7

Study design and field methods

7.1 Introduction

The analysis methods presented in Chapters 3–5 depend on proper field methods, a valid design, and adequate sample size. This chapter presents broad guidelines for the design of a distance sample survey and outlines appropriate field methods. In general, a statistician or quantitative person experienced in distance methods should be consulted during the initial planning and design of the study. Just as important is the need for a pilot study. Such a preliminary study will provide rough estimates of the encounter rate n/L (line transect sampling) or n/k (point transect sampling), and of variance components from which refined estimates of n and of L or k for the main study are obtained. Additionally, operational considerations can be reviewed and training of participants can occur. **A pilot study is strongly recommended as it can provide insights into how best to meet the important assumptions.**

Careful consideration should be given to the equipment required to allow collection of reliable data. This may include range finders, binoculars with reticles, angle boards or rings, a camera, a compass, and various options for an observation platform, which might vary from none (i.e. one pair of feet) to a sophisticated aircraft or ship, or even a submersible (Fig. 7.1).

The primary purpose of material presented in this chapter is to ensure that the critical assumptions are met. Considerable potential exists for poor field procedures to ruin an otherwise good survey. Survey design should focus on ways to ensure that three key assumptions are true: $g(0) = 1$, no movement in response to the observer prior to detection, and accurate measurements (or accurate allocations to specified distance categories). If the population is clustered, it is important that cluster

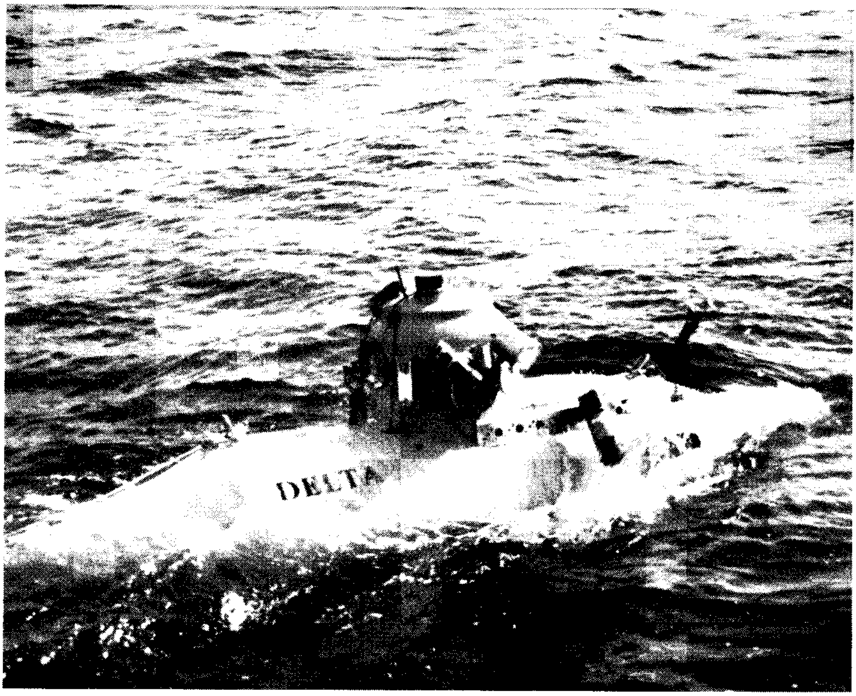

Fig. 7.1. Line transect sampling can be carried out from several different types of observation platform. Here, a two-person submersible is being used to survey rockfish off the coast of Alaska. Distances are measured using a small, hand-held sonar gun deployed from inside the submersible.

size be determined accurately. In addition, a minimum sample size (n) in the 60–80 range and $g(y)$ with a broad shoulder are certainly important considerations. Sloppiness in detecting objects near, and measuring their distance from, the line or point has been all too common, as can be seen in Section 8.4. In many line and point transect studies, **the proper design and field protocol have not received the attention deserved**.

Traditional strip transects and circular plots should be considered in early design deliberations. These finite population sampling methods deserve equal consideration with the distance sampling methods. However, if there is any doubt that all objects within the strip or circle are detected, then distances should be taken and analysed (Burnham and Anderson 1984). The tradeoffs of bias and efficiency between strip transects and line transects have been addressed (Burnham *et al.* 1985). Other sampling approaches should also be considered; Seber (1982, 1986) provided a compendium of alternatives and new methods are occasionally developed, such as adaptive sampling (Thompson 1990). A common alternative for animals is capture–recapture sampling, but Shupe *et al.* (1987) found that costs for mark–recapture sampling exceeded those of walking line transects by a factor of three in rangeland studies in Texas. Guthery (1988) presented information on time and cost requirements for line transects of bobwhite quail.

If all other things were equal, one would prefer line transect sampling to point transect sampling. More time is spent sampling in line transect surveys, whereas more time is often spent travelling between and locating sampling points in point transect sampling (Bollinger *et al.* 1988). In addition, it is common to wait several minutes prior to taking data, to allow the animals (usually birds) time to readjust to the disturbance caused by the observer approaching the sample point. Point transect sampling becomes more advantageous if the travel between points can be done by motorized vehicle, or if the points are established along transect lines, with fairly close spacing (i.e. rather than a random distribution of sampling points throughout the study area). If the study area is large, the efficient utilization of effort may be an order of magnitude better for line transect surveys. This principle is reinforced when one considers the fact that it is objects on or near the line or point that are most important in distance sampling. Thus, in distance sampling, the objects seen at considerable distances (i.e. distances y such that $g(y)$ is small, say less than 0.1) from the line or point contain relatively little information about density. In point transect surveys, the count of objects beyond $g(r) = 0.1$ may be relatively large because the area sampled at those distances is so large.

Point transect sampling is advantageous when terrain or other variables make it nearly impossible to traverse a straight line safely while also expending effort to detect and record animals. Multispecies songbird surveys in forest habitats are usually best done using point transect sampling. Point transects may often be more useful in patchy environments, where it may be desirable to estimate density within each habitat type; it is often difficult to allocate line transects to allow efficient and unbiased density estimation by habitat. One could record the length of lines running through each habitat type and obtain estimates of density for each habitat type (Gilbert *et al.* in prep.). However, efficiency may be poor if density is highly variable by habitat type, but length of transect is proportional to the size of habitat area. Additionally, habitat often varies continuously, so that it is more precisely described at a single point than for a line segment. Detection may be enhanced by spending several minutes at each point in a point transect, and this may aid in ensuring that $g(0) = 1$. Remaining at each point for a sufficient length of time is particularly important when cues occur only at discrete times (e.g. bird calls). Some species may move into the sample area if the observer remains at the site too long. Even in line transect sampling the observer may want to stop periodically to search for objects.

7.2 Survey design

Survey design encompasses the placement (allocation) of lines or points across the area to be sampled and across time. The population to be sampled must be clearly defined and its area delimited. A good map or aerial photo of the study area is nearly essential in planning a survey. An adequate survey must always use multiple lines or points (i.e. replication). Consideration must be given to possible gradients in density. If a substantial transition in density is thought or known to exist, it is best to lay the lines parallel to the direction of the gradient (Fig. 1.4). This would also be true if points were to be placed systematically along lines. Alternatively, spatial stratification of the study area might be considered. For example, if two main habitat types occurred in the area of interest, one might want to estimate density in each of the two habitat types. A consideration here is to be sure that adequate sample size is realized in both habitat types. If little is known *a priori*, the strata (i.e. habitat types) should be sampled in proportion to their size. Detection probability often varies with topography, habitat type, and density of objects of interest. Proper design, such as the approaches suggested below, will cope with these realities.

It was often thought that an observer could roam through an area and record only the sighting distances r_i to each object detected. This type of cruising may lead to nearly useless data and unreliable density estimates (Burnham *et al.* 1980; Hayes and Buckland 1983).

7.2.1 Transect layout

Several options exist for the layout of individual lines in a line transect survey or points in a point transect survey. A favoured and practical layout is a systematic design using parallel transects, with a random first start (e.g. Figs 1.4 and 1.6). Then transects extend from boundary to boundary across the study area and are usually of unequal length. Transects are normally placed at a distance great enough apart to avoid an object being detected on two neighbouring transects, although this is not usually critical. Care must be taken such that the transect direction does not parallel some physical or biological feature, giving an unrepresentative sample. For example, if all the lines were on or near fence rows, the sample would be clearly unrepresentative (Guthery 1988).

A common mistake is to have lines follow established roads or corridors. If there is a strong density gradient perpendicular to a linear physical feature, then a design in which lines are parallel to this gradient, and hence perpendicular to the linear feature, should be considered.

A second approach might be to lay out a series of contiguous strips of width $2w$, pick k of these at random, and establish a line or point transect in the centre of each selected strip. Thus, transects would be parallel, but the spacing between transects would be unequal. In some sense, theory would suggest that a valid estimate of the sampling variance could be obtained only with a completely random sample. However, the precision of the systematic sample is often superior to random sampling. There is no compelling reason to use randomly placed lines or points, although a grid of lines or points should be positioned randomly, and oriented either randomly or perpendicular to density contours. Designs that permit overlapping transects should probably be avoided except in specialized cases; this requirement limits the number of possible layouts. Also, designs that require extensive and time-consuming travel between transect lines or points are inefficient.

A third approach is to establish a system of rectangles, whereby the observer travels the perimeter searching for objects along the line or around the points along the line (Fig. 7.2). This allows, for example, an observer on foot to return to a vehicle without losing time walking between transects. This design may be advantageous where a system of roads exists on the study area. The position of the sample rectangles can be selected in several ways (e.g. the southwest corners of the rectangles could be selected at random or they could be placed systematically with a random first start). Many parts of central and western North America have roads on a 1-mile grid, 'section lines', making this design easy to implement in the field.

Transects should not be deliberately placed along roads or trails, as these are very likely to be unrepresentative. Transects following or paralleling ridgetops, hedgerows, powerlines, or stream bottoms are also likely to be unrepresentative of the entire area. We strongly recommend against biasing samples towards such unrepresentative areas. Transects placed subjectively (e.g. 'to avoid dense cover' or 'to be sure the ridge is sampled') are poor practice, and should always be avoided.

The design of point transects would best be done, from a statistical viewpoint, completely randomly (ignoring, for the moment, any need to stratify). This follows from sampling theory whereby the layout of plots (circular or rectangular) should be placed at random. However, in this random design, the amount of time to travel from point to point is likely to be excessive and occasional pairs of points may be quite close

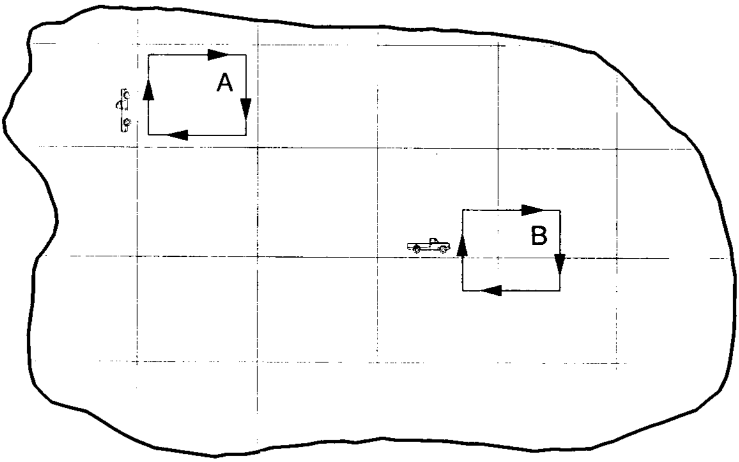

Fig. 7.2. A practical design for line or point transect surveys is to establish a series of rectangles for which the perimeters (or points along the perimeter) are sampled. This design is useful when a network of roads exists on the study area. **A** might be appropriate for surveys where density in undisturbed habitats is of interest, while **B** would be useful in studies of the entire area. Many landscapes have extensive habitat along roads and associated roadsides, fence rows, borrow pits, etc. Perimeter areas to be surveyed can be established at random or systematically with a random first start.

together. This consideration has led ornithologists, in particular, to place a series of points along a transect line. Thus, there might be 20 lines, each having, say, 10 sampling points. These should not be analysed as if they are 200 independent samples; one must be certain that the estimated sampling variance is correctly computed, by taking the transect line of 10 points as the sampling unit. Points could be established at grid intersections of a rectangular grid to achieve a systematic design. Again, the problem here might be the amount of time required to travel from point to point. One might spend 30 minutes walking between successive points and only 5–10 minutes sampling objects at each point.

Detection probability often varies with topography, habitat type, and the density of objects of interest. Proper design, such as the approaches suggested above, will cope with these realities.

If the survey is to be repeated over time to examine time trends in density, then the lines or points should be placed and marked permanently. Sampling of duck nests at the Monte Vista National Wildlife Refuge has been done annually for 27 years using permanent transect markers set up in 1963 (numbered plywood signs atop 2.5 m metal poles). Repeated sampling should be done at time intervals large enough so that the stochastic errors of successive samples are not highly dependent. If an area is to be sampled twice within a short time period, one could consider using a system of transects running north–south on the first occasion and another set of transects running east–west on the second occasion. This scheme, although using overlapping transects, might give improved coverage. However, other schemes might be considered if a strong gradient in density was suspected.

Point transects should also be permanently marked if the survey is to be repeated. One must be cautious that neither the objects of interest nor predators are attracted to the transect markers (e.g. poles and signs would not be appropriate for some studies if raptors used these markers for perching and hunting). A good cover map would aid in establishing sample points and in relocating points in future surveys. In addition, a cover map or false colour infrared image might be useful in defining stratum boundaries.

If there are smooth spatial trends in the large-scale density over an area, then systematically placed lines or points are better than random placement. Ideally, the analysis would fit these trends by some means and derive the variance from the model residuals (Burdick 1979). This topic is addressed in Section 6.3, but is in need of more theoretical development.

No problem arises if a stationary object is detected from two different lines or points. If an animal moves after detection from one line or point to another in a short time period (e.g. the same day), then this may become problematic if it happens frequently and is in response to the presence of the observer. Some sophisticated surveys are designed to obtain double counts of the same object from independent platforms, to allow estimation of $g(0)$ or to correct for the effects of movement (Section 6.4).

7.2.2 Sample size

A basic property of line and point transect sampling theory is that it is the absolute size of the sample that is important when sampling large populations, not the fraction of the population sampled. Thus, if $L = 2400$ m (corresponding to, say, $n = 90$) was sufficient for estimating the density of box turtles on a square kilometre of land, it would also be sufficient for the estimation of density on 25 square kilometres of land (assuming the sampling was done at random with respect to the turtle population). Thus, it would **not** take 25×2400 m of transect to sample the 25 square kilometres area.

