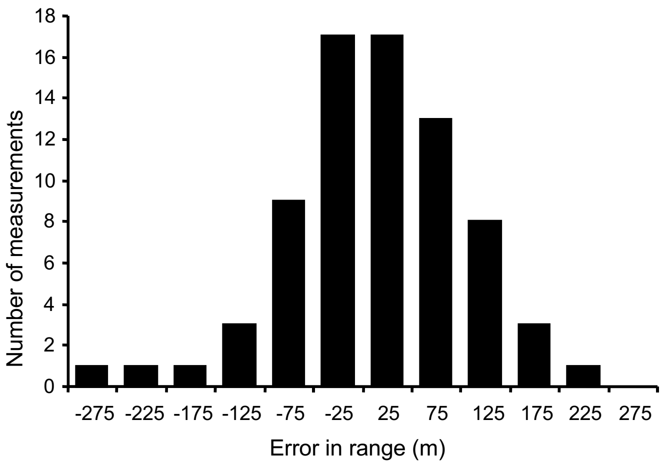

Fig. 4. Distribution of errors in distance from 'growler' tracks. Hand-held frame. 18m eye height.

If refraction was ignored, then the mean error was minus 98m ($\sigma^2 = 31$) suggesting a bias over the distances for which calibration tests were conducted. This resulted in a mean error of –5.1%. This bias will increase with increasing distance. The observed mean bias of –5.1% from the calibration tests agrees well with the values predicted by the refraction model of –6.8% at 8km, –4.0% at 5km and –2.2% at 2km. The simple model for refraction used in this study would appear to give good results but the method may still be susceptible to errors due to refraction in unusual atmospheric conditions such as strong temperature inversion.

Fig. 5 shows the overall RMS error taken from data from seven different tracking experiments with wind speeds in the range 5-13ms^{-1} (Beaufort 3-6) and estimated swell heights in the range 1-3m (i.e. typical survey conditions). The RMS error is approximately linear with distance with relationship RMS error = 0.033 distance. This gave an approximate 95% confidence interval for distance estimates of +6.5%.

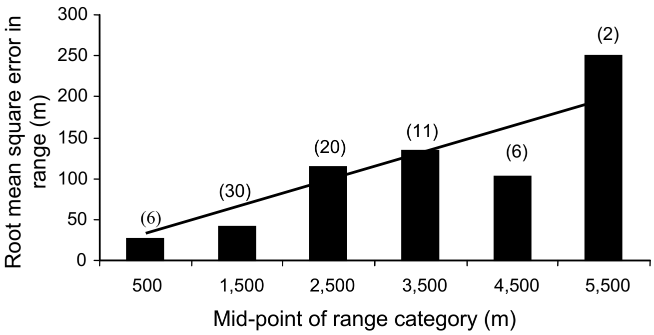

Fig. 5. Mean RMS error in distance estimates to 'growlers' for different distance categories (numbers in brackets indicate sample sizes). Hand held frame, 18m eye height.

Distance measurements from small research vessel

Fig. 6 shows data collected from the deck of *Song of the Whale* with an eye height of 4m. Whale location data can clearly only be collected at closer distances from smaller vessels with lower vantage points and the majority of data were collected within 500m of the whale. In this case the approximate relationship between RMS distance error and distance was RMS error = 0.08 distance. This gave an approximate 95% confidence interval for distance estimates of +16%.

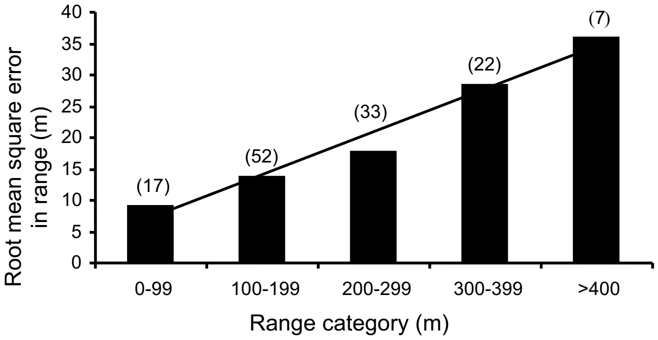

Fig. 6. Combined RMS error for different distance categories from calibration experiments. Hand-held frame. Data from *Song of the Whale* with an eye height of 4m. Numbers in brackets indicate sample sizes.

