# Application of Modern Inventory Techniques in the Forests of Western Australia

*CALM Occasional Paper No. 1/92 JANUARY 1992*

Edited by R.D. Spencer
with an Introduction by H. Campbell

Published by the
Department of Conservation and Land Management
Como, Western Australia

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# *FOREWORD*

The jarrah forest of Western Australia has supplied large quantities of timber for the local and overseas markets almost since the time the colony was first settled. It is a tribute to the forest managers of the past that, despite the ravages of fire and disease and the use of the forest for timber production, the forest still remains a major source of hardwood timber, continues to protect the water catchments which supply a large proportion of the water for Perth, is a major reservoir of plants and animals and is an extremely popular resource for outdoor recreation.

Over the past two decades there has been an almost exponential increase, however, in the demand to use the forest for a multiplicity of purposes. Parallel to this there has been a corresponding increase in public awareness about forests. A by-product of both these phenomena has been the incidence of increasing conflict over forest use and management.

To the forest managers of today this has meant that the almost involuntary approach to forest management in the past, which was sufficient to meet the demands on the forests, is no longer sufficient.

In some parts of the world forest policy-makers and managers have reacted to the increasing demands and consequent conflict over forests by segmenting the forest into specific uses. This has the perceived advantage of clarifying management objectives and accountability and partitioning conflict. Unfortunately, the reality has been that the conflict continues in the form of a war on the borders between each defined use area.

In Western Australia while we have developed an extensive scientifically-based reserve system from which forest harvesting activities are excluded, the balance of the forest is managed with the objective of optimizing all forest values. This integrated approach to forest management, we believe, is more efficient because the sum of all of the values is greater than if an area were used for a specific use.

But integrated forest management can only succeed if the forest database is comprehensive and accurate. A major prerequisite to the development of the sophisticated forest management strategies, which are required for successful integrated management, was a comprehensive and accurate documentation of the timber resource in the forest. The jarrah forest inventory provides us with this database.

The outcomes of the inventory project demonstrate major achievements in the coordination of complex technologies to provide more efficient systems for acquiring, analysing and reporting information on forest condition.

Aerial photographs have been used traditionally in forest inventory systems to stratify the sample area. The jarrah inventory used photography more intensively as a means to measure the parameters of individual trees. Although the potential benefits of this approach have long been understood, practical progress towards their realization has generally been slow and application of the techniques has not been widespread.

There seems little doubt that during the next decade geographic information systems (GIS) will become more firmly established as key elements of management planning methodologies. The integration of the jarrah inventory data with the CALM GIS as described in this document is seen therefore as a significant technical advance.

These and other developments reported in this document have been made possible by the foresight, knowledge and dedication of CALM staff drawn from a range of disciplines working in close collaboration with an inventory specialist from the Forestry Section at the University of Melbourne. In terms of its approach and achievements the work provides a model for wider application in other States and overseas.

Dr Syd Shea
Executive Director
Department of Conservation and Land Management

# ACKNOWLEDGEMENTS

Work described in this document has been supported at all levels within the Department of Conservation and Land Management but it could not have proceeded without the strong support of Mr. Don Keene, Director of Forest Resources Division and Dr. Syd Shea, Executive Director of the Department.

The work has required innovative, multidisciplinary approaches to define and resolve numerous challenges that have arisen as a result of applying various complex new technologies. Valuable contributions have come from numerous people within the Department, especially from Inventory, Land Information, Tim Westcott from Computing Services, and Fire Protection Branches. Mr Jerry Van Didden of the Fire Protection Branch made significant contributions to the design and testing of airborne equipment, while other staff have contributed as camera operators, navigators, photo-interpreters and ground measurement crews.

The University of Melbourne supported visits by Mr Ray Spencer, Senior Lecturer, to advise on various aspects of project design and implementation. Mr Bruce Montgommery and Mr Chris Dixon, from the Surveying Department, Curtin University, assisted with camera calibrations and photogrammetry; Adam Technology provided advice and technical support on analytical stereo-digitizing equipment; West Coast Helicopters contracted for aircraft support.

Barbara Spencer managed the exacting tasks of compiling the various draft materials for the report.

All of these contributions, together with many others that have assisted with the project's development, are gratefully acknowledged.