The size n of the sample is an important consideration in survey design. If the sample is too small, then little information about density is available and precision is poor. Verner (1985) notes that some surveys have had very small sample sizes ($n \doteq 10$); almost no information about density is contained in so few observations and little can be done regardless of the analysis method used. If the sample is too large, resources might have been used more advantageously elsewhere.

As a practical minimum, n should usually be at least 60–80. Even then, the components of variance associated with both n and $\hat{f}(0)$ (line transects) or $\hat{h}(0)$ (point transects) can be large. If the population is clustered, the sample size (i.e. the number of clusters detected) should be larger to yield similar precision for the abundance estimate of individuals, substantially so if the variance of cluster size is large. If there is a target cv for the density estimate of 25% and $n = 100$ would achieve this for the density of clusters, then a larger n is needed to yield a cv of 25% for the density of individuals. This increase is because variation in cluster size increases the cv of the density estimate for individuals. The variance component associated with cluster size is rarely the largest component.

Sample sizes required are often quite feasible in many survey situations. For example, in aerial surveys of pronghorn (*Antilocapra americana*), it is possible to detect hundreds of clusters in 15–20 hours of survey time. The long-term surveys of duck nesting at the Monte Vista National Wildlife Refuge have detected as few as 41 nests and as many as 248 nests per year over the past 27 years. Effort involved in walking approximately 360 miles per year on the refuge requires about 47 person days per year. Cetacean surveys may need to be large scale to yield adequate sample sizes; in the eastern tropical Pacific, dolphin surveys carried out by the US National Marine Fisheries Service utilize two ships, each housing a cruise leader and two teams of three observers, together with crew members, for 4–5 months annually. Even with this effort, sample sizes are barely sufficient for estimating trends over eight or more years with adequate precision, even for the main stock of interest.

Sample size in point transects can be misleading. One might detect 60 objects from surveying k points and believe this large sample contains a great deal of information about density. However, the area sampled increases with the square of distance, so that many of the observations are actually in the tail of $g(r)$ where detection probability is low. Detections at some distance from the point may be numerous partially because the area sampled is relatively large. Thus, sample size must be somewhat larger for point transect surveys than line transect surveys. As a rough guideline, the sample size for point transects should be approximately 25% larger than that for line transect surveys to attain the same level of precision.

Generally, w should be set large in relation to the expected average distance (either $E(x)$ or $E(r)$). The data can be easily truncated during the analysis, but few (if any) detected objects should be ignored during the actual field survey because they are beyond some preset w, unless distant detections are expensive in terms of resources. For example, dolphin schools may be detected during shipboard surveys at up to 12 km perpendicular distance. These distant sightings add little to estimation and are likely to be truncated before analysis, so that the cost of taking these data is substantial (closing on the school, counting school size, determining species composition) relative to the potential value of the observations. A pilot study would provide a reasonable value for w for planning purposes.

Although we focus discussion here on sample size, the line or point is usually taken as the sampling unit for estimating the variance of encounter rate, and often of other parameter estimates. Thus a sample size of $n = 200$ objects from just one or two lines forces the analyst to make stronger assumptions than a smaller sample from 20 short lines. The strategy of dividing individual lines into segments, and taking these as the sampling units, can lead to considerable underestimation of variance (Section 3.7.4).

(a) *Line transects* The estimation of the line length to be surveyed depends on the precision required from the survey and some knowledge of the encounter rate (n_0/L_0) from a pilot study or from comparable past surveys. Here it is convenient to use the coefficient of variation, $\text{cv}(\hat{D}) = \widehat{\text{se}}(\hat{D})/\hat{D}$, as a measure of precision. One might want to design a survey whereby the estimated density of objects would have a coefficient of variation of 0.10 or 10%; we will denote this target value by $\text{cv}_t(\hat{D})$. Two general approaches to estimating line length are outlined.

First, assume that a small-scale pilot study can be conducted and suppose n_0 objects were detected over the course of a line (or series of lines) of total length L_0. For this example, let $n_0 = 20$ and $L_0 = 5$ km. This information allows a rough estimate of the line length and, thus, sample size required to reach the stated level of precision in the estimator of density. The relevant equation is

$$L = \left(\frac{b}{(\text{cv}_t(\hat{D}))^2}\right)\left(\frac{L_0}{n_0}\right) \tag{7.1}$$

where $$b \doteq \left\{\frac{\text{var}(n)}{n} + \frac{n \cdot \text{var}\{\hat{f}(0)\}}{\{f(0)\}^2}\right\}$$

While a small pilot survey might be adequate to estimate L_0/n_0 for planning purposes, the estimation of b poses difficulties. However, the value of b appears to be fairly stable and Eberhardt (1978b) provided evidence that b would typically be between 2 and 4. Burnham *et al.* (1980: 36) provided a rationale for values of b in the range 1.5–3. They recommended use of a value of 3 for planning purposes, although 2.5 was tenable. They felt that using a value of 1.5 risks underestimating the necessary line length to achieve the required precision. Another consideration is that b will be larger for surveys where the detection function has a narrow shoulder. Here we use $b = 3$ so that

$$L = \left(\frac{3}{(0.1)^2}\right)\left(\frac{5}{20}\right) = 75.0 \text{ km}$$

Equating the following ratios

$$\left(\frac{L_0}{n_0}\right) = \left(\frac{L}{n}\right)$$

and solving for n gives $n = 300$; the proper interpretation here is that we **estimate** that there will be 300 detections given $L = 75$ km, although the actual sample size will be a random variable. Thus, to achieve a coefficient of variation of 10% one would need to conduct 75 km of transects and expect to detect about 300 objects.

A pilot study to estimate L_0/n_0 can be quite simple. No actual distances are required and n_0 can be as small as, perhaps, 10. Thus, one could traverse randomly placed transects of a predetermined length L_0 and record the number of detections n_0 in estimating (L_0/n_0). The value of w used in the pilot study should be the same as that to be used in the actual survey. Alternatively, the ratio might be taken from the literature or from one's experience with the species of interest. Of course, the results from the first operational survey should always be used to improve the survey design for future surveys.

Second, if the pilot survey is quite extensive, then b can be estimated from the data as $\hat{b} \doteq n_0 \cdot (\text{cv}(\hat{D}))^2$ (Burnham *et al.* 1980: 35). From this more intensive pilot survey, the coefficient of variation is computed empirically and denoted as $\text{cv}(\hat{D})$. Substituting $\hat{b}$ into Equation 7.1, the line length required to achieve the target precision is given by

$$L = \frac{L_0(\text{cv}(\hat{D}))^2}{(\text{cv}_t(\hat{D}))^2}$$

For this approach to be reliable, n_0 should be in the 60–80 range; it is perhaps most useful when refining the second year of a study, based on the results from the first survey year.

Many surveys are limited by money or labour restrictions such that the maximum line length is prespecified. Thus, it is advisable to compute the coefficient of variation to assess whether the survey is worth doing. That is, if the $\text{cv}(\hat{D})$ is too large, then perhaps the survey will not provide any useful information and, therefore, should not be conducted. The equation to use is

$$\text{cv}(\hat{D}) = \left(\frac{b}{L(n_0/L_0)} \right)^{1/2}$$

For the example, if practical limitations allowed only $L = 10$ km,

$$\text{cv}(\hat{D}) = \left(\frac{3}{10(20/5)} \right)^{1/2} = 0.274 \text{ or roughly } 27\%$$

The investigator must then decide if this level of precision would adequately meet the survey objectives. If for example $\hat{D} = 100$, then an approximate 95% log-based confidence interval would be [59, 169]. This information might still be useful because the encounter rate is quite high in this example.

If animals occur in clusters, the above calculations apply to precision of the estimated density of clusters. That is, $\hat{D}$ becomes $\hat{D}_s$, the number of animal clusters per unit area. For clustered populations, a pilot survey yields an estimate of the standard deviation of cluster size,

$$\widehat{\text{sd}}(s) = \sqrt{\frac{\sum_{i=1}^{n} (s_i - \bar{s})^2}{n-1}}$$

The coefficient of variation of mean cluster size for a survey in which n clusters are detected is then

$$\widehat{\text{se}}(\bar{s})/\bar{s} = \widehat{\text{sd}}(s)/(\bar{s} \cdot \sqrt{n})$$

For the case of cluster size independent of detection distance, we have

$$\{\text{cv}(\hat{D})\}^2 = \{\text{cv}(\hat{D}_s)\}^2 + \left[\frac{\widehat{\text{sd}}(s)}{\bar{s}} \right]^2 \cdot \frac{1}{n} \tag{7.2}$$

Now we substitute $n = L \cdot (n_0/L_0)$ and $\{\text{cv}(\hat{D}_s)\}^2 = \frac{b}{L} \cdot \frac{L_0}{n_0}$ to get

$$\{\text{cv}(\hat{D})\}^2 = \frac{b}{L} \cdot \frac{L_0}{n_0} + \left[\frac{\widehat{\text{sd}}(s)}{\bar{s}}\right]^2 \cdot \frac{1}{L} \cdot \frac{L_0}{n_0} = \frac{1}{L} \cdot \frac{L_0}{n_0} \cdot \left[b + \left\{\frac{\widehat{\text{sd}}(s)}{\bar{s}}\right\}^2\right]$$

We must select a target precision, say $\text{cv}(\hat{D}) = \text{cv}_t$. Solving for L gives

$$L = \frac{L_0\,[b + \{\widehat{\text{sd}}(s)/\bar{s}\}^2]}{n_0 \cdot \text{cv}_t^2} \tag{7.3}$$

Suppose that a coefficient of variation of 10% is required, so that $\text{cv}_t = 0.1$. Suppose further that, as above, $n_0 = 20$, $L_0 = 5$ and $b = 3$, and in addition $\widehat{\text{sd}}(s)/\bar{s} = 1$. Then

$$L = \frac{5 \cdot (3 + 1)}{20 \cdot 0.1^2} = 100 \text{ km}$$

rather than the 75 km calculated earlier for 10% coefficient of variation on $\hat{D}_s$.

Paradoxically, these formulae yield a more precise estimate of population size for a population of (unknown) size $N = 1000$ animals, for which 50 animals are detected in 50 independent detections of single animals, than for a population of 1000 animals, for which 500 animals are detected in 50 animal clusters, averaging 10 animals each. This is partly because finite population sampling theory is not used here. If it was, variance for the latter case would be smaller, as 50% of the population would have been surveyed, compared with just 5% in the first case. A disadvantage of assuming finite population sampling is that it must be assumed that sampling is without replacement, whereas animals may move from one transect leg to another or may be seen from different legs. Use of finite population corrections is described in Section 3.7.5.

In some studies, animals occur in loose agglomerations. In this circumstance, it may be impossible to treat the population as clustered, due to problems associated with defining the position (relative to the centreline) and size of animal clusters. However, if individual animals are treated as the sightings, the usual analytic variance estimates are invalid, as the assumption of independent sightings is seriously violated. Resampling methods such as the bootstrap (Section 3.7.4) allow an analysis based on individual animals together with valid variance estimation.

(b) *Point transects* The estimation of sample size and number of points for point transect surveys is similar to that for line transects. The encounter rate can be defined as the expected number of detections per point, estimated in the main survey by n/k. Given a rough estimate n_0/k_0 from a pilot survey and the desired coefficient of variation, the required number of sample points can be estimated as

$$k = \left(\frac{b}{(\text{cv}(\hat{D}))^2}\right) \cdot \left(\frac{k_0}{n_0}\right) \tag{7.4}$$

As for line transect sampling, b may be approximated by n_0 multiplied by the square of the observed coefficient of variation for $\hat{D}$ from the pilot survey. If the pilot survey is too small to yield a reliable coefficient of variation, a value of 3 for b may again be assumed. If the shoulder of the detection function is very wide, this will tend to be conservative, but if detection falls off rapidly with distance from the point, a larger value for b might be advisable. Some advocates of point transects argue that detection functions for point transect data are inherently wider than for many line transect data sets, because the observer remains at each point for some minutes, ensuring that all birds within a few metres of the observer are recorded, at least for most species. For line transects, the observer seldom remains still for long, so that probability of detection might fall away more rapidly with distance from the line.

Having estimated the required number of points k, the number of objects detected in the main survey should be approximately $k \cdot n_0/k_0$. Suppose a pilot survey of 10 points yields 30 detected objects. Then, if the required coefficient of variation is 10% and b is assumed to be 3, the number of points for the main survey should be $k = (3/0.1^2) \cdot (10/30) = 100$, and roughly 300 objects should be detected.

The above calculations assume that the points are randomly located within the study area, although these procedures are also reasonable if points are regularly spaced on a grid, provided the grid is randomly positioned within the study area. If points are distributed along lines for which separation between neighbouring points on the same line is appreciably smaller than separation between neighbouring lines, precision may prove to be lower than the above equations would suggest, depending on variability in density; if objects are distributed randomly through the study area, precision will be unaffected.

Point transects have seldom been applied to clustered populations, although no problems arise beyond those encountered by line transect sampling. Equation 7.2 still applies, but the expression $n = k \cdot n_0/k_0$ should be substituted, giving

$$\{\text{cv}(\hat{D})\}^2 = \{\text{cv}(\hat{D}_s)\}^2 + \left[\frac{\widehat{\text{sd}}(s)}{\bar{s}}\right]^2 \cdot \frac{1}{k} \cdot \frac{k_0}{n_0}$$

In Equation 7.4, $\{\text{cv}(\hat{D})\}^2$ is replaced by $\{\text{cv}(\hat{D}_s)\}^2$. Solving for $\{\text{cv}(\hat{D}_s)\}^2$ and substituting in the above gives

$$\{\text{cv}(\hat{D})\}^2 = \frac{1}{k} \cdot \frac{k_0}{n_0} \cdot \left[b + \left\{\frac{\widehat{\text{sd}}(s)}{\bar{s}}\right\}^2\right]$$

Selecting a target precision $\text{cv}(\hat{D}) = \text{cv}_t$ and solving for k gives

$$k = \frac{k_0\{b + [\widehat{\text{sd}}(s)/\bar{s}]^2\}}{n_0 \cdot \text{cv}_t^2} \tag{7.5}$$

Continuing the above example, now with clusters replacing individual objects, the number of points to be surveyed is

$$k = \frac{10 \cdot \{3 + [\widehat{\text{sd}}(s)/\bar{s}]^2\}}{30 \cdot 0.1^2}$$

If the pilot survey yielded $\widehat{\text{sd}}(s)/\bar{s} = 1$ (a plausible value), then

$$k = \frac{10 \cdot (3 + 1)}{30 \cdot 0.1^2} = 133$$

so that roughly 133 points are needed.