These two calibration tests from very different vessel types and platform heights give an indication of the range of accuracy that can be achieved. The main controlling factors on distance error will be platform height and the effects of waves and swell. These results are consistent with Gordon (2001) who found that errors in distance were approximately inversely proportional to platform height and lower from larger more stable vessels.

Accuracy of photogrammetric bearings

For fixed targets with the vessel moored alongside a quay, the RMS error in bearing measurement was 0.37° and this error should be considered as the limit to the accuracy of the system in terms of measuring bearing relative to the ship. The RMS error in bearing measurements at sea ranged from 0.6-1.7° for tracks where the ship made no course alterations, and the overall RMS error was 1.21°. For tracks during which the ship altered course, RMS errors were as high as 3.2°. This was most likely due to timing errors between obtaining correct gyro-compass readings and bearing measurements but the cause of these errors was not identifiable. For the ship steaming in a straight line, the mean RMS variation in gyro-compass readings was 0.5° with swell height and orientation being the main factor affecting the variation in heading. These results suggest that the current system achieved close to the maximum accuracy that can be achieved from a moving vessel at sea.

Practical use of the system to track cetaceans

Examples of the use of the system for tracking whales are given in Figs 7-10. These examples illustrate the type of data that can be obtained tracking right whales from a small vessel (Fig. 7) and humpback whales from a large vessel (Fig. 8). Fig. 7 shows an example of the track of a right whale over a period of four hours during which time it was approached several times by whalewatching vessels.

Fig. 8 shows the track of a group of three humpback whales that were followed from the *James Clark Ross* during an experimental small-scale study during the IWC/CCAMLR survey. The boxes around each position represent the standard deviation of the errors in distance and bearing derived from the calibration tests. The numbers in boxes refer to the time in minutes from the start of the tracking sequence with dotted lines linking the position of the vessel with the corresponding whale location. The plot illustrates the change in accuracy of the whale locations with distance from the vessel. One of the proposed components of the SOWER 2000 programme included small-scale studies to relate krill distribution to whale movements. This short experiment showed that the video system could be a useful tool for such work in that it would allow accurate mapping of the whale movements in relation to concentrated krill patches located by the ship's echo-sounders.

The tracking data shown in Figs 7 and 10 were collected when the vessels were manoeuvring to follow the whales. This meant that the whales remained well within distances at which they could be easily detected on video images. Successful tracking studies have also been conducted in this way with minke whales. Sperm whales also proved easy to locate and track using the 'Big Eye' mounted system in the Gulf of Mexico.

Use of system for line transect survey

The requirements for tracking whales during sightings surveys are more demanding because of the need to determine the location of the initial sighting. Fig. 10 shows an example of tracking a group of fin whales under survey conditions. In this case the first location obtained was within a few seconds of the initial detection by the observer. However, there were situations in which whales could not be detected on video at the same distance that they could be seen by visual observers and also occasions where the initial surfacing sequence was not captured. The maximum distances of detection of different species that have been made using the hand-held and 'Big Eye' systems are given in Table 1. These do not necessarily represent the maximum under optimum conditions but do give an idea of the likely effective distance under good conditions. In general, it appeared that the distance at which measurements could be made from the video using a lens equivalent to the field of view of the 7 $\times$ 50 binoculars were roughly the same as the distance at which whales could be detected with the naked eye.