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# *ABBREVIATIONS AND TERMS DEFINED*

| | |
|---|---|
| **b.t.** | Bark thickness. |
| **CALM** | Department of CALM: Department of Conservation and Land Management. |
| **d.b.h.** | Diameter at breast height. |
| **d.b.h.o.b.** | Diameter at breast height over bark. |
| **d.c.** | Diameter at crown break. |
| **d.o.b.** | Diameter over bark. |
| **d.u.b.** | Diameter under bark. |
| **GIS** | Geographic information system; a computer-based system for storing,analysing and presenting spatial data. |
| **GPS** | Global positioning system; a system for accurate positioning and navigation based on signals from NAVSTAR satellites. |
| **hip-chain** | Calibrated disposable cotton measuring tape. |
| **hotspot** | Over-exposure of part of a photograph when the sun is almost directly overhead. |
| **metric camera.** | A camera designed for accurate photogrammetry. |
| **semi-metric camera.** | A camera with many of the characteristics of a metric camera, that may provide accurate measurements. |
| **stereopair** | A pair of overlapping aerial photographs suitable for stereoscopic viewing. |
| **t.d.l.** | Top diameter limit. |
| **t.d.l.u.b.** | Top diameter limit (under bark). |
| **window** | Area of forest defined using GIS,for which a volume estimate is required. |

# SUMMARY

This document describes the techniques developed for a major resource-level inventory of the jarrah (*Eucalyptus marginata*) forest of Western Australia. It reviews the requirements for estimating timber volumes from aerial photographs and discusses the use of large-scale aerial photographs as the first-phase sample in a two-phase inventory. The document also discusses new techniques for assessing wood quality on the second-phase ground sample plots and describes the use of Geographic Information Systems (GIS) for combining photo and ground sample data with other forest resource information.

Following commitments in the State's new Timber Strategy, the jarrah inventory was designed to provide information over 1.4 million ha of multiple-use State forest (CALM 1987). The design objectives for the inventory were :

- completion by 1991 (i.e. within three years);
- provision to estimate volumes for all potentially usable wood and to partition the gross bole volume into different timber grades, however defined;
- sampling error for sawlog-volume estimates not to exceed 25 per cent (0.95 probability) for management units of 10 000 ha; and
- establishment of the inventory as a subsystem of a Geographic Information System.

The new inventory was designed as a two-phase sample. In the first phase, sample plots were interpreted and measured on 1:1200 scale aerial photographs taken at points on a rectangular grid. This scale was selected as the most suitable for measuring individual tree heights and identifying species. In the second phase, a subsample of the first-phase plots was measured intensively from the ground.

Photographs were acquired with a fixed-base photographic system using twin 70 mm cameras attached to each end of a 7.5 m boom mounted transversely on a helicopter. Stereopairs were obtained by simultaneously exposing the two cameras and photo scale was calculated from the ratio of photo-base over actual air-base (i.e. camera separation).

A Global Positioning System (GPS) receiver coupled to a laptop computer was used to navigate during photography and to determine the location of each pair of photographs. The system ensured efficient inflight navigation and regular spacing between stereopairs. It also enabled quick location of ground plots in the forest and integration of sample data with the GIS database.

The species of each tree was interpreted from the photographs and stem volumes were estimated from an exponential relationship between bole volume and total height. Ten per cent of the photo samples were then located on the ground and measured to correct for any bias and to estimate the volume of log products. Ground plots were located using 1:25 000 scale maps produced from the GPS data and by point-to-point navigation using the large-scale photographs.

Ground measurements involved recording of quality characteristics, both defects and other attributes, on the boles of all sample trees. Computer programs were then used to relate these characteristics to specific products under defined sets of specifications. This allowed for volume estimates to be calculated for new products and for changes in product specifications over time.

All data collected from the photo and ground samples were linked to geographic coordinates stored in a GIS. Forest management constraints could be modelled in the GIS and used to identify land available for timber harvesting within specific 'windows'. A volume statement could then be derived for this geographical zone by identifying and processing data from the sample plots within that zone.

The system used for the jarrah forest inventory has provided timely and flexible information for strategic forest management. The use of large-scale aerial photographs has allowed a large area of forest to be sampled in a short period. The assessment of wood qualities has allowed flexibility in volume estimates to reflect different product standards. The linking of the inventory data with geographic information has allowed the development of applications such as resource density mapping, resource access and economic analysis and for estimates to be provided under changing management constraints.

# *1 INTRODUCTION*

**H.Campbell**

## 1.1 Background

Some two million hectares of jarrah (*Eucalyptus marginata*) forest are managed by the Department of Conservation and Land Management (CALM). This forest contains a mixture of jarrah and marri (*E. calophylla*) together with about twenty-five minor species. Timber production is permitted in 1.4 million ha that lie within multiple use zones of the forest (Fig.1). The remaining areas are either reserved for conservation purposes or will be reserved when management plans published in 1987 are fully implemented (CALM 1987a).