7.2.3 Stratification

Sampling effort can be partitioned into several strata in large-scale surveys. This allows separate estimates of density in each stratum (such as different habitat types). Sampling can be partitioned into temporal strata during the day or seasonally. Post-stratification can be used in some cases. For example, the individual lines can be repartitioned by habitat type, based on a large-scale aerial photo on which line locations are drawn accurately. Thus, estimates of density by habitat type can be made. For example, Gilbert *et al.* (in prep.) used a geographic information system (GIS) in this manner for the long-term nesting studies of waterfowl at the Monte Vista National Wildlife Refuge.

For stratified survey designs, the formulae for sample size determination are more complex. The starting point for a given stratum is the formula

$$\text{var}(\hat{D}) = D^2 [\{\text{cv}(n)\}^2 + \{\text{cv}(\hat{f}(0))\}^2]$$

Each of the two coefficients of variation is proportional to $1/E(n)$, hence

$$\text{var}(\hat{D}) = D^2 \left[\frac{b_1}{E(n)} + \frac{b_2}{E(n)} \right]$$

where $b_1 = \text{var}(n)/E(n)$ and $b_2 = E(n) \cdot \text{var}\{\hat{f}(0)\}/\{f(0)\}^2$
Now use

$$E(n) = \frac{2LD}{f(0)}$$

to get

$$\text{var}(\hat{D}) = D^2 \left[\frac{(b_1 + b_2) f(0)}{2LD} \right]$$

$$= \left[\frac{D}{L} \right] \left[\frac{(b_1 + b_2) f(0)}{2} \right]$$

If, over the different strata, the detection function is the same, then $f(0)$ and b_2 will be the same over strata. This is often a reasonable assumption. It is plausible that b_1 may be constant over strata; this can be checked by estimating $b_1 = \text{var}(n)/E(n)$ in each stratum. If these conditions hold, then for stratum v,

$$\text{var}(\hat{D}_v) = \left[\frac{D_v}{L_v} \right] K$$

for some K, which can be estimated. To allocate total line length effort, $L = \Sigma\, L_v$, we want to minimize the sampling variance of the estimated total number of objects in all strata, $\hat{N} = \Sigma\, A_v\, \hat{D}_v$, where A_v is the size of area v and summation is over $v = 1, 2, \ldots, V$. If we pretend that each $\hat{D}_v$ is independently derived (it should **not** be under these assumptions), then

$$\text{var}(\hat{N}) = \sum [A_v]^2 \,\text{var}(\hat{D}_v)$$

$$= K \sum [A_v]^2 \left[\frac{D_v}{L_v}\right] \tag{7.6}$$

For fixed L, it is easy to minimize Equation 7.6 with respect to the L_v. The answer is expressible as the ratios

$$\frac{L_v}{L} = \frac{A_v \sqrt{D_v}}{\sum A_v \sqrt{D_v}} \tag{7.7}$$

The total effort L comes from

$$[\text{cv}(\hat{N})]^2 = \left[\frac{K}{L}\right]\left[\frac{\sum A_v \sqrt{D_v}}{\sum A_v D_v}\right]^2 \tag{7.8}$$

Formula 7.7 shows that allocation proportional to $\sqrt{D_v}$ is not unreasonable if stratum sizes are similar. The result in Equation 7.7 is derived under an inconsistency in that given the assumptions made, $f(0)$ should be based on all distance data pooled and the estimators would look like

$$\hat{D}_v = \frac{n_v \cdot \hat{f}(0)}{2L_v}$$

and

$$\hat{N} = \left[\sum_{v=1}^{V} \frac{A_v n_v}{2L_v}\right] \hat{f}(0) \tag{7.9}$$

The first order approximate variance of Equation 7.9 is expressible as

$$\text{var}(\hat{N}) = N^2 \left[\frac{f(0)}{2}\right]\left[\frac{b_2}{\sum L_v D_v} + b_1 \sum \frac{(N_v/N)^2}{L_v D_v}\right]$$

from which we get an expression for the coefficient of variation of $\hat{N}$ in this case of using pooled distances to get one $\hat{f}(0)$:

$$\text{cv}(\hat{N}) = \left[\frac{b_2 f(0)}{2L}\right]\left[\frac{1}{\sum \pi_v D_v} + R \sum \frac{p_v^2}{\pi_v D_v}\right] \tag{7.10}$$

where

$$R = \frac{b_1}{b_2}$$

$$p_v = \frac{N_v}{N} = \frac{A_v D_v}{\sum A_v D_v}$$

and the relative line lengths by stratum are

$$\pi_v = \frac{L_v}{L}$$

Thus, given L, the allocation problem is to minimize Equation 7.10.

We can use the Lagrange multiplier method to derive the equations to be solved for the optimal $\pi_1, \pi_2, \ldots, \pi_V$. Those equations can be written as

$$\frac{D_j}{(\sum \pi_v D_v)^2} + R\frac{p_j^2}{\pi_j^2 D_j} = \left[\frac{1}{\sum \pi_v D_v} + R \sum \frac{p_v^2}{\pi_v D_v}\right] \qquad j = 1, \ldots, V$$

Fixed point theory can sometimes be used to solve such equations numerically; in this case, it seems to work well. The previous V equations are rewritten below and one must iterate until convergence to compute the π_j. This method is related to the EM algorithm in statistics (Dempster *et al.* 1977; Weir 1990).

$$\pi_j = \sqrt{\frac{R \cdot p_j^2 / D_j}{\left[\frac{1}{\sum \pi_v D_v} + R \sum \frac{p_v^2}{\pi_v D_v}\right] - \frac{D_j}{(\sum \pi_v D_v)^2}}} \qquad j = 1, \ldots, V$$

We programmed these in SAS, explored their behaviour, and concluded that a good approximation to the optimal π_j is to use $\pi_j = p_j$, $j = 1, 2, \ldots, V$. Thus, approximately in this case of pooled distance data,

$$\pi_j = \frac{A_j D_j}{\sum A_v D_v} \qquad (7.11)$$

Note the relationship between Equations 7.11 and 7.7. Optimal relative line lengths (i.e. $\pi_1, \ldots, \pi_V$) should fall somewhere between the results of Equations 7.7 and 7.11; the exact values of $\pi_1, \ldots, \pi_V$ are not as critical to the precision of $\hat{D}_1, \ldots, \hat{D}_V$ as the total line length L.

7.2.4 Trapping webs

Trapping webs represent an application of point transect theory (Anderson *et al.* 1983). The method has been evaluated by computer simulation (Wilson and Anderson 1985b) and on known populations of beetles (Parmenter *et al.* 1989) and has performed well. The method was conceived for use in trapping studies of small mammals where the estimation of population density was of interest. The use of distance sampling theory relaxed the assumptions of traditional capture–recapture models (essentially ball and urn models). The method may perform well for populations whose members move relatively little or have somewhat fixed home ranges. Populations of individuals that move randomly over areas large in relation to the trapping web are problematic. In this respect, the positive results found by Parmenter *et al.* (1989) may have been somewhat fortuitous, or at least, require some alternative analysis methods (Section 6.11).

The design of studies using the trapping web approach should be laid out as in Fig. 1.7. As with point transects, some movement of objects through time will result in objects being overrepresented by the traps near the centre of the web, thus leading to overestimation of population density. Placing additional traps near the centre of the web may exacerbate this overestimation, and is not now recommended. Use of at least eight lines is suggested, and 10, 12 or even 16 might be considered. Guidelines for the number of traps are less well defined, although a practical objective is to obtain a sample of trapped animals of at least 60–80, and preferably around $n = 100$. A pilot study using 100–150 traps may often lead to insight on the number required to achieve an adequate sample size. A variety of traps can be used, including snap, live or pitfall traps. Animals, of course, do not have to be marked, unless they are to be returned to the population and thereafter ignored in future samples ('removal by marking'). Simple marking with a felt-tip pen will often suffice.

Trap spacing remains to be studied and we offer only the guideline that traps be spaced along the lines at a distance roughly equal to half the home range diameter of the species being studied. Wilson and Anderson (1985b) suggested 4.5–8 m spacing for mice, voles or kangaroo rats and 8–12 m spacing for larger mammals such as rabbits or ground squirrels. Commonly, captured animals are removed from the population after their initial capture. The field trapping can be done over sequential nights (or days) until it seems clear that no new animals are being caught near the centre. Alternatively, if at the centre of the web most animals that have been marked and released have subsequently been recaptured, then one might conclude that sufficient trapping occasions have been carried out.

Trapping webs can be established using a stake at the web centre and a long rope with knots to denote the trap spacing. Then, the investigator can travel in a circle laying out traps in roughly straight lines radiating from the centre. However, it is not important the traps be on perfectly straight lines. In multiyear surveys, the location of each trap is often marked by a numbered metal stake. We recommend that recaptures of released animals are recorded, and that each trap has a unique number, allowing captures to be assigned to traps. These data allow assumptions to be assessed, and additional analytic methods, such as bootstrap sampling within a web, to be implemented. Further research on the trapping web is needed before more detailed guidelines can be given. DISTANCE can perform analyses on single or multiple trapping web surveys, and provides a useful tool for such research.

7.3 Searching behaviour

Line and point transects are appropriately named because so much that is critical in this class of sampling methods is at or near the line or point. Search behaviour must try to optimize the detection of objects in the vicinity of the line or point, and search effort or efficiency should decrease smoothly with distance. The aims are to ensure that the detection function has a broad shoulder and the probability of detection at the line or point is unity ($g(0) = 1$).

(a) *Line transects* In line transect surveys, the above aims might be enhanced by moving slowly, emphasizing search effort on and near the line, having two or more observers traverse the transects, or using aids to detection such as binoculars. In surveys carried out by foot, the observer is free to use a trained dog, to walk slowly in clumps of heavy cover and faster in low or less suitable cover, or stop frequently to observe. The observer may leave the centreline temporarily, provided he or she records detection distances from the transect line, not from his or her current position. Aerial surveys commonly employ two observers, one covering each side of the aircraft, in addition to the pilot, who might guard the centreline. Shipboard surveys frequently use three or more observers on duty at any one time. In many surveys, it is good practice to look behind occasionally in case an object that was hidden on first approach can be seen.

The survey must be conducted so as to avoid undetected movement away or toward the line or point in response to the observer. To achieve this, most detection distances should exceed the range over which objects might respond to the observer. If a motorized observation platform is used, the range of response might be reduced by using platforms with quiet motors or by travelling faster. In surveys carried out by foot, the observer can ensure more reliable data by moving quietly and unobtrusively. Detection distances can be improved by use of binoculars. If detection cues are continuous, high power binoculars might be used, for example tripod-mounted 25 × binoculars on shipboard surveys of dolphins that typically occur in large schools. If cues are discrete, for example whales surfacing briefly, or songbirds briefly visible amongst foliage, lower magnification is necessary, so that field of view is wider. Indeed, binoculars are often used only to check a possible detection made by the naked eye. In some studies, one observer might scan continuously with binoculars while another searches with the naked eye. Tape cassette players are sometimes used to elicit calls from songbirds, although the observer should avoid attracting birds in towards the transect line. (Note that regular use of tape-cassette players in the territories of some species can cause unacceptable disturbance.)

Certain types of double counting can be problematic. If the objects of interest are immobile objects such as nests, then the fact that a particular nest is detected from two different lines or points is fully allowed under the general theory. Double counting becomes a potential problem only if motile objects are surveyed such that the observer or the observation platform chases animals from one line or point to another or if animals ‘roll ahead’ of the observer, hence being counted more than once (e.g. ‘chain flushes’ in surveys of grouse). Movement in response to the observer that leads to double counting should be recognized and avoided in the planning and conduct of a survey.

Although the analysis theory allows the observer to search on only one side of the line (i.e. $\hat{D} = n \cdot \hat{f}(0)/L$), we caution against this practice unless the animal's position relative to the line can be determined reliably and animal movement is relatively minor. If there is a tendency to include animals from the non-surveyed side of the line, then counts near the line will be exaggerated (this is a special type of heaping) and density will be overestimated. Animal movement from one side of the line to the other adds further complications and possible bias in the estimators. No problem would be anticipated if a single observer searches through a side window of an aircraft because there is little chance of including animals from the non-surveyed side of the transect (unless, again, undetected movement is taking place ahead of the observer's view). However, if the aircraft has forward visibility, such as a helicopter, there may be a tendency to include animals on both sides of and very near to the line into the first distance category.

Two alternatives exist for aerial surveys where forward visibility is good but only one observer is available; both involve searching both sides of the line. First, the observer could search a more narrow transect (smaller w) on both sides of the line. This procedure would concentrate most of the searching effort close to the line and this would help ensure that $g(0) = 1$. Second, and perhaps less satisfactory, the width of the transect could be larger on one side of the line than the other side. This would result in an asymmetric detection function and could be more difficult to model. Theory allows asymmetry in $g(x)$, and, if modelling proved too problematic, one could always truncate the distance data and alleviate the problem. In all cases, one should always be cautious to make sure that animals close to the line are not missed. Whenever possible, more than one observer should be used in aerial surveys.

Survey design such as searching only one side of the line illustrates the importance of carefully considering the assumptions of the theory in deciding how best to conduct a survey. Surveying only one side of the line makes the assumptions about movement and measurement error crucial because they will more directly affect the data near the transect centreline. Errors in assigning the detection of an animal to the left or right side of the line are irrelevant if both sides of the line are surveyed, but they are critical if only one side is surveyed. Data near the centreline are most important in obtaining valid estimates of density.

(b) *Point transects* For point transect surveys, the longer the observer remains at each point, the more likely is the probability of detection at the point to be unity, and the broader is the shoulder of the detection function. This advantage is offset by possible movement of objects into the sampled area, which leads to overestimation of density. Optimal time to spend at each point might be assessed from a pilot study. In some cases, it might be useful to observe the point from a short distance and record distances to objects of interest before any disturbance caused by the approach of the observer. Another option is to wait at the point a short period of time before recording, to allow objects to resume normal behaviour. As for line transects, binoculars may be useful for scanning, for checking possible detections, or for identifying the species. Tape cassette recorders may help elicit a response, but as for line transects, great care must be taken not to attract objects towards the observer. After the recording period, the observer may find it necessary to approach an object detected during that period, to identify it.

Detection distances can also be measured out before moving to the next point. If distances are assessed by eye, the task is made easier by use of markers at known distances.

If the radius of each point is fixed at some finite w, one could consider the population 'closed' and use a removal estimator to estimate the population size N (White *et al.* 1982: 101–19). To keep the option of this approach open, the time (measured from the start of the count at the point) at which each object is first detected should be recorded. The count period may then be divided into shorter time intervals, and data for each interval pooled across points. The relevant data would be the number of objects detected in the first time interval, the number of **new** objects detected in the second time interval, and so on. The theory exists, but it has not been used in this type of application. We recommend experimentation with this approach, perhaps with relatively small truncation distances w so that heterogeneity in probability of detection is reduced, as a check on the point transect estimates. Of special interest with such time/distance data is the potential to check that no new detections occur near the point towards the end of the counting period.