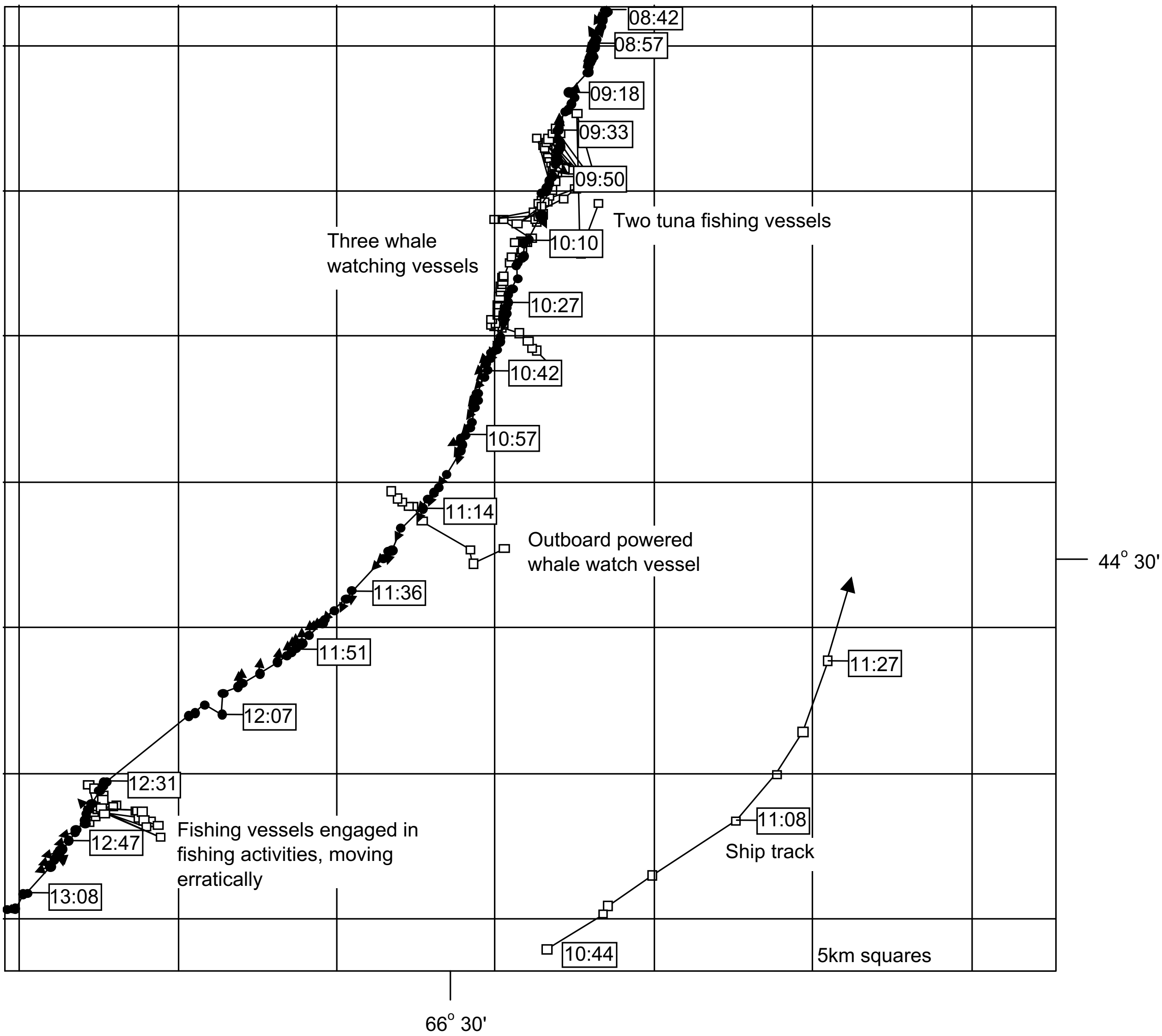

Fig. 7. Track of right whale and other vessels in the Bay of Fundy. Tracked from *Song of the Whale*.

The tests of the system during the IWC/CCAMLR survey were not part of the primary data collection tasks of relaying reticle and angle board readings to a data recorder via a hand-held radio (Reilly *et al.*, 2000). The observer's other duties meant that it was not possible to evaluate the proportion of encounters for which distances would have been successfully obtained by video had this been the primary method of data collection. In practice, use of the video system was found not to interfere with the collection of other data.

During the 1999 NMFS harbour porpoise abundance cruise, video was used to locate animals beyond the view of the primary sightings team and track them as the boat moved past them; this exercise was a feasibility trial and the video data did not contribute to the final abundance analysis. This provided suitable data for mark-recapture line transect methods (e.g. Borchers *et al.*, 1998). Data were only collected in good sighting conditions with a sea state of less than three. It was found that, provided a good commentary was spoken onto the tape, the cues of distant porpoises could be identified on the tape and accurate measurements made. These were often very small features on the captured image and without the benefit of a commentary they could not have been identified as porpoises with any confidence. Fig. 9 shows some of the tracks obtained during this exercise. Although porpoises were the focus of this survey, several other species were also sighted and the maximum distances for these are shown in Table 1.