Over the past decade, land use policies have resulted in reservations that have reduced the available area of jarrah forest for timber production by about 17 per cent. These reductions have led to progressive reductions in the allowable annual cut of sawlogs, amounting to about 20 per cent for first-grade sawlogs since 1977.

The impacts of such land use policies on the sawmilling industry have been twofold: a reduction in the level of sawmilling activity and a lowering of confidence in the long-term viability of the industry. The effect of reducing the areas of available forests has been offset to some extent by a lowering of utilization standards, resulting in sawlogs of lesser quality now being used. The perceived lack of secure raw-material supplies to industry has, however, mitigated against investment in new sawmilling technology. Such investment is essential to enable the utilization of a greater range of wood grades and, in particular, the utilization of immature and small dimension logs becoming available from regrowth forests.

## 1.2 Timber production strategies

The Department of Conservation and Land Management's timber production strategies, also published in 1987 (CALM 1987b), set radically new directions for organizing the supply of timber to a restructured sawmilling industry. The strategies seek to :

- restore confidence in the security of access to timber;
- promote investment in new technology;
- at least maintain the current level of sawmilling activity and to increase its contribution to the economy of the State by directing its out-turns to locally based, value-adding industries;
- promote the establishment of new industries capable of utilizing sawmill residues and inferior quality logs not suitable for sawmilling.

An important consequence of the strategies is a realization of the need to modify the basis for regulating the yield of the jarrah forest. The strategy requires a redetermination of the sustainable yield of jarrah sawlogs of all grades, together with the allowable annual cut, by 1992. Currently the basis for yield regulation is the sustainable yield of first grade sawlogs. In order to recalculate an allowable cut and plan for the supply of a wide range of timber quality-grades it is necessary to carry out a new inventory because the required information cannot be obtained from the existing jarrah inventory.

## 1.3 Existing jarrah inventory

The last jarrah inventory, carried out from 1964 to 1971, is considerably out of date and even with progressive past adjustments it fails to account completely for depletions in growing stock owing to logging since 1971, or for the substantial forest growth that has occurred since that time.

The 1964 - 1971 inventory provides estimates of sawlog volumes according to the standards of that time. These standards do not apply today and will be even less applicable in the future because of incentives that encourage changes in utilization standards. Many of the industrial developments being promoted by the current timber production strategies will depend upon the supply of timber grades that have either not been measured at all, or have not been measured exhaustively in past inventories.

## 1.4 New jarrah inventory

### 1.4.1 Corporate objectives

The new inventory has been designed to facilitate implementation of the timber production strategies by providing information required to :

- recalculate annual allowable cut as prescribed by the strategy, thereby placing upper limits on total processing capacities for different products by the various industrial sectors;
- determine the optimum location and capacities for individual industrial units;
- plan a strategic road network to service the industries.