(c) *General comments* Ideally, provided $g(0) = 1$, one would like to collect distance data with a very broad shoulder. The choice of an adequate model for $g(y)$ is then relatively unimportant, and D can be estimated with good precision. For many studies, proper conduct of the survey can achieve high detection probabilities out to some distance. Many of the methods employed to ensure $g(0) = 1$ also help to widen the shoulder of the detection function.

Survey data for which the detection function drops off quickly with distance from the line or point, with a narrow shoulder and long tail, are far from ideal (Fig. 2.1). Model selection is far more critical and precision is compromised. Occasionally, little can be done at the design stage to avoid spiked data, but usually, such data indicate poor survey design or conduct (e.g. poor allocation of search effort near the line or point, poor precision in distance or angle estimation, or failure to detect objects prior to responsive movement towards the observer).

In multispecies surveys in diverse or complex habitats, there are likely to be errors in species identification (Bart and Schoultz 1984). As density increases, 'swamping' may occur; accurate data recording might be compromised by the number of sightings, calls, and other cues experienced during a short time interval (Bibby *et al.* 1985). Here, the binomial method of Järvinen and Väisänen (1975; line transects) or Buckland (1987a; point transects), in which distances are assigned to one of just two distance intervals, might be considered, especially if estimates of only **relative** abundance are required.

7.4 Measurements

Accurate measurement of distances and angles is quite important. The observer must work carefully and avoid errors in recording or transcribing data. Ancillary data, such as sex, species, and habitat type, are often taken. These data are partitioned by individual line or sample point and recorded. A field form is suggested to structure the recording of data. A field form for recording data is efficient and nearly essential. Figure 7.3 shows two examples; another was presented by Burnham *et al.* (1980: 34). The format for such field forms can usually be improved upon after use during the pilot study. Note-taking on various aspects of the survey should be encouraged and these can be recorded on separate sheets.

Fatigue can compromise accurate data, thus the field effort must consider the time spent surveying each day. Certainly it is unreasonable to believe that an observer can remain at peak searching ability throughout a 7–10-hour day. Fatigue may play a larger role in aerial surveys or foot surveys in difficult terrain. These are important issues and this section provides guidance on data collection.

The careful measurement or estimation of distances near the line or point is critical. **In summary, every possible effort must be made to ensure that accurate measurements are made, prior to any undetected movement, of *all* objects on or near the line or point**. This cannot be overemphasized.

7.4.1 Sighting distance and angle data

For point transects, analyses are based on observer-to-object distances, but for line transects, the widely used methods all require that the shortest distance between a detected object and the line is recorded or estimated. By the time the observer reaches the closest point on the line, the object may not be visible or may have moved in response to the observer's presence. These problems are minor for aircraft surveys in which the speed of the observation platform is sufficient to render movement of the object between detection and the point of closest approach unimportant. For shipboard surveys of marine mammals, sighting distances are frequently several kilometres, and it may take up to half an hour to arrive at the point of closest approach. Further, for many surveys, it is necessary to turn away from the centreline when an animal cluster is detected, both to identify and to count the animals in the cluster. Hence the natural distance to record is the sighting or radial distance r; by recording the sighting angle θ also, the shortest distance between the animal and the line, i.e. the perpendicular distance x, may be calculated as $x = r \cdot \sin(\theta)$ (Fig. 1.5). However, rounding errors in the data cause problems. Angles are seldom recorded to better accuracy

Study area ______________ Cloud cover (%) ______ Wind speed ______

Observer name ______________ Date ______

Line number ______ Line length (km) ______ Start time ______ End time ______

Sighting number	Perpendicular distance	Covey size	Number of		
			Males	Females	Unknown
1	___	___	___	___	___
2	___	___	___	___	___
3	___	___	___	___	___
⋮					

Sighting number	Covey size	Perpendicular distance interval (m)				
		0 – 50	50 – 100	100 – 150	150 – 250	250 – 400
1	___	___	___	___	___	___
2	___	___	___	___	___	___
3	___	___	___	___	___	___
⋮						

Fig. 7.3. Two examples of a hypothetical recording form for a line transect survey of grouse. The example at the top is for taking ungrouped perpendicular distance data for coveys and the sex of covey mates as ancillary information. The example at the bottom allows for recording of covey sizes and grouped perpendicular distance data. Information on each line, such as its length and the proportion of that length in each habitat type, would be recorded just once on a separate form. Most surveys are somewhat unique, requiring specialized forms for use in the field.

than the nearest 5°, so that an animal recorded to have a sighting distance $r = 8$ km and sighting angle $\theta = 0°$ will have a calculated perpendicular distance of $x = 0$ km, when the true value might be

$x = 350$ m or more. Since estimation of abundance depends crucially on the value of the fitted probability density for perpendicular distances evaluated at zero distance, $\hat{f}(0)$ (Burnham and Anderson 1976), the false zeros in the data may adversely affect estimation. The problem is widespread, and more than 10% of distances are commonly recorded as zero, even for land surveys in which distances and angles are apparently measured accurately (e.g. Robinette *et al.* 1974). Possible solutions, roughly in order of effectiveness, are:

1. Record distances and angles more accurately
2. 'Smear' the data (see below)
3. Use models for the detection function that always have a shoulder
4. Group the data before analysis
5. Use radial distance models.

Only the first of these solutions comes under the topic of this chapter, but we cover the others here for completeness, and to emphasize that solution 1, better survey design, is far more effective than the analytic solutions 2–5.

1. Improving accuracy in measuring angles and distances is certainly the most effective solution. It may be achieved by improving technology, for example by using binoculars with reticles (graticules) or range finders, and using angle boards or angle plates on tripods. Most important is that observers must be thoroughly trained, and conscientious in recording data; there is little benefit in using equipment that enables angles to be measured to the nearest degree if observers continue to record to the nearest 5°. Training should include explanation of why accuracy is important, and practice estimates of distances and angles for objects whose exact position is known should be made, under conditions as similar as possible to survey conditions.

2. The concept of 'smearing' the data was introduced by Butterworth (1982b). Although often criticized, for example by Cooke (1985), the technique has become widely used for data from cetacean shipboard surveys. It is an attempt to reduce the effects on the estimates of recording inaccurate locations for detections, through rounding sighting distances and angles to favoured values. When rounding errors occur, the recorded position of an animal may be considered to be at the centre of a sector called the 'smearing sector' (Fig. 7.4); the true position of the animal might be anywhere within the sector. Butterworth and Best (1982) assigned each perpendicular distance a uniform distribution over the interval from the minimum distance between the sector and the centreline to the maximum distance, and selected a distance at random from this distribution to replace the calculated perpendicular distance. Hammond (1984) compared this with assigning a uniform distribution

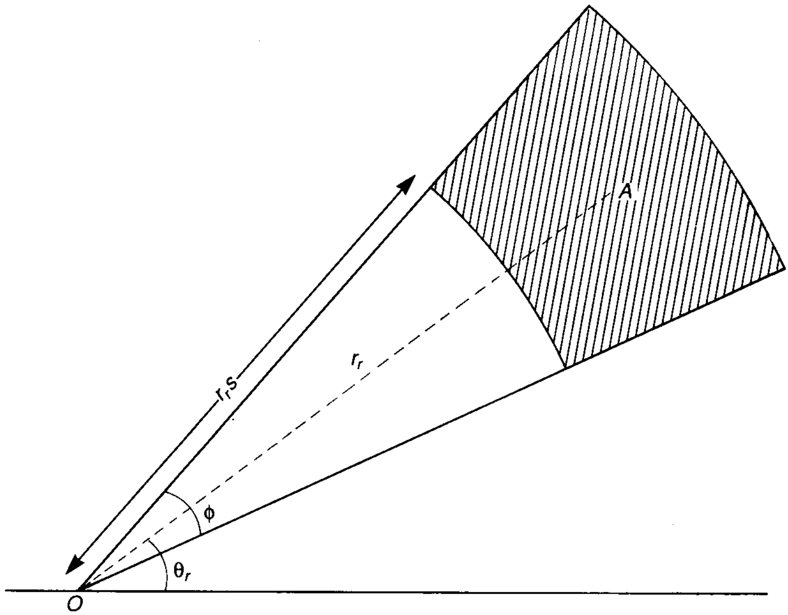

Fig. 7.4. The observer at O records an animal at position A, at radial distance r_r and with sighting angle θ_r. The true position of the animal is considered to be anywhere within the shaded smearing sector. The size of the sector is determined by smearing parameters ϕ and s.

over the sector, selecting a new sighting distance/angle pair at random from the sector and calculating the corresponding perpendicular distance. He also investigated assigning a normal distribution to both the distance and the angle instead of a uniform distribution. He concluded that the degree and method of smearing had relatively little effect on estimation of $f(0)$, but that estimation under either method was improved relative to the case of unsmeared data.

If the data are grouped before analysis, it is unnecessary to sample at random from the assumed distribution within the smearing sector. For example if smearing is uniform over the smearing sector, the sector can be considered to have an area of unity, and the proportion of the sector within each perpendicular distance interval may be calculated. This is carried out for each observation and the resulting proportions are summed within each interval. They can then be rounded to the nearest integer values and line transect models applied in the normal way for grouped data. Alternatively the methods of Section 3.4 (grouped data) follow through when the 'frequencies' are not integer, so that rounding is not required. This approach is described by Buckland and Anganuzzi (1988a).

Values must be assigned to the smearing parameters to control the level of smearing. Butterworth (1982b) incorporated time and vessel speed in his routine, since distance was calculated as speed by time taken to close with a whale or whales. The values for the smearing parameters were selected in a semi-arbitrary manner, by examining the apparent accuracy to which data were recorded. Hammond and Laake (1983) chose the level of smearing in a similar way, although the method of smearing was different; the semicircle ahead of the vessel was divided into smearing sectors so that any point within the semicircle fell in exactly one sector. Objects (in this case, dolphin schools) recorded as being in a given sector were smeared over that sector. Butterworth *et al.* (1984) used data from experiments with a buoy that was fitted with a radar reflector to estimate smearing parameters. None of these offer a routine method for smearing, whereas the angle and distance data contain information on the degree of rounding, suggesting that estimation of the smearing parameters from the data to be smeared should be possible. Buckland and Anganuzzi (1988a) suggested an *ad hoc* method for this. Denote the recorded sighting distance and angle by r_r and θ_r respectively, and the corresponding smearing parameters by s and ϕ (Fig. 7.4), to be estimated. Then the smearing sector is defined between angles $\theta_r - \phi/2$ and $\theta_r + \phi/2$, and between radial distances $r_r \cdot s$ and $r_r \cdot (2 - s)$. Smearing is uniform over the sector, and grouped analysis methods are used, so that Monte Carlo simulation is not required (above). This is the method recommended by Buckland and Anganuzzi, although they also considered two improvements to it. First, rounding error increases with distance from the observer, so that a recorded distance of 1.3 km say is more likely to be rounded down to 1.0 km than 0.7 km is to be rounded up. This may be accounted for by defining the smearing sector between radial distances $r_r \cdot s$ and r_r/s. Second, there are fewer observations at greater perpendicular distances, since the probability of detection falls off. Hence smearing should not be uniform over the smearing sector, but should be weighted by the value of a fitted detection function at each point in the sector. The recommended method therefore has two identifiable sources of bias. One leads to oversmearing, and the other to undersmearing. Buckland and Anganuzzi concluded that the more correct approach did not lead to better performance, apparently because the two sources of bias tend to cancel, and considered that the simpler approach was preferable.

Buckland and Anganuzzi (1988a) estimated the smearing parameters by developing an *ad hoc* measure of the degree of rounding in both the angles and the distances. In common with Butterworth (1982b), they found that errors seemed to be larger in real data than the degree of rounding suggests. They therefore introduced a multiplier to increase the level of smearing and investigated values from 1.0 to 2.5. They noted that undersmearing was potentially more serious than oversmearing, and recommended that the estimated smearing parameters be multiplied by two, which would be correct for example if an angle between 5° and 10° was rounded at random to either endpoint of the interval rather than rounded to the nearest endpoint.

The above methods are all *ad hoc*. Methodological development is needed here to allow the rounding errors to be modelled.

3. If many perpendicular distances are zero, a histogram of perpendicular distances appears spiked; that is the first bar will be appreciably higher than the rest. If, for example, the exponential power series model is fitted to the data, it will fit the spike in the data, leading to a high value for $\hat{f}(0)$ and hence overestimation of abundance. Models for which $g'(0)$ is always zero (i.e. the slope of the detection function at $x = 0$ is zero) are usually less influenced by the erroneous spike, and are therefore more robust. This does not always follow; if distance data fall away very sharply close to zero, then only very slowly at larger distances, the single-parameter negative exponential model is unable to fit the spike, whereas the more flexible two-parameter hazard-rate model can. If the spike is spurious, the negative exponential model can fortuitously provide the more reliable estimation (Buckland 1987b), although its lack of flexibility and implausible shape at small perpendicular distance rule it out as a useful model.

4. If data are grouped such that all perpendicular distances that are likely to be rounded to zero fall in the first interval, the problem of rounding errors should be reduced. This solution is less successful than might be anticipated. First, interval width may be too great, so that the histogram of perpendicular distances appears spiked; in this circumstance, different line transect models can lead to widely differing estimates of object density (Buckland 1985). Second, the accuracy to which sighting angles are recorded often appears to be quite variable. If a detection is made at a large distance, the observer may be more intent on watching the object than recording data; in cetacean surveys the animal may no longer be visible when he/she estimates the angle. Thus for a proportion of sightings, the angle might only be recorded to the nearest 10° or 15°, and 0° is a natural value to round to when there is considerable uncertainty. An attempt to impress upon observers that they should not round angles to 0° in minke whale surveys in the Antarctic led to considerable rounding to a sighting angle of 3° on one vessel!

5. Because rounding errors in the angles are the major cause of heaping at perpendicular distance zero when data are recorded by

sighting angle and distance, it is tempting to use radial distance models to avoid the difficulty. Such models have been developed by Hayne (1949), Eberhardt (1978a), Gates (1969), Overton and Davis (1969), Burnham (1979) and Burnham and Anderson (1976). However, Burnham *et al.* (1980) recommended that radial distance models should not be used, and Hayes and Buckland (1983) gave further reasons to support this recommendation. First, hazard-rate analysis indicates that r and θ are not independently distributed, whereas the models developed by the above authors all assume that they are. Second, hazard-rate analysis also suggests that if detectability is a function of distance r but not of angle θ, then the expected sighting angle could lie anywhere in the interval 32.7° to 45°, whereas available radial distance models imply that it should be one or the other of these extremes, or use an *ad hoc* interpolation between the extremes. Third, all models utilize the reciprocal of radial distances, which can lead to unstable behaviour of the estimator and large variances if there are a few very small distances. Fourth, despite claims to the contrary, it has not been demonstrated that any existing radial distance models are model robust. A model might be developed from the hazard-rate approach, but it is not clear whether it would be pooling robust, or whether typical data sets would support the number of parameters necessary to model the joint distribution of (r, θ) adequately. We therefore give a strong recommendation to use perpendicular distance models rather than any existing radial distance model.