DISCUSSION

Under suitable conditions, the system described here allows whales to be located and tracked from vessels at sea, with a measurable degree of accuracy, using standard, readily available equipment. As with the use of reticle binoculars, the method described relies on a clear horizon to enable distances to be measured. Nevertheless, the system offers considerable advantages over methods that rely solely on observer estimates of distance. The methods described are by no means the only way of making such measurements and the capability of systems will undoubtedly improve with the rapid development of digital imaging technology. However, we believe that the results obtained are sufficiently encouraging for there to be no reason to wait for improved technology before incorporating this level of instrumentation into standard survey design. Many researchers are understandably reluctant to adopt new survey methodologies if these complicate comparison with previous datasets. This system merely provides the data that existing methods require but with a higher degree of accuracy. Further, the

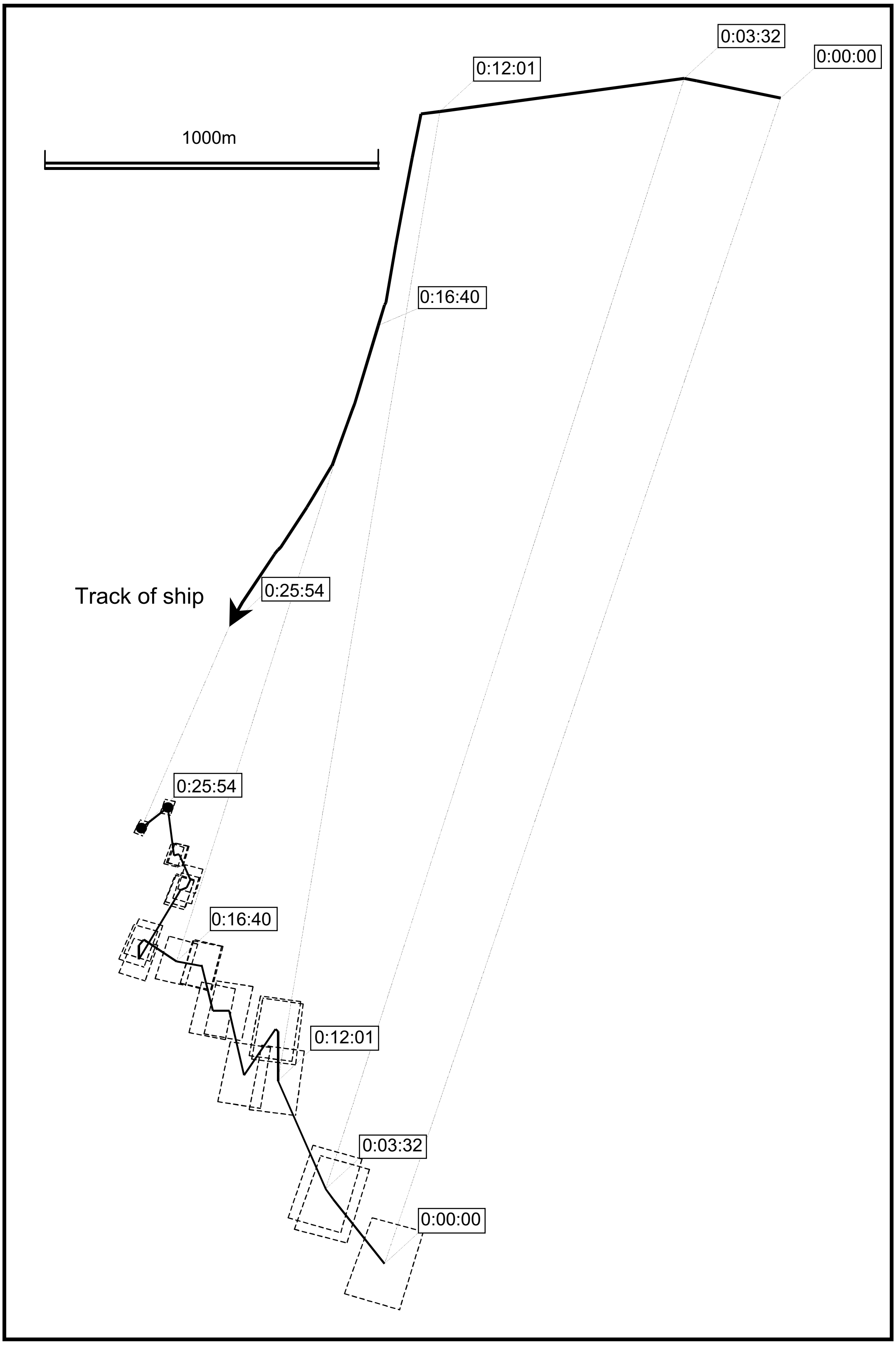

Fig. 8. Track of humpback whale group during small scale study in Southern Ocean. Dotted lines link ship's position at a particular time to whale location at the same time. The boxes around each position represent the standard deviation of the errors in distance and bearing derived from the calibration tests. Tracked from *James Clark Ross.*

experimental use of the system during the IWC/CCAMLR survey demonstrated that it could be used by an observer who was additionally collecting data visually using an angle-board and reticle binoculars.