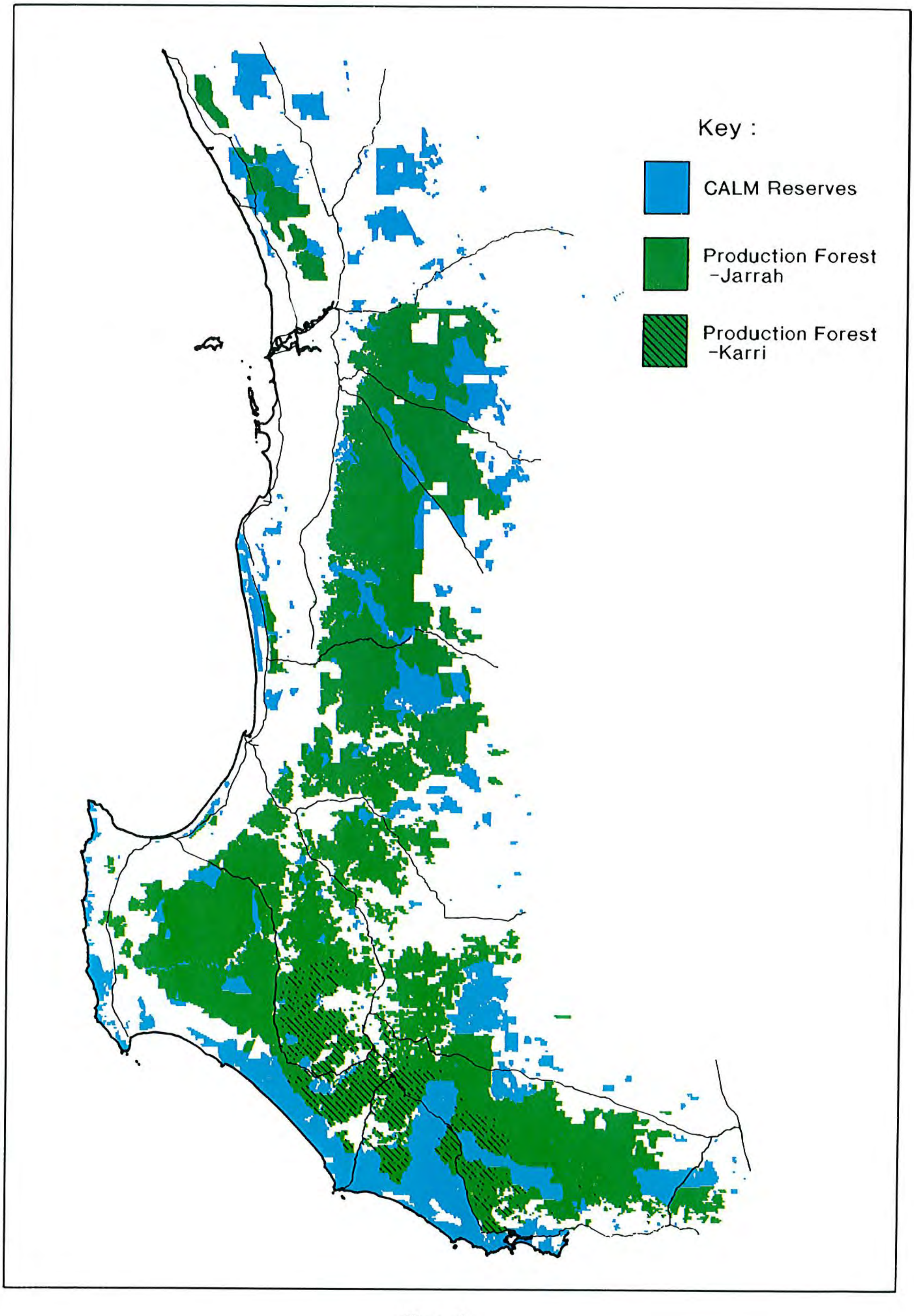


**Figure 1**
Geographic distribution of the jarrah forest within multiple use areas and conservation reserves in Western Australia.

The new inventory data will also contribute to medium range logging planning. This level of planning broadly directs and sequences logging operations in a manner which allows contractual commitments to be met, minimizes adverse visual impacts, and conforms to the silvicultural and fire protection priorities.

### 1.4.2 Inventory design objectives

Inventory design features that are essential for achieving the corporate objectives are :

- the techniques adopted must allow for completion of the inventory by 1991 (i.e. within three years);
- the inventory must provide volume estimates for all potentially utilizable wood. This includes the whole of the gross bole volume, some of the crownwood, all of the standing dead wood and some of the fallen dead wood of 28 tree species occurring in the jarrah forest;
- the sampling error associated with the sawlog volume estimate for management units of about 10 000 ha should not exceed 25 per cent (with 95 per cent confidence);
- the design must accommodate the facility to partition the gross bole volume into timber grades suitable for supply to a variety of industries and, without remeasurement, to repartition the gross bole volume as utilization standards change.

The Department's Geographic Information System (GIS) is well developed and is capable of supporting an inventory processing subsystem. An integrated processing system of this kind has the potential to provide a very powerful planning tool, therefore an additional design objective was adopted :

- to establish the inventory as a subsystem of the GIS.

### 1.4.3 Design principles

An important aim was to integrate the data collection tasks to meet current and perceived future planning needs. The benefits of integration are associated with the facility that a computerized GIS provides to isolate zones of forest with specific characteristics of significance to particular planning problems. Significant characteristics may be related, for example, to land use, tenure, management responsibility, disease status, various land attributes or any combinations of these factors. Zones of interest defined in terms of their spatial relationships with wood processing centres or access routes are relevant to the logistical problems of timber supply.

To fully exploit the benefits of an integrated inventory design, an inventory subsystem must be capable of providing resource-estimates that are free of association with predetermined forest units. Otherwise, unbiased estimates will not be available for any particular zones of interest. For example, stratified random designs do not provide unbiased estimates for forest units which overlap strata.

The new jarrah inventory uses a systematic sampling design, in spite of its higher costs, because of its great flexibility in addressing multiple objectives, many of which cannot be foreseen during the design phase. Its integration with a GIS provides the means to fully realize its potential in this regard, which adequately justifies the acceptance of the higher costs involved.