7.4.2 Ungrouped data

The basic data to be recorded and analysed are the n distances. Generally, these are the individual perpendicular distances x_i for line transect surveys or the sighting distances r_i for point transect surveys. Alternatively, in line transect surveys, the sighting distances r_i and sighting angles θ_i can be measured, from which $x_i = r_i \cdot \sin(\theta_i)$ (above). These ungrouped data are suitable for analysis, especially if they are accurate. Heaping at zero distance is especially problematic, again illustrating the need to know the exact location of the line or point. Well-marked, straight lines are needed for line transect surveys. Upon detection of an object of interest, the surveyor must be able to determine the exact position of the line or point, so that the proper measurement can be taken and recorded. If sighting angles are being measured, a straight line is needed or the angle will not be well defined.

We recommend the use of a steel tape for measurements for foot surveys of terrestrial populations up to about 30 m. If a stick or lath is used for 'beating', it can be marked off in appropriate measures and used as a measuring stick. If this is to be done, it is wise to use a yard or metre rule. Many surveyors have successfully used a range finder in obtaining estimates of distances out to about 100 m. We discourage the use of visual observation alone in estimating distances and angles. Unless the observers are unusually well trained, such a procedure invites heaping of measurements (at best) or biased estimates of distance with different biases for different observers (at worst). Scott *et al.* (1981) found significant variability in precision among observers and avian species, but no bias in the errors. Often, even simple pacing is superior to ocular estimation.

Observers have a tendency to record objects detected just beyond w as within the surveyed area. This might be called 'heaping at w' and was noted in the surveys at the Monte Vista National Wildlife Refuge (Chapter 8) where $w = 8.25$ or 12 ft in differing years. In either case, there were more observations in the last distance category than expected for nearly all years.

For shipboard surveys, sighting distances are frequently estimated using reticles or graticules, which are marks on binocular lenses (Fig. 7.5). The observer records the number of marks down from the horizon to the detected object. This number may be transformed to a distance from the observer using a modification of a method proposed by R. C. Hobbs (pers. comm.), as follows (Fig. 7.6).

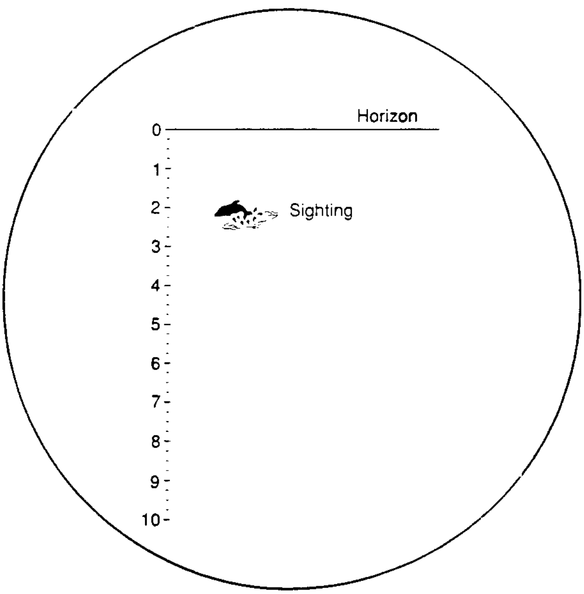

Fig. 7.5. Diagram of reticles used on binoculars on shipboard surveys of marine mammals. Use of these marks allows the computation of sighting distance (text and Fig. 7.6).

Let R = radius of the Earth $\doteq$ 6370 km;
v = vertical height of the binoculars above the sea surface;
δ = angle of declination between successive divisions on the reticle;
ϕ = angle between two radii of the Earth, one passing through the observer and the other passing through any point on the horizon, as seen by the observer
$= \cos^{-1}\{R/(R+v)\}$

Now suppose that the reticle reading is d divisions below the horizon, so that the angle of declination between the horizon and the sighting is $\psi = d \cdot \delta$. Then the sighting distance is approximately

$$r = \frac{R+v-\sqrt{R^2-r^2}}{\tan(\phi+\psi)}$$

This is a quadratic in r, and the smaller root provides the solution we require:

$$r = \cos(\phi+\psi)\left[(R+v)\sin(\phi+\psi) - \sqrt{R^2\sin^2(\phi+\psi) - v(2R+v)\cos^2(\phi+\psi)}\right]$$
$$\simeq \cos(\phi+\psi)\left[R\sin(\phi+\psi) - \sqrt{R^2\sin^2(\phi+\psi) - 2Rv\cos^2(\phi+\psi)}\right]$$

For example, if the observer's eyes are 10 m or 0.01 km above sea level, the angle between successive divisions of the reticle is 0.1°, and the reticle reading is 3.6 divisions below the horizon, then

$$\phi = \cos^{-1}\{6370/(6370+0.01)\} = 0.10^\circ \text{ and } \psi = 0.36^\circ$$

so that

$$r = \cos(0.46^\circ)\left[6370\sin(0.46^\circ) - \sqrt{6370^2\sin^2(0.46^\circ) - 2\times 6370\times 0.01\cos^2(0.46^\circ)}\right] = 1.26\text{ km}$$

Note that the horizon is at $h = R \cdot \tan(\phi) = 11.3$ km (Fig. 7.6). These calculations ignore the effects of light refraction, which are generally small for sightings closer than the horizon.

If binoculars are tripod-mounted, sighting angles can be accurately measured from an angle ring on the stem of the tripod, provided observers are properly trained, and the importance of measuring angles accurately is stressed. If binoculars are hand-held, angle boards (Fig. 7.7), perhaps mounted on ship railings, may be found useful; although accuracy is likely to be poor relative to angle rings on tripods, it should still be appreciably greater than for guessed angles. Distance and angle experiments, using buoys at known positions, should be carried out if at all possible, both to estimate bias in measurements and to persuade observers that guesswork can be poor!

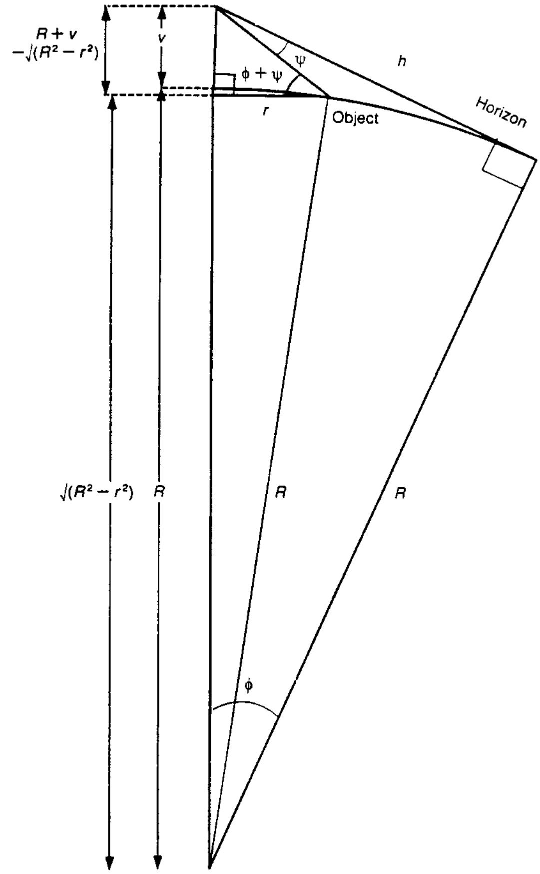

Fig. 7.6. Geometry of the procedure for computing sighting distances from ocular data for shipboard surveys of marine mammals. Reticles provide an estimate of ψ, the angle of declination of the detected object from the horizon, which must be converted into the distance r from the observer to the object.

Ungrouped sightings data are seldom collected for aerial surveys (see below), but if terrain is uneven, so that it is not possible to fly at a fixed altitude, perpendicular distance can be estimated by recording both the angle of declination and the altitude at the time the aircraft passes the detected object.

7.4.3 Grouped data

It is sometimes difficult to measure distances exactly and, therefore, it might be convenient to record data only by distance interval. Then, the

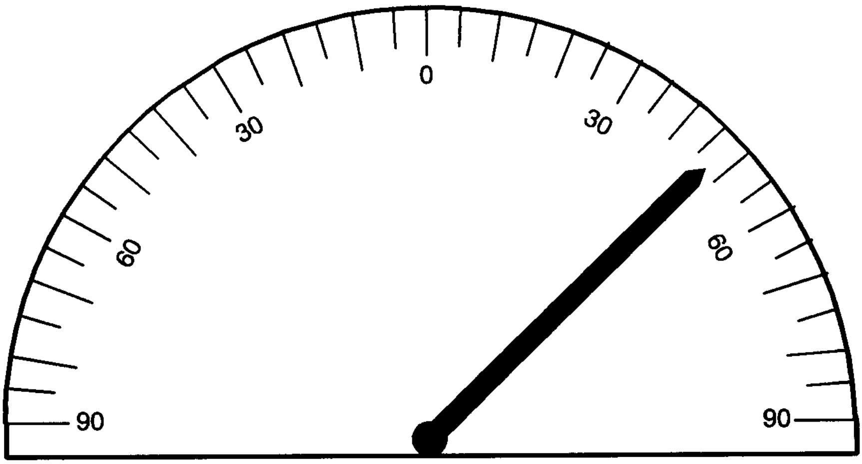

Fig. 7.7. Sighting angles can often be more accurately estimated by the use of an angle board as shown here. Such devices can be hand made and are useful in many applications of distance sampling.

exact distance of an object detected somewhere between, say, 0 and 40 m will not be recorded, but only that it was in the distance interval 0–40. During the course of the survey, a count n_1 will be made of objects in this first distance interval. The survey results will be the frequencies $n_1, n_2, \ldots, n_u$ corresponding to the u distance classes with total sample size $n = \sum n_i$.

In general, let c_i denote the designated distance from the line or point and assume that we have u such distances: $0 = c_0 < c_1 < c_2 \ldots < c_u = w$. In the case of left truncation, $c_0 > 0$. Note, also, that c_u can be finite or infinite. These 'cutpoints' result in u distance intervals and the grouped data are the frequencies n_i of objects detected in the various intervals. Specifically, let n_i = the number of objects in distance interval i corresponding to the interval (c_{i-1}, c_i). If at all possible, there should be at least two intervals in the region of the shoulder. In general, the width of the distance intervals should increase with distance from the line or point, at least at the larger distances. The width of each distance interval might be set so that the n_i would be approximately equal. This rough guideline can be implemented if data from a pilot study are available. Alternatively, if the underlying detection function is assumed to be approximately half-normal, then Table 7.1 indicates a reasonable choice for group interval widths for various u, where Δ must be selected by the biologist. Thus for a line transect survey of terrestrial animals, if $u = 5$ distance intervals were required, and it was thought that roughly 20% of detections would be beyond 500 m, then $\Delta = 100$ m, and the interval cutpoints are 100 m, 200 m, 350 m, 500 m and ∞. The grouped data would be the frequencies $n_1, n_2, \ldots, n_5$. As a guideline, u, the number of distance classes in line transect surveys, should not be less than four and five is much better than four. Too many distance intervals tend to defeat the advantages of such grouping; certainly 7–8 intervals should be sufficient in most cases. Defining too many intervals makes classification of objects into the correct distance interval error-prone and time-consuming. In addition, the use of too many distance intervals distracts attention from the main goal: detections near the line or point.

Table 7.1 Suggested relative interval cutpoints for line and point transects. An appropriate value for Δ must be selected by the user

Number of intervals, u	Suggested relative interval cutpoints for line transects	Suggested relative interval cutpoints for point transects
4	Δ, 2Δ, 4Δ, ∞	2Δ, 3Δ, 4Δ, ∞
5	Δ, 2Δ, 3.5Δ, 5Δ, ∞	2Δ, 3Δ, 4Δ, 5.5Δ, ∞
6	Δ, 2Δ, 3Δ, 5Δ, 7Δ, ∞	2Δ, 3Δ, 4Δ, 5Δ, 6.5Δ, ∞
7	Δ, 2Δ, 3Δ, 4.5Δ, 6Δ, 8Δ, ∞	2Δ, 3Δ, 4Δ, 5Δ, 6Δ, 7.5Δ, ∞
8	Δ, 2Δ, 3Δ, 4Δ, 5.5Δ, 7Δ, 9.5Δ, ∞	2Δ, 3Δ, 4Δ, 5Δ, 6Δ, 7Δ, 8.5Δ, ∞

Collection of grouped data allows a relaxation of the assumption that distances are measured exactly. Instead, the assumption is made only that an object is counted in the correct distance interval. Holt and Powers (1982) reported on an aerial survey of several species of dolphin where counts were made by the following distance intervals: 0.0, 0.05, 0.15, 0.25, . . . nautical miles. Terrestrial surveys of jackrabbits might use 0, 50, 100, 175, 250, ∞ m. Note, here the final distance interval is between 250 m and ∞. As few as two distance intervals (i.e. 'binomial' models) are sometimes used in point transect surveys (Buckland 1987a) and in line transect surveys (Järvinen and Väisänen 1975; Beasom *et al.* 1981), although, no goodness of fit test can be made. In general, the use of between five and seven distance intervals will be satisfactory in many line transect surveys.

It is commonly thought that all objects in the first distance interval must be detected (i.e. a census of the first band). This is incorrect; the width of this interval might be 40 m and it is not necessary that all objects be detected in the 0–40 m band. Of course, as the shoulder in the data is broadened, there are significant advantages in estimation. As a guideline, we recommend that the probability of detection should not fall appreciably below unity over at least the first two intervals.

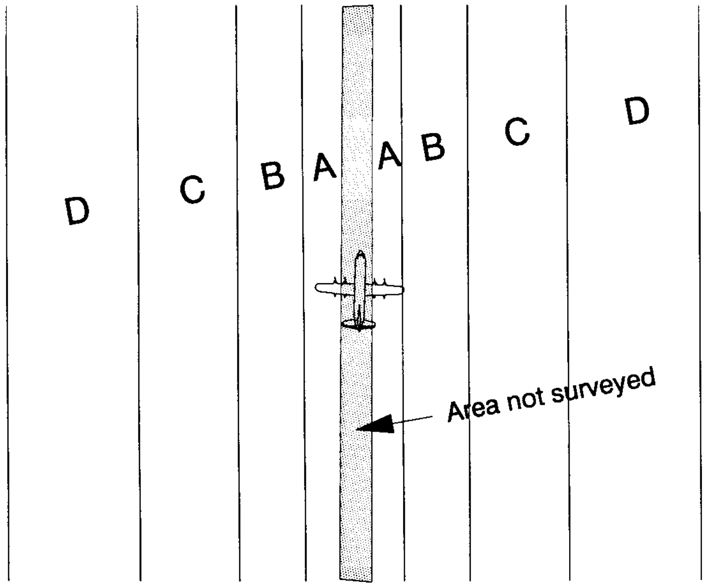

Fig. 7.8. The area below an aircraft can be excluded as shown (shaded area). Here grouped data are recorded in four distance intervals (**A–D**) of increasing widths with distance. Adapted from Johnson and Lindzey (unpublished).