For sightings surveys, the ranges at which the radial distance of the initial detection can be measured will clearly be an issue for the utility of the system. It is difficult to establish the distances at which detections are made visually but cannot be measured because they are not detected on the video image. However, it is inevitable that depending on weather conditions and the species being studied, the video system will only provide distances for a certain proportion of the initial sightings made during a survey. The focal length of the lens used with the 7 $\times$ 50 binoculars provided a

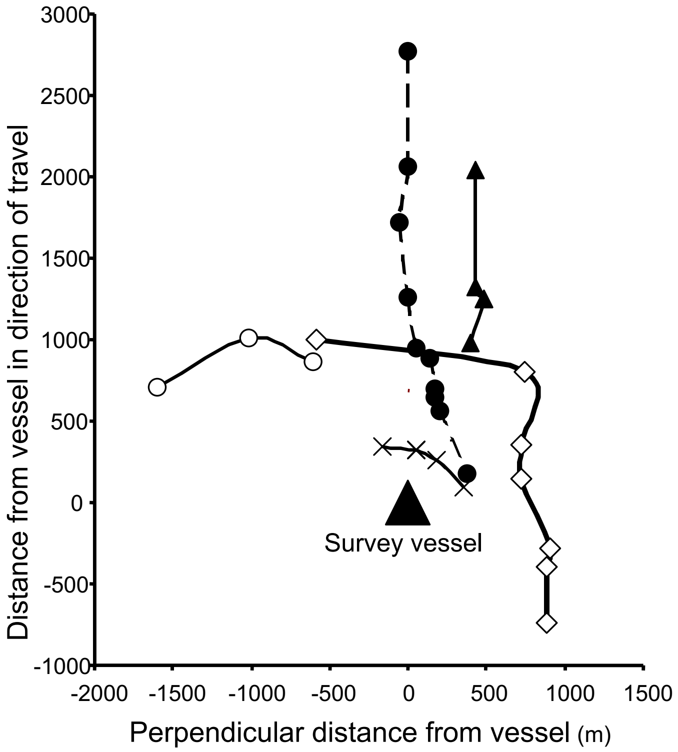

Fig. 9. Tracks of harbour porpoises, from *Abel-J* using video camera mounted on ‘Big Eye’ binoculars. Porpoise locations are shown relative to the survey vessel with different symbols representing different encounters.

vertical resolution of 3.5 pixels per minute of arc. This is theoretically better than the typical one cone per minute of arc in the human eye (Spillman and Werner, 1990). However, the performance of the human eye is enhanced by hyper-acuity (the ability to resolve objects subtending angles smaller than the theoretical resolution). The enhanced performance of the human eye relative to the current video system is offset by the fact that the observer needs sufficient visual cues to determine that the sighted object is in fact a surfacing cetacean whereas distance measurement just requires that the sighting can be located on the video image. It is likely that within the next few years, digital imaging technology will have advanced sufficiently that the quality of image obtained can match that of the human eye for an equivalent field of view. The use of computer based systems to store video data will also enable images to be stored prior to the observer responding to the sighting. This will ensure that initial surfacings are not missed because of delays in operating the equipment.

These techniques are particularly appropriate for survey methods that require tracking of whales subsequent to the initial detection. These methods frequently require additional personnel to act as data recorders as well as the observers. This adds to the expense, and the number of berths required on the survey vessel may also be a limiting factor. There are also practical problems and the potential for error when observers have to relay data to a second person. The video system allows the complete dataset to be recorded without observers taking their eyes from the binoculars. For behavioural studies, the fine scale data on movements and behaviour from a large number of animals that this technique can provide is complimentary to sparser, coarse-scale data from only a few individuals from VHF and satellite telemetry, and may also assist with interpretation of these data.