The new inventory has been designed as a two-phase sample. In the first phase, sample plots are interpreted and measured on approximately 1:1000 scale aerial photographs taken at points on a rectangular grid. The second phase is a systematically selected subsample of the first phase plots which are measured intensively from the ground. This very efficient technique is being used to achieve the first design objective, the time limit.

Plot data from the first phase sample include spatial co-ordinates for the plot centres. These coordinates are calculated by a Global Positioning System (GPS) receiver interfaced with the camera control system. The positional data provide the means for consolidating the sample plot measurements within the GIS.

The achievement of the fourth design objective depends on data obtained from the second phase plots. In conventional inventories, the technique used to partition the bole volume of sample trees into quality timber grades relies on the expert knowledge of trained assessors. Specifically, the assessors correlate visible bole characteristics with internal defects to divide each tree into hypothetical logs that meet the various standards for established industries.

As the *processed* data generated in this way are clearly inadequate to meet flexible product objectives, it has become necessary to record the *raw* data describing visible bole features and then to develop complex sorting algorithms to process these data to meet a variety of product-specifications.

## 1.5 Report objectives

The objectives of this report are to describe the methods that have been developed and the reasons for their selection in order to stimulate interest in their wider application and further development.

# 2 *INVENTORY DESIGN CONCEPTS*

**P.H. Biggs and G.J. Strelein.**

## 2.1 Introduction

A forest resource inventory is

> *a qualitative and quantitative investigation of the location, ownership, extent, nature, condition, purpose and capacity of the forest estate on a broad scale.*
> (Carron 1968)

It involves a combination of textual information (the nature, condition and capacity) and spatial or geographic information (the location, extent and ownership-pattern) about the forest resource. Inventory design covers the methods of collecting, analysing and presenting such information. Selection of a particular design depends on the inventory objectives and various limitations of cost, time, equipment and personnel.

As it is impractical, indeed unnecessary, to measure every tree in a forest other than for its smallest units, various methods of sampling are used to estimate mean values per unit area (e.g. timber volumes) and then to expand these values to obtain estimates for the entire forest and/or its major sections. Simple random sampling, whereby samples are selected at random across the whole forest, is one of the simplest sampling methods. Alternatively, simple systematic sampling uses samples that are selected on a regular pattern, often a rectangular grid, to ensure that the resource is evenly covered by samples. The relative merits of systematic versus random sampling, together with other sampling designs, are discussed in most basic texts on sampling (e.g. Cochran 1977) and forest inventory (e.g. Husch *et al.* 1982).

Sampling efficiency is often improved by subdividing the forest into uniform strata followed by sampling within each stratum separately - called stratified sampling. Stratified sampling is effective in forest types where there are distinctive homogeneous subunits (i.e. strata) in which the variability is low compared with the variability between strata. Examples include forests consisting of a mosaic of even-aged stands of different ages; forests where pure stands of one species occur separated from pure stands of another or several other species. Even if the stratification does not improve statistical efficiency, the map produced in the process may have other benefits for management, such as priority for treatment (Kendall and Sayn-Wittgenstein 1961).

Double sampling (syn. two-phase sampling) is another method that can be applied, with or without stratification, in combination with either random or systematic sample selection to increase the sampling efficiency (Fig. 2). The method involves using a quick and cheap estimation

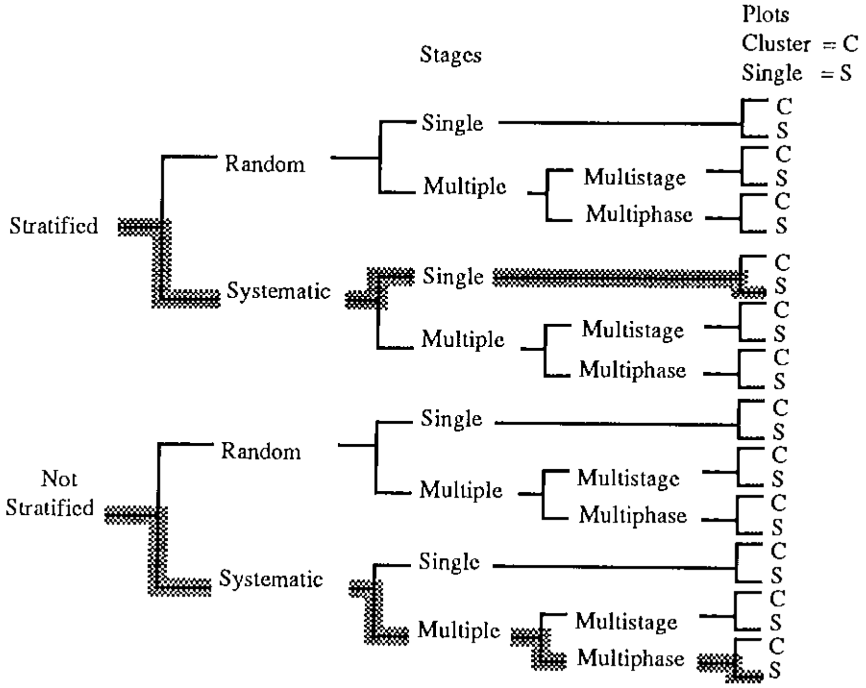


**Figure 2**

Survey-design options. In multiple-survey designs, alternatives shown are not necessarily mutually exclusive. For example, multistage and multiphase sampling (i.e. double sampling) can be and frequently are used together in large-scale photographic sampling programs. The stratified, systematic, single-stage sampling approach using single samples (e.g. plots) at each sample point is commonly used by ground-based forest surveys. The non-stratified, systematic, multiphase approach with single samples per sample point is the method selected for the jarrah inventory.

process, such as aerial photography, to obtain an intensive first-phase sample, supplemented by a second-phase sample to obtain more detailed and accurate measurements on a small percentage of the first-phase samples. The purpose of the double sample is to refine the first-phase estimates to correct for any bias and to provide more details, such as the apportionment of gross volumes into product classes. Normally this is done by establishing mathematical relationships between the two sets of data, usually by linear regression. A useful account of double sampling is given in Wear *et al.* (1966).

Double sampling differs from *multistage sampling* wherein increasingly detailed information is obtained by successively sampling from progressively smaller subunits of the population.

Spatial data in forest inventories depicting point locations, boundaries, routes, bearings, distances and areas have traditionally been recorded and displayed on hard copy maps. In modern inventories the evolving technology of computerized GIS now offers a much more efficient and flexible approach for the recording, analysis and presentation of spatial information. These GIS store and analyse spatial information as digital coordinate data that can readily be processed to produce a wide variety of outputs such as maps, graphs and tables. Such outputs may relate to single themes or multiple themes of overlapping spatial information (Burrough 1986).

## 2.2 System components and relationships

Major components of the inventory system are illustrated in Figure 3 and explained as follows :

Two-phase sampling was selected as the sampling scheme most likely to provide the required volume estimates in the given time frame, while giving the potential for flexible

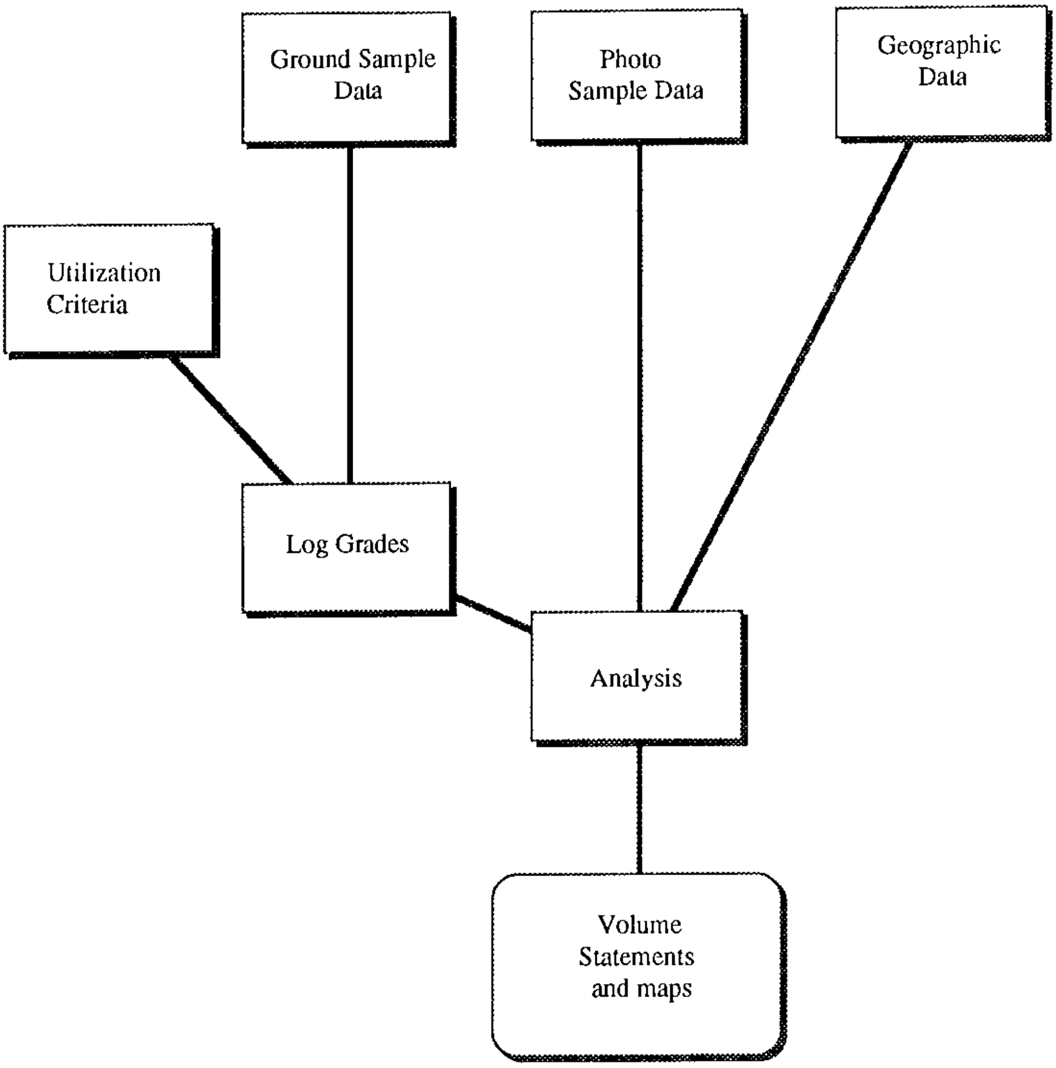


**Figure 3**
Major components of the inventory system.

spatial analysis of the data. Stratified sampling was rejected because it was not desirable to have volume estimates restricted to predetermined strata. It was also recognized that stratification in the jarrah forest may not have significant statistical advantage, given that the forest is uneven-aged and exhibits gradual changes in species composition. This means that the variability per hectare of volume within stands of jarrah that are defined as *uniform* may actually be quite high although the average volume may differ little from that of adjacent stands.

The use of photography in the two-phase sampling scheme gives the added advantage of providing a permanent record of each plot at the time of the initial measurement, which allows for further measurements to be made to check calibrations or to account for additional unmeasured variables.

Photo sampling was selected to provide the basis for estimating gross bole volume in the first phase because it allows for large numbers of samples to be obtained quickly and at low unit cost. Gross bole volumes are estimated from photo-measurements of heights.

Ground samples provide more accurate estimates of bole volumes and a breakdown into log volumes to serve as correction and conversion factors for the photo estimates. Using a new technique, the quality of each bole is described in terms that can be modified with computer programs to determine the volumes of different log grades under a range of utilization criteria.

Spatial analysis is arranged with the aid of a GIS, in which the sample data are linked with map information. The aim is to allow for the generation of volume statements for any areas of interest.

## 2.3 Methods for acquiring large-scale aerial photographs

Aerial photography has a significant, largely untapped, potential for reducing the time and cost of data collection in extensive forest inventories. Medium scale photographs (1:10 000 - 1:25 000) for example, are frequently interpreted to stratify large heterogeneous forests into smaller, more uniform areas that may then be sampled efficiently on the ground. Maps produced in this way provide a means for determining the size of different areas and they also represent a useful management tool for recording and monitoring other forest quantities and conditions.

Alternatively, timber volumes are sometimes estimated by reference to standard images (e.g. Stellingwerf 1967) or by estimating stand parameters such as stand height and crown cover, then using aerial stand volume tables to predict stand volumes (e.g. Meyer and Worley 1957). This method can be implemented successfully in uniform forests where the relationships are strong, but it is inadequate in more complex forest types where the structure of the stands cannot be adequately described, or where species cannot be identified.

Large-scale photographs (1:1000 - 1:3000) are required to estimate volumes in such forests. They enable species to be identified more accurately, smaller trees to be counted and the dimensions of individual trees to be measured. Their distinguishing characteristic is the provision of ground-quality measurements from aerial sampling independent of ground control.

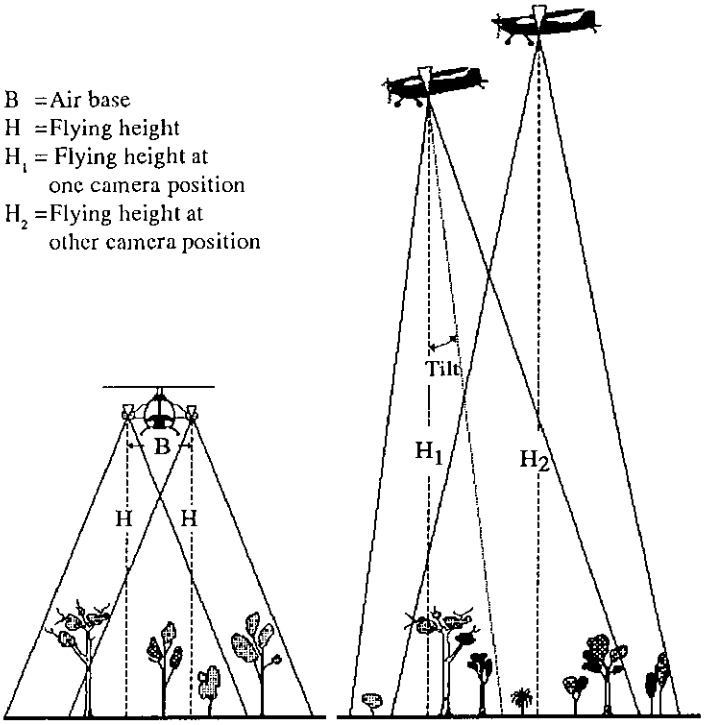
Progressive accounts of developments in large-scale photographic equipment and methods have been published by various authors, principally from Canada, over the past 30 years (Spencer and Hall 1988). The current work draws upon the Canadian experiences plus related research in the USA (Avery 1958, 1959), Australia (Spencer 1972, 1979) and Europe (Rhody 1977).

Application of large-scale photographic techniques requires specialized equipment and methods for managing major problems associated with image-motion, scale-determination, and camera tilt. Owing to the small coverage per frame, it is impractical to use ground control to determine photo scale for operational inventories. Therefore, alternative approaches have been developed for obtaining and scaling large-scale photographs without reference to ground control: twin-camera fixed-based systems (Fig. 4a) and single-camera sequential systems with and without a radar or laser altimeter and a tilt recorder (Fig. 4b).

Large format cameras are generally not well suited for very large scales because of limitations with camera cycling rates, image motion, and higher costs (Spencer and Hall 1988). Consequently, small format cameras, in particular 70 mm cameras, are common. The twin-camera fixed-base system and single camera sequential system use different methods for photo scaling and photo orientation for measurement purposes. Different designs are also used according to choice of aircraft, camera mountings, air-base orientation, and application. The two basic systems are described in the following sections.

### 2.3.1 Twin-camera fixed-base systems

Early developments of this system for Canadian forestry (Lyons 1961, 1964, 1966, 1967) were based on recommendations from the USA (Avery 1958, 1959). The method uses two identical, synchronized cameras mounted a set distance apart with their principal axes parallel (Fig. 4a). Stereopairs are obtained by simultaneously firing the two cameras, thereby providing a means for determining photo scale based on the ratio of photo-base over actual air-base (i.e. camera separation). The relationship between this scale and focal length of the cameras then provides a simple method for determining flying height that does not require ground control.



(a) Twin-camera fixed-base aerial photography

(b) Single-camera sequential photography.

**Figure 4.**
Methods of large-scale aerial photography.

The fixed-base method provides stereopairs of photographs of known relative orientation and freezes dynamic scenes, such as tree crowns swaying in the wind. A disadvantage of the method is that the fixed-base controls the amount of overlap at each scale, thereby affecting differential parallax, and, consequently, the accuracy of photo height-measurement (i.e. less stereo effect at smaller scales because of reduction in the base-to-flying-height ratio).

Based on Lyons' early work, the Ministry of Forests in British Columbia, Canada, developed a twin-camera system with a boom mounted longitudinally on a helicopter and twin Hasselblad MK70 photogrammetric 70 mm cameras (Bradatsch 1980).

Other workers (Spencer 1972, 1979; Rhody 1977; Rivest 1980) have investigated the use of transverse booms, which enable photographic scales to be calculated more precisely because minor mis-synchronization of the cameras does not change the effective length of the boom, as is the case with a longitudinal orientation.

Adaptation of the twin-camera concept to fixed-wing aircraft offers the potential advantages of a longer air-base, lower operating costs, and greater flying range (Williams 1978). Conversely, it suffers disadvantages owing to the adverse effect of higher aircraft