Nearly all aerial surveys collect grouped data. The proper speed and altitude above the ground can be selected after some preliminary survey work. Here it may not be practical to record counts for the first distance interval because visibility below the aircraft is impaired (Fig. 7.8). Ideally the altitude would be high enough so as to leave the objects undisturbed and, thus, avoid movement prior to detection. After this consideration, the aircraft should be flown as low as practical to enhance detection of objects. The altitude should be recorded occasionally during the survey to be sure the pilot is flying at the proper height. The distance intervals may be substantially in error if altitude is not as recorded or if the altitude varies due to terrain. Markers of some type are typically fixed to the aircraft to delineate the distance intervals on the ground for a fixed height above ground (Fig. 7.9). Two sets of markers are required (like the front and rear sight on a rifle); usually markers can be placed on the aircraft windows and wing struts. Observers should be cautioned not to assign objects to distance intervals until they are nearly

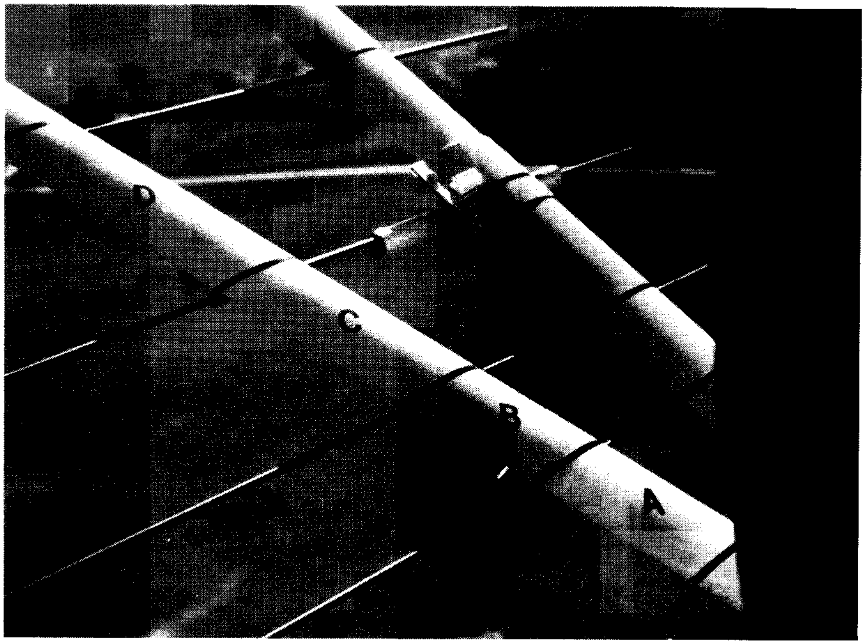

Fig. 7.9. Airplane wing struts can be marked to delineate boundaries of the distance intervals on the ground. Other marks on the side window of the airplane are used to assure proper classification of animals to the correct distance interval. Compare with Fig. 7.8. From Johnson and Lindzey (unpublished).

perpendicular to the aircraft. If such assignment is attempted while the object is still far ahead of the aircraft, there is a tendency to assign incorrectly the object to the next largest distance interval (this problem is related to parallax). Occasionally observations are made from only one side of the aircraft, but this is fairly inefficient, often problematic, and should be used only in unusual situations.

Some types of aircraft are far better for biological surveys than others (Fig. 7.10). Ideally, the aircraft should allow good visibility ahead of and directly below the observer. Some helicopters meet these requirements, but are expensive to rent and operate. Airplanes with a high wing and low or concave windows can also make excellent platforms for aerial detection, and craft with clear 'bubbles' at the nose, designed for observation work, are available.

The density of many populations of interest is fairly low, so that recording the counts n_i (and perhaps cluster sizes) can be done by hand

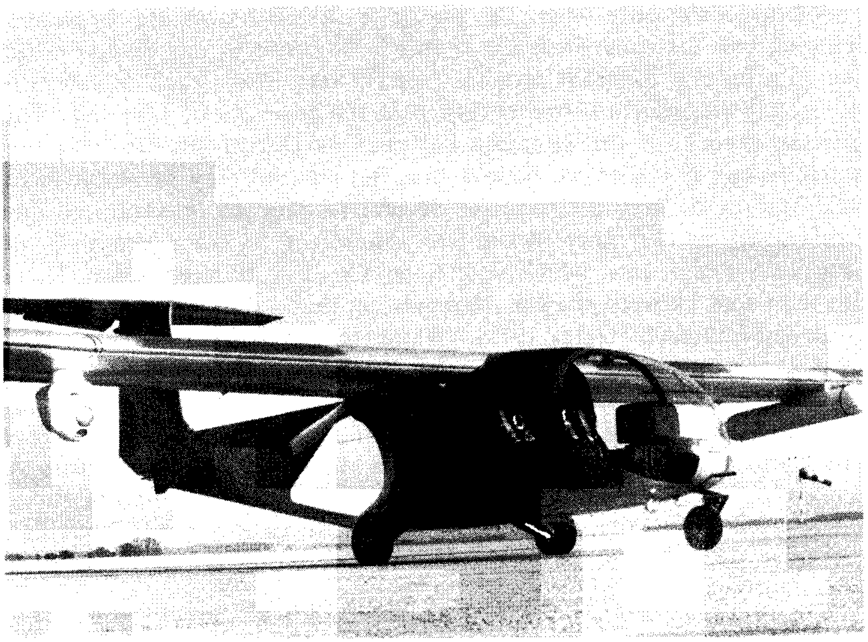

Fig. 7.10. Some aircraft are specifically designed for aerial observation. Note the forward and lateral visibility and the high wing on the aircraft. Helicopters, while more expensive, often provide similar advantages plus the ability to hover or proceed more slowly than a fixed-wing aircraft.

without distracting the observer and, thus, failing to monitor the line. However, it is often best to use a tape recorder, ideally with an automatic time signal, so that the observer can continue searching without distraction. In some cases it might be feasible to use a laptop computer to record data. Some aerial surveys have used the LORAN C navigation system to maintain a course on the centreline, monitor altitude, position and distances (Johnson and Lindzey unpublished). A video camera has been mounted in the aircraft to record the area near the line in pronghorn surveys in Wyoming (F. Lindzey, personal communication). The video can be studied after the flight in an effort to verify that no objects were missed on or near the line. Bergstedt and Anderson (1990) used a video camera mounted on an underwater sled pulled by a research vessel to obtain distance data.

An advantage of collecting grouped data in the field is that exact distances are not required. Instead, one merely classifies an object detected into the proper distance class. Thus, if an object is somewhere near the centre of the distance class, proper classification may be easy. Problems occur only when the object is detected near the boundary between two distance intervals. If this is of concern, one could record the data on two different distance interval sets. Thus, each detection is accurately recorded on one or other of the two sets of intervals. The analysis theory for this situation has been developed but the computer software has not, and we believe that the method may be sensitive to assumptions on how the observer decides to allocate detections to one interval set or the other. A simpler solution is to use a single set of cutpoints, and record which detections are close to a cutpoint. These are then split between the two intervals, so that a frequency of one half is assigned to each (Gates 1979). Of course, a reduction in the number of distance intervals will result in fewer incorrect classifications.

Field studies of measurement error in aerial surveys have been limited. Chafota (1988) placed 59 bales of wood shavings (22.7 kg each) in short grass prairie habitat in northeastern Colorado to mimic pronghorn. A fixed-wing aircraft (Cessna 185) was flown at 145 km/hr at 91.4 m above the ground to investigate detection and measurement errors. Four line transects were flown using existing roads to mark the flight path ($L = 83.8$ km). The centreline of the transect was offset 60 m on both sides of the plane because of the lack of visibility below and near the aircraft (Fig. 7.8). Coloured streamers were attached to the wing struts of the aircraft to help the observer in delineating distance intervals (0–25, 25–50, 50–100 and 100–400 m). No marks were put on the window, thus the observer had only a 'front sight'. Neither the pilot nor the observer had experience in line transect surveys, although both had had experience with aerial strip transect sampling, and neither had knowledge of the number or placement of the bales. The observer did not have training in estimating distances. The performance of the observer on two assessments was reported.

In the first assessment 59 bales were placed in the 0–25 m band to assess the observer's ability to detect objects on or near the centreline (which was offset 60 m). Here the observer detected 58 out of 59 objects in the first band (0–25 m), and the undetected bale was at 22.9 m. However, six of the 58 were recorded as being in the 26–50 band. Worse, two bales were classed in the 50–100 band and an additional two bales were classed in the 100–400 band. Chafota (1988) suggested that possibly the aircraft was flown too low or went off the flight line during part of the survey, thus leading to the large estimation errors.

The second assessment employed 53 bales, including one outside the 400 m distance. The results are shown in Table 7.2. Here, the detection was quite good, as one might expect in the case of relatively large objects placed in short grass prairie habitat. Only one of the 53 bales went undetected (193.9 m). However, the tendency to exaggerate distances is quite clear. Chafota (1988) stressed the need for training in the estimation of distances, an effective pilot study and a carefully designed field protocol. We would concur with these recommendations and add the need for window marking to be used in conjunction with the streamers on the wing struts, an accurate altimeter to maintain the correct altitude, and a navigation system that allows accurate flight lines and positioning (see Johnson and Lindzey unpublished). Chafota (1988) also offered insight into the effects of measurement errors on $\hat{D}$ from the results of Monte Carlo studies.

Table 7.2 Performance of an observer in detecting bales of wood shavings placed at known distances from the centreline in short grass prairie habitat (from Chafota 1988)

		Observed distance interval (m)				
Distance interval (m)	Actual frequencies	0–25	25–50	50–100	100–400	> 400
0–25	21	8	12	1	0	0
25–50	14	1	3	10	0	0
50–100	12	0	1	9	2	0
100–400	5	0	0	1	3	0
> 400	1	0	0	0	0	1
Recorded frequencies:		9	16	21	5	1

It is possible to record sighting distances and sighting angles as grouped. This procedure is not recommended except under unusual circumstances. Transformation of grouped sighting distances and angles into grouped perpendicular distances has several problems and often calls for additional analytic methods to be used prior to the estimation of density. The smearing procedure can be applied to grouped or ungrouped (but heaped) data. It is invariably preferable to collect data that do not require smearing, if at all possible.

7.4.4 Cluster size

Ideally, the size of each cluster observed would be counted accurately, regardless of its distance from the line or point. In practice, one may only be able to estimate the size of the clusters, and such estimates may be biased. Additionally, there may be a tendency to underestimate the size of clusters at the larger distances and small clusters may remain undetected at the larger distances (i.e. size-biased sampling), leading to overestimation of average cluster size if $\bar{s}$ is used. In general, proper estimation of $E(s)$ is possible, but more complicated than use of the simple mean.

Survey design and conduct should attempt to minimize the difficulties in measuring cluster size. More than one observer may aid in getting an accurate count of cluster size. Photography may be useful in some clustered populations, and this has been tried in surveys of dolphin populations. It may be possible to leave the centreline to approach the more difficult clusters, and thereby obtain an accurate count. Sometimes it may be reasonable to obtain estimates of average cluster size from the data in only the first few distance bands for which both size-biased and poor estimation of cluster size are less problematic.

Clusters should be recorded only if the centre of the cluster is within the sampled area (0 to w), but the size of detected clusters should include all individuals within the cluster, even if some of the individuals are beyond w. If the centre of a detected cluster is beyond w, it should not be recorded and no individuals in the cluster should be recorded, even though some individuals might be within the sampled area ($< w$).

Cluster size and the variability among clusters may vary seasonally. For example, Johnson and Lindzey (unpublished) found that pronghorn populations split into small groups of nearly equal size in the spring, whereas much larger and more variable clusters were found during the autumn and winter months. Surveys should be conducted while variability in cluster size is low to avoid a relatively large variance in $\hat{D}$ from the contribution of $\widehat{\text{var}}(\hat{E}(s))$. Small, variable clusters are preferable to large clusters with little variability because the number of detections (i.e. independent observations) will be greater.

7.4.5 Other considerations

In distance sampling it is important to use an objective method in establishing the exact location of the lines or points in the field. Subjective judgement should not play a role here.

If more than one observer is used, the design should allow estimation by individual observer. In line transect surveys, it may be interesting to partition and record the detections and cluster size by whether they are to the left or right of the centreline. Examination of these data may allow a deeper understanding of the detection process that might be useful in the final analysis. For example, in marine surveys, glare may be worse one side of the line than the other, and such data allow the effect of glare to be quantified.

In point transect surveys it might be useful to record a sighting angle θ_i (where $0° \leqslant \theta_i \leqslant 360°$) for each detected object. Here, 0° would be

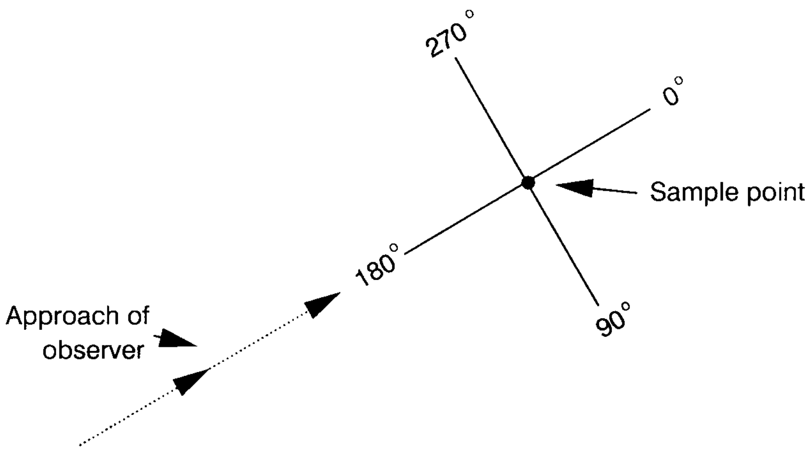

Fig. 7.11. Disturbance by an observer approaching a sample point can often be detected by recording angles θ (0° ≤ θ ≤ 360°) where 0° is directly ahead of the observer's direction of approach. Thus, an angle is recorded for each object detected. These angles might be recorded by group (e.g. 45–135, 136–225, 226–315, and 316–45°).

directly ahead of the direction of approach by the observer (Fig. 7.11). Analysis of such angles could be used to identify a disturbance effect by the observer approaching the sample points. If found to be present, the disturbance effect might be due to animals moving ahead (toward 0°) or merely remaining silent and hidden from the observer.

7.5 Training observers

Large-scale surveys usually employ several technicians to gather the data to be used in estimation of density. This section provides some considerations in preparing technical staff members for their task.

Perhaps the first consideration is to interest the staff in the survey and its objectives and to familiarize them with the study area and its features. Then they must be carefully trained in species identification and become familiar with relevant information about the biology of the species of interest. Particular attention must be given to activity patterns and calls or songs or other cues of the species. Some time in the field with a good biologist is essential. Clear survey instructions must be given and proper data recording forms should be available. Again, a small-scale pilot survey will be highly beneficial. People with prior experience are helpful to a team effort. Discussions held at the end of each day of surveying can be used to answer questions and listen to suggestions. A daily review of histograms of the incoming data will likely reveal possible problems to be corrected (e.g. heaping).

Training of observers is essential if estimates of absolute abundance are required. It is particularly difficult to estimate distances to purely aural cues; Reynolds *et al.* (1980) used an intensive 2-week training period, during which distances to singing or calling birds were first estimated and then checked by pacing them out or by using rangefinders. This is done for different species and for different cues from a single species. The training period should also be used to validate identifications made by each observer. Ramsey and Scott (1981a) recommended that observers' hearing ability be tested, and those with poor hearing be eliminated.

If most objects are located aurally, then the assumption that they are not counted more than once from the same line or point may be problematic. If for example a bird calls or sings at one location, then moves unseen by the observer to another location and again vocalizes, it is likely to be recorded twice. Training of observers, with warnings about more problematic species, can reduce such double counting. In some point transect surveys, points are sufficiently close that a single bird may be recorded from two points. Although this violates the independence assumption, it is of little practical consequence.

In point transect surveys, bias arising from either random or responsive movement and from inadvertent double counting is likely to be less if the time spent at each point is short, but assumptions that the detection function is unity at the point and has a shoulder are then more likely to be violated. Scott and Ramsey (1981) give a useful account of the effect on bias of varying the count period, and in particular warn against longer times, as bird movement can lead to serious overestimation.

Technicians should have instruction and practice in the use of instruments to be used in the survey (e.g. rangefinders, compass, LORAN C, 2-way radios). If distances are to be paced or ocularly estimated, then calibration and checking is recommended.

Basic safety and first aid procedures should be reviewed in planning the logistics of the survey. In particular, aircraft safety is a critical consideration in aerial survey work (e.g. proper safety helmets, fire resistant clothing, fire extinguisher, knowledge of emergency and survival procedures). Radio communication, a good flight plan, and an emergency locator transmitter (ELT) are important for surveys in remote areas or in rugged terrain. Fortunately, many conservation agencies have strict programmes to help ensure aircraft safety for their employees.

7.6 Field methods for mobile objects

We listed among the assumptions for line transect sampling that any movement of animals should be slow relative to the observer (Hiby 1986) and independent of the observer. In fact it is possible to relax the requirement that movement is slow. Consider for example seabird surveys. Procedures as laid down by Tasker *et al.* (1984) work well for birds feeding or resting on the sea, or for strip transects for which an instantaneous count of flying birds within a specified area can be made, but traditional line or strip transect estimates can have large upward bias for seabirds in flight. Provided the seabirds do not respond to the observation platform, the following approach allows valid abundance estimation. For birds resting on the sea or feeding in one place, use standard line or strip transect methods; for species that occur in flocks, treat the flock as a detection, and record flock (cluster) size. The position recorded for a flock should be the 'centre of gravity' of the flock, **not** the closest point of the flock to the observer. Record and analyse seabirds in flight separately. Whenever a flying bird (or flock) is detected, wait until it comes abeam of the observation platform, and only then record its position. For line transects, its perpendicular distance is estimated at this point; for strip transects, the bird is recorded only if it is within the strip when it comes abeam. Do not record the bird if it is lost from view before it comes abeam. If it alights on the water, record its position at that time, and record it as resting on the water. Having obtained separate density or abundance estimates for resting/feeding and for flying birds, sum the two estimates. If birds are known to respond to the observation platform, but only when quite close to it, the above procedure may be modified. Determine the smallest distance d beyond which response of flying birds to the platform is likely to be minimal. Instead of waiting for the bird to come abeam, its position is now recorded when its path intersects with a line perpendicular to the transect a distance d ahead of the platform. For this procedure to work, probability of detection at distance d, $g(d)$, should equal, or be close to, one. In this circumstance, flying birds that are first detected after they have crossed the line will have mostly intersected it at relatively large perpendicular distances, and can be ignored.

For point transect surveys, objects that pass straight through the plot, such as birds flying over the plot, should be ignored. Strictly, the count should be instantaneous. If the count is considered to correspond to the start of the count period, objects moving into the plot during the count should be ignored, whereas those that move out of the plot should be recorded at their initial location. If the count is intended to be of all detected objects present at the end of the count period, the converse holds. The first option is the easier to implement in the field. If objects that are moving through the plot are recorded at the location they were detected, density is overestimated (Chapter 5).

7.7 Field methods when detection on the centreline is not certain

A similar strategy to that of Section 7.6 can be adopted for objects that are only visible at well-spaced discrete points in time, so that $g(0) < 1$. Consider for example a species of whale that dives for prolonged periods. Suppose detected whales are only recorded if they are at the surface at the time they come abeam of the observation platform, and their perpendicular distance is estimated at that time. Then a conventional line transect analysis yields an estimate of the density of whales multiplied by the proportion of whales at the surface at any given time. If that proportion can be estimated, then so can population abundance. This strategy is of little use on slow-moving platforms such as ships, since most detected whales will have dived, or moved in response to the vessel, by the time the vessel comes abeam. However, it can be very successful for aerial surveys. Its weakness is that further survey work must be carried out to estimate the proportion of whales at the surface at a given time. This is done by monitoring individual whales over prolonged periods. Possible problems are that it may not be possible to monitor sufficient whales for sufficiently long periods; monitored whales may be affected by the presence of the observer, and may spend an atypical amount of time at the surface; if whales go through periods of short dives followed by longer dives, most of the monitored sequences may be short-dive sequences, since whales are more likely to be lost if they dive for a longer period; whales that habitually spend more time at the surface are more likely to be detected and monitored; it can be difficult to define exactly what is meant by at the surface, especially if monitoring of individual whales is done from a surface vessel, and the line transect surveys from the air.

Methods for estimating $g(0)$ from cetacean shipboard surveys were described in Section 6.4. Discussion of survey design is given there; we do not address the topic here because methodological development is not sufficiently advanced to allow us to make general recommendations with confidence. However, most of the methods described in Section 6.4 rely on detections made from two 'independent observer' platforms. These methods usually require that duplicate detections (whales detected from both platforms) are identified. In this circumstance, general recommendations on field procedures can be made. First, **all** sighting cues should be recorded, for easier assessment of which detections are duplicates. To facilitate this goal further, the exact time of each cue should be noted, preferably using a computerized recording system. Methods are generally sensitive to the judgement of which detections are duplicates, so every attempt should be made to minimize uncertainty, and the uncertainty should be reflected in the estimated variance of $\hat{g}(0)$ (Schweder *et al.* 1991). Ancillary data such as animal behaviour, cluster size and weather should be recorded for each detection, to allow the analyst to use stratification or covariate modelling to reduce the impact of heterogeneity on $g(0)$ estimation.

7.8 Field comparisons between line transects, point transects and mapping censuses

Several researchers have attempted to evaluate the relative merits of point transect sampling, line transect sampling and mapping censuses through the use of field surveys. We summarize their conclusions here.

7.8.1 Breeding birds in Californian coastal scrub

DeSante (1981) examined densities of eight species of breeding bird in 36 ha of Californian coastal scrub habitat. True densities were established by an intensive programme of colour banding, spot-mapping and nest monitoring. Point transect data were collected by four observers who were ignorant of the true densities. Points were chosen on a grid with roughly 180 m separation between neighbouring points. This gave 13 points, three of which were close to the edge of the study area. Only one-half of those three plots were covered, so that in effect 11.5 points were monitored. The recording time at each point was 8 minutes. Each point was covered four times by each of the four observers. Detection distances were grouped into bands 9.14 m (30 ft) wide out to 182.9 m (600 ft), and into bands twice that width at greater distances. The 'basal radius', within which all birds are assumed to be detected, was estimated as the internal radius of the first band that had a density significantly less than the density of all previous bands. Significance was determined by likelihood ratio testing with a critical value of four (Ramsey and Scott 1979). The density of territorial males was estimated using counts of singing males only, unless twice that number was less than the total count for that species, in which case the density of territorial males was estimated from half the total count. This follows the procedure of Franzreb (1976) and Reynolds *et al.* (1980). Only experienced observers were used, and they were given four days of intensive training. One day was spent verifying observers' identifications from calls and songs, one day estimating and verifying distances to both visual and aural detections, and two days carrying out simultaneous counts at points. DeSante found that the point transect data yielded underestimates of density, by about 18% when estimates for all eight species are summed. Individual species were underestimated by between under 2% and roughly 70% (Table 7.3; taken from DeSante 1981). Correlation between actual density and estimated density across the eight species was good ($r = 0.982$). Variation in bias between observers was small. The use of the method of Ramsey and Scott (1979) undoubtedly contributed to underestimation of density in DeSante's study; the method assumes that all birds within the basal radius are detected, and the basal radius is estimated here from a small number of points, almost certainly giving rise to estimates of basal radii that are too large. An analysis of the original data by more recent methods might prove worthwhile.

Table 7.3 Actual density and point transect estimates of density of eight bird species in a Californian coastal scrub habitat (from DeSante 1981). The negative errors indicate that the point transect estimates are low, possibly due to poor choice (in the light of recent developments) of point transect detection model

Species	Actual density/36 ha	Point transect estimates		
		Density/36 ha	% error	Basal radius (m)
Scrub jay	3.8	1.1	- 70.0	64.0
Bushtit	2.2	2.1	- 5.0	45.7
Wrentit	36.3	26.9	- 25.9	54.9
Bewick's wren	9.4	8.3	- 11.4	91.4
Rufous-sided towhee	14.0	8.5	- 39.4	91.4
Brown towhee	0.6	0.4	- 36.7	64.0
White-crowned sparrow	32.4	31.8	- 1.9	91.4
Song sparrow	35.5	31.2	- 12.2	64.0
Total	134.2	110.3	- 17.8	

7.8.2 Breeding birds in Sierran subalpine forest

DeSante (1986) carried out a second assessment of the point transect method, in a Sierran subalpine forest habitat. On this occasion a 48 ha study plot was identified in the Inyo National Forest, California. Methods were similar to the above study, with actual densities estimated by intensive spot-mapping and nest monitoring. Twelve points were established with a minimum separation of 200 m, and count time at each point was eight minutes, preceded by one minute to allow bird activity

Table 7.4 Actual density and point transect estimates of density of 11 bird species in a Californian subalpine forest habitat (from DeSante 1986). Densities were estimated from detections of singing males alone, except where indicated by *, for which densities were estimated from counts of all birds. The first row for each species corresponds to late June and the second to mid-July

Species	Actual density/ 48 ha	Point transect estimates		
		Density/ 48 ha	% error	Basal radius (m)
Cassin's finch	26.9	16.5	− 38.6	90
Cassin's finch*	20.6	16.8	− 18.5	60
Dark-eyed junco	23.0	16.5	− 28.2	60
	23.1	10.0	− 56.7	110
Dusky flycatcher*	17.1	28.5	+ 66.8	40
	16.4	19.7	+ 20.3	50
Yellow-rumped warbler	15.3	14.7	− 3.6	100
	15.0	19.4	+ 29.3	80
Mountain chickadee*	12.0	14.9	+ 24.3	40
	11.9	9.7	− 18.3	60
Pine siskin*	12.0	13.6	+ 13.2	50
	13.3	8.9	− 32.7	40
Hermit thrush	5.7	2.8	− 51.6	100
	7.8	12.9	+ 65.3	110
White-crowned sparrow	3.8	1.3	− 67.0	120
	3.0	1.6	− 46.9	100
American robin*	3.4	6.6	+ 95.0	40
	–	–	–	–
Clark's nutcracker*	2.1	4.1	+ 95.9	70
	–	–	–	–
Ruby-crowned kinglet	1.6	1.5	− 3.3	120
	–	–	–	–
Total	122.9	121.1	− 1.5	
	111.1	99.1	− 10.8	

to return to normal after arrival at the point. Counts were carried out on four days in late June and a further four days in the second week of July. Statistical methodology was the same as for the above study. Estimated densities are shown in Table 7.4. Although DeSante gave confidence intervals for point transect density estimates, we do not quote them here, as they were calculated as if 48 points had been counted, when in fact 12 points were each counted four times. His intervals are therefore too narrow; repeat counts on the same point do not provide independent detections, and such data should be entered into DISTANCE with sample effort for a point set equal to the number of times the point was covered. The empirical variance option for n combined with the bootstrap option for $\hat{f}(0)$ then gives valid intervals. We further condense DeSante's table to include only common species – those species for which there were more than 25 point transect detections. DeSante concluded that the results were less encouraging than those obtained in his earlier study, and he gave thorough discussion of the possible reasons. These include a higher proportion of birds missed close to the observer, due to the tall canopy, leading to underestimation, and more double-counting of individuals through greater mobility, leading to overestimation. Greater mobility relative to the scrub habitat of his earlier survey occurred because densities were lower and there were more large species, both contributing to larger territories. Further, birds flying over the plot were counted; this is poor practice, leading to overestimation. Birds first detected flying over the point should either be ignored, or counted only if they land within detection distance, and that distance should then be recorded (Section 7.6). The relatively poor performance of the point transect method may be partially attributable to the fact that just 12 points were covered. DeSante considers that an alternative scheme of relocating points each day would not have significantly increased accuracy. Although this may be true for many species, for those species which tend to sing from favoured song posts, four counts from each of 12 points is appreciably less informative than one count from each of 48 points, even when, as here, the study area is too small to accommodate 48 non-overlapping plots.

7.8.3 Bobolink surveys in New York state

Bollinger *et al.* (1988) compared line and point transect estimates with known densities of bobolinks (*Dolichonyx oryzivorus*) in one 17.6 ha meadow and one 12.6 ha hayfield in New York state. Intensive banding and colour marking established population sizes, and whether each individual was present on a given day. Twelve and ten line transects, respectively, of between 200 and 500 m length were established at the two sites, together with 18 and 14 point transects. One or two transects were covered per day, each transect taking 3–7 minutes. The observer waited four minutes after arriving at the start of a transect to allow birds to return to normal behaviour, and the line(s) was/were covered in both morning and afternoon. A four minute waiting period was also used for point transects, and a four minute counting period was found to be adequate. Two points were covered each morning of the study and two each afternoon. Thus, as for DeSante's studies, adequate sample sizes were obtained by repeatedly sampling the same small number of transects. The Fourier series model was applied to both line and point transect data. For point transects, it was applied to squared detection distances, which can lead to poor performance, as noted earlier.

Bollinger *et al.* found that their point transects took longer to survey than line transects on average, but appreciably less time was spent counting. The number of males counted during point transects was slightly greater on average than during line transects, but substantially fewer females, which are more secretive, were counted. Thus, density estimates were obtained for both males and females from the line transect data, but for males only from the point transect data. The Fourier series was unable to fit adequate non-increasing detection functions to the morning point transect counts, which the authors suggest may be indicative of movement of bobolinks away from the observer. Both methods overestimated male abundance, with the point transect method showing the greater bias (mean relative bias of 140%, compared with 76% for line transects). Bias was found to be lower in general for the afternoon count data. Line transect estimates of female densities were approximately unbiased, although there was a suggestion of underestimation during incubation, countered by overestimation when the young were large nestlings or had fledged. About 25% of bias in male density estimates was attributed to avoidance of field edges by the birds; transects were deliberately positioned so that field edges were not surveyed. Survey design to eliminate or reduce this source of bias is discussed in Section 7.2. Additional bias was considered to be possibly due to 'random' movement of birds, with detection biased towards when the birds were relatively close to the observer, or to attraction to the observer – although this latter explanation is difficult to reconcile with the suggestion that poor fits for point transect data might be due to observer avoidance. It may be that the Fourier series model was inappropriate for the squared distance data, as was found by Buckland (1987a) for the point transect data of Knopf *et al.* (1988), rather than that birds avoided the observer.

7.8.4 Breeding bird surveys in Californian oak–pine woodlands

Verner and Ritter (1985) compared line and point transect counts in Californian oak–pine woodlands. They also considered counts within fixed areas (strip transects and circular plots) and unbounded counts from both lines and points as measures of abundance. They defined four scales for measures of abundance: a 'nominal scale', which requires information only about occurrence; an 'ordinal scale', which requires sufficient information to rank species in order of abundance; a 'ratio scale', which requires relative abundance estimates – bias should be either small or consistent across species and habitats; and an 'absolute scale', which requires unbiased (absolute) estimates of abundance. They assessed the performance of different survey methods in relation to these scales. True bird densities were unknown. Although the area comprised 1875 ha of oak and oak–pine woodlands in the western foothills of the Sierra Nevada, the study plots were just two 19.8 ha plots of comparable relief and canopy cover, one grazed and the other ungrazed. This study, in common with most others of its type, therefore suffers from repeated sampling of the same small area, and hence non-independent detections.

Sampling took place over 8-day periods, with two transects and ten counts covered per day. The transects were 660 m long and were positioned randomly at least 60 m apart each day. The points were located at intervals of 150 m along the transects. The design was randomized and balanced for start time, starting point and count method. All counts were done by a single observer. Four methods of analysis were considered: bounded counts (strip transects of width 60 m and circular plots of radius 60 m); Emlen's (1977) *ad hoc* estimator; Ramsey and Scott's (1978) method; and the exponential polynomial model (Burnham *et al.* 1980). Note that we do not recommend any of these estimators for songbird data. The Fourier series model was found to perform less well than the exponential polynomial model, so results for it were not quoted. Interval estimates were computed for the exponential polynomial model only. Without more rigorous analysis of the data and with no information on true densities, comparisons between the methods of analysis and between line and point transects are severely constrained. However, the authors concluded that line and point transects showed similar efficiency for determining species lists (for point separation of 150 m and 8 min per point); point transects yielded lower counts per unit time, but would be comparable if point separation was 100 m and counting time was 6 min per point; Ramsey and Scott's (1978) method gave widely differing estimates from line transect data relative to those from point transect data; more consistent comparisons between models were obtained from line transects than from point transects; most species showed evidence of movement away from the observer; the exponential polynomial model was thought to be the most promising of the four methods.

7.8.5 Breeding birds in riparian vegetation along the lower Colorado River

Anderson and Ohmart (1981) compared line and point transect sampling of bird populations in riparian vegetation along the lower Colorado River. All observers were experienced, and each carried out replicate surveys under both sampling methods in each month from March to

Table 7.5 Density estimates from line and point transect sampling and spot mapping of ten bird species in honey mesquite habitat along the lower Colorado River (from Anderson and Ohmart 1981). Densities are numbers per 40 ha, averaged for March, April and May 1980

Species	Line transect	Point transect, first interval 15 m wide	Point transect, first interval 30 m wide	Territory mapping
Gila woodpecker	2	2	2	2
Ladder-backed woodpecker	4	3	6	8
Ash-throated flycatcher	11	12	10	12
Black-tailed gnatcatcher	14	28	26	24
Verdin	7	8	10	10
Cactus wren	4	4	4	8
Lucy's warbler	37	32	28	41
Northern oriole	12	15	14	13
Crissal thrasher	2	1	2	14
Abert's towhee	21	25	23	21
Total	114	130	125	153

June 1980. The distance walked was identical for each sampling method. The line transect data were analysed using the method of Emlen (1971), and the point transect data using method M1 of Ramsey and Scott (1979). Thus, models that can perform poorly were again used, and this may have compromised some of the authors' conclusions. For example, they sometimes obtained inflated density estimates from the point transect data when detection distances less than 30 m were divided into two or more groups, whereas the method performed well when all observations within 30 m were amalgamated into a single group. A more robust method would be less sensitive to the choice of grouping. Anderson and Ohmart concluded that the point transect surveys took longer to complete when the time spent at each point was 8 minutes, but that times were comparable for recording times of 6 or 7 minutes. More area was covered and more birds detected using the line transect method, because of the dead time between points for the point transect method. The authors tabulated estimated average densities of ten of the more common species, which appear to show relatively little difference between line and point transect estimates, or, for most species, between those estimates and estimates from territory mapping, although overall, line transect estimates were significantly lower than mapping estimates (Table 7.5). Neither method generated average estimates significantly different from the point transect estimates. However, the authors noted that day-to-day variation in point transect estimates was greater than for line transect estimates, and suggested that at least three repeat visits to point transects are necessary, whereas two are sufficient for line transects. They concluded that the line transect method is the more feasible, provided stands of vegetation are large enough to establish transects of 700–800 m in length, and provided that the topography allows ambulation. They indicated that these transects should be adequately cleared and marked. In areas where vegetation occurs in small stands, or where transects cannot be cleared, they suggested that point transects might be preferable.

7.8.6 Bird surveys of Miller Sands Island in the Columbia River, Oregon

Edwards *et al.* (1981) compared three survey methods, two of which were line and point transect sampling. They described the third as a 'sample plot census', in which an observer records all birds that can be detected within a sample plot. Distances were not recorded, so corrections for undetected birds cannot be made. The method gives estimates of absolute density only if all birds in the sample plot are detected. The study was carried out on Miller Sands Island in the Columbia River, Oregon. Four habitats were surveyed: beach, marsh, upland and tree-shrub. The method of Emlen (1971) was used for the line transect data, and the method of Reynolds *et al.* (1980) for the point transect data. The authors found that significantly more species were detected using point transects than either line transects or sample plots. However, the truncation point for line transects had been 50 m, and for point transects 150 m, and the sample plots were circles of radius 56.4 m, so the difference is unsurprising. Density estimates were found to be similar for all three methods, although the point transect estimate was significantly higher than the line transect estimate in a handful of cases. The methods were not standardized for observer effort or for time spent in the field, making comparison difficult.

7.8.7 Concluding remarks

More studies, carefully standardized for effort, would be useful. A large study area, too large for all territories to be mapped, is required for a fair comparison of line and point transect sampling and of mapping methods. Within such an area, line and point transect sampling grids could be set up using the recommendations of this chapter, so that both methods require roughly the same time in the field on the part of the observer. In addition, territory mapping should be carried out on a random sample of plots within the area, again so that time in the field is comparable with each of the other methods. The analyses of the line and point transect data should be comparable, for example using the hazard-rate or the Fourier series model in both cases. More than one model should be tried. The precision of each method should then be compared, and an assessment should be made of whether at least one of the methods over- or underestimates relative to the others. If different researchers could agree on a common design, this could be repeated in a variety of habitats, to attempt to establish the conditions and the types of species for which point transect sampling is preferable to line transect sampling or *vice versa*.

The studies described here tend to favour line transects over point transects. This may partly reflect that line transect methodology has had longer to evolve than point transect methodology. It is important to realize that point transect sampling is essentially passive, whereas line transect sampling is active. For birds that are unlikely to be detected unless they are flushed or disturbed, such as many gamebirds or secretive female songbirds, line transect sampling should be preferred. Very mobile species are also likely to be better surveyed by line transects, provided the guidelines for such species given in this chapter are adhered to. For birds that occupy relatively small territories, and which are easily detected at close range, such as male songbirds of many species during the breeding season, point transects may be preferable, especially in patchy or dense habitat. Attempts to estimate abundance of all common species in a community by either method alone are likely to perform poorly for at least some species. If only relative abundance is required, to monitor change in abundance over time, either technique might prove useful. However, bias may differ between species, so great care should be taken if cross-species comparisons are made. Equally, bias may differ between habitats, although well-designed line or point transect studies yield substantially more reliable comparisons across both species and habitats than straight counts of birds without distance data or other corrections for detectability.

Several other authors compare line transect sampling with census mapping. Franzreb (1976, 1981) gives detailed discussion of the merits of each, concluding that census mapping is substantially more labour intensive, but for some species at least, provides better density estimates. Choice of method must take account of the species of interest, whether density estimates for non-breeding birds are required, the habitat of the study area, resources available, and the aims of the study. In the same publication, O'Meara (1981) compares both approaches. His study includes an assessment of the binomial models of Järvinen and Väisänen (1975). These models were found to be more efficient, both in terms of time to record detections into one of just two distance intervals and in terms of variance of the density estimate, than Emlen's (1971, 1977) method, which requires detection distances to be recorded so that they can be assigned to successive bands at increasing distances from the line. Line transect estimates were found to be lower than census mapping estimates, apparently due to imperfect detection of birds at or near the line (Emlen 1971; Järvinen and Väisänen 1975), but estimates could be obtained for twice as many species from the line transect data. Redmond *et al.* (1981) also compared census mapping with the line transect methods of Emlen (1971) and Järvinen and Väisänen (1975), for assessing densities of long-billed curlews (*Numenius americanus*). They also found that the method of Järvinen and Väisänen was easier to apply than that of Emlen, because it requires just two distance intervals, and was far more efficient than census mapping in terms of resources in the case of territorial male curlews. Female curlews were not reliably surveyed using line transects, nor were males during brood rearing.

Several field evaluations have been made of distance sampling theory in which a population of known size or density is sampled and estimates of density made (Laake 1978; Parmenter *et al.* 1989; White *et al.* 1989; Bergstedt and Anderson 1990; Otto and Pollock 1990). Strictly speaking, these are not evaluations of the distance sampling methods, but rather an assessment of the degree to which the critical assumptions have been met under certain field conditions. We encourage more studies of this type as such results often provide insights into various issues. **We strongly recommend that the person performing the data analysis should not know the value of the parameter being estimated.**

7.9 Summary

Line and point transect sampling are well named because it is the area near the line or point that is critical in nearly all respects. In many ways the statistical theory and computational software are now more adequately developed than the practical field sampling methods. **The proper design and field protocol have not received the attention deserved prior to data collection.**

Having determined that line or point transect sampling is an appropriate method for a study, the planning of the sampling programme must focus on the three major assumptions and attempt to ensure their validity: (1) $g(0) = 1$, (2) no undetected movement, and (3) accurate measurements or counts (e.g. no heaping, especially at zero distance). Furthermore, if the population exists in clusters, then accurate counts of cluster size must be taken. Sample size, as a rough guideline, should be at least 60–80; formulae for determining appropriate sample size are

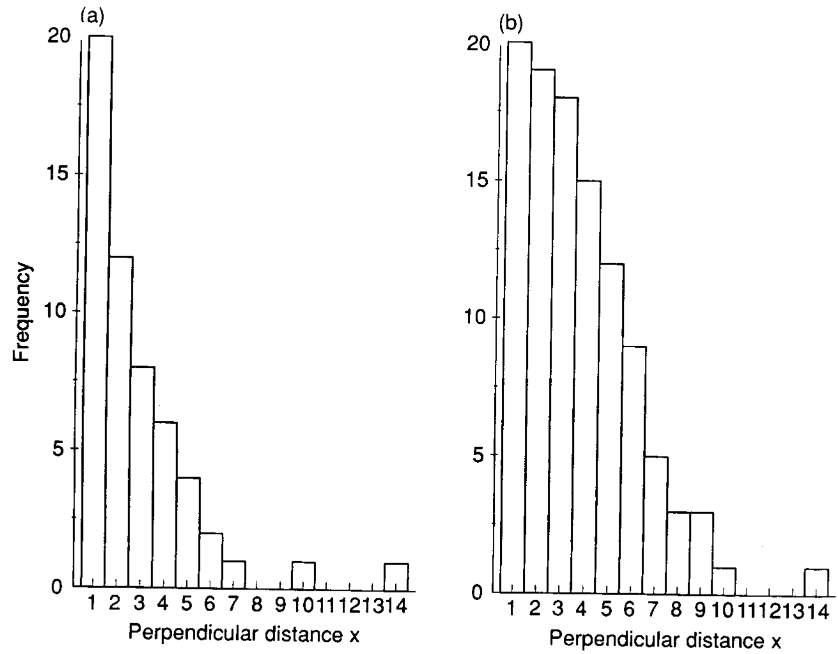

Fig. 7.12. (a) These line transect data are spiked, difficult to model, subject to imprecision in estimating density, and usually the result of poor survey design or conduct. Proper design and field procedures should result in data more nearly as depicted in (b). These data exhibit a shoulder and can be analysed effectively if no undetected movement occurred and distances were measured accurately. Some truncation prior to analysis is suggested in both cases.

given in Section 7.2. The distance data should be taken such that the detection function $g(y)$ has a shoulder (Fig. 7.12). Transect width w should be large enough so relatively few detections are left unrecorded; plan on data truncation as part of the analysis strategy.

A pilot study is highly recommended. A preliminary survey provides the opportunity to assess a large number of important issues, assumptions, practicalities, and logistical problems. Failure to complete a pilot programme often means wasted resources at a later stage of the survey. Consultation with a biometrician familiar with sampling biological populations is strongly advised.