An unavoidable overhead of the video system is the time required for analysis. However, for some surveys the difficulties of accounting for measurement error have necessitated considerable additional analysis effort (e.g. IWC, 1997). The specially written software reduces the number of keystrokes required for analysis of video images to a minimum and writes the data into a database automatically. On average, for a number of different operators and a number of different sequences, it took about two hours to analyse each hour of video. On a survey with a high sighting rate, such as the Gulf of Maine porpoise survey, around one hour of video was collected each day. The additional analysis time can be offset against the time required to analyse datasets using visual estimates that are subject to a much greater degree of estimation error. The effort and financial expenditure expended in any ship-based sightings survey is likely to more then justify these small overheads if they contribute to a significant increase in the quality of the survey’s primary data.

During the process of testing the video system, the use of laser binoculars to measure distance to cetaceans was evaluated. In theory, laser-based devices have a number of potential advantages over the video system. There is no need for a clear horizon or an elevated viewing platform and instant readings can be obtained. However, obtaining a reading from a surfacing cetacean requires considerable skill and distances appeared to be limited to a few hundred metres

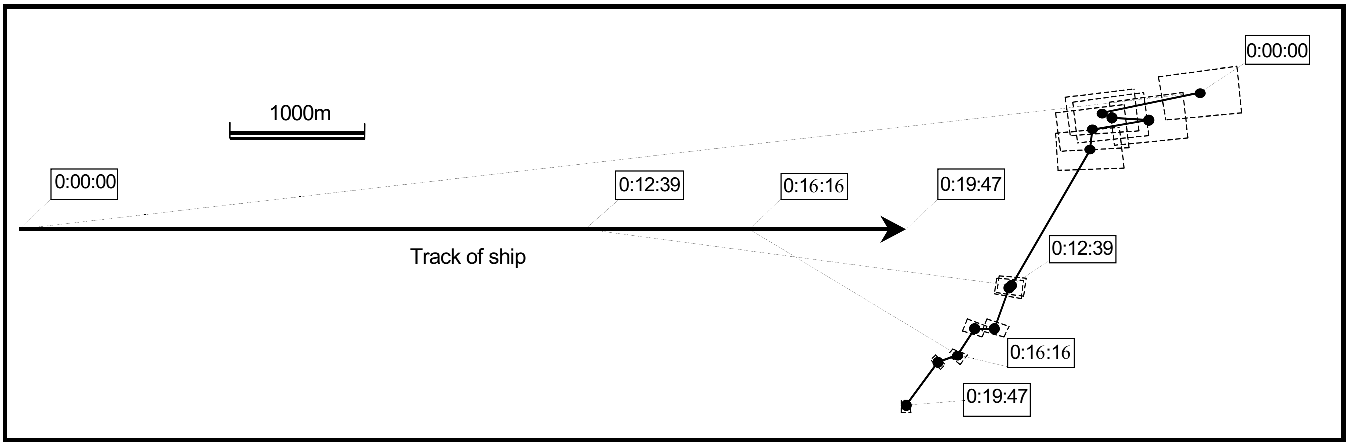

Fig. 10. Track of fin whale group during survey transect. Dotted lines link ship’s position at a particular time to whale location at the same time. The boxes around each position represent the standard deviation of the errors in distance and bearing derived from the calibration tests. Tracked from *James Clark Ross*.

Table 1

Maximum distances at which most visual cues from different species were measured under optimum sighting conditions.

		Maximum distance (km)	
Species	Cue	Shoulder mount system (2.7° vertical field of view)	'Big Eye' system (1.8° vertical field of view)
North Atlantic minke	Body	1.3	3.7
Southern bottlenose whale	Body	1.5	
Harbour porpoise	Body		2.8
White-sided dolphin	Splash		2.5
Southern right	Blow	3.3	
Killer whale	Blow	2.6	
Fin whale	Blow	8.8	7.9
Humpback whale	Blow	6.9	
Sei whale	Blow	3.5	
Sperm whale	Blow	3.9	8.0

even for large whales. There is also considerable scope for obtaining precise readings from false targets and these errors would be very difficult to quantify.

The model used to predict refraction has implications for other surveys that rely on measurements of distance using reticle binoculars. If refraction is not allowed for, then distances will be negatively biased, resulting in a positive bias in abundance estimates. Although the effects of refraction are relatively small in relation to the likely errors in reticle readings, there is nevertheless the possibility of a consistent bias of several percent depending on the distances at which most observations are made.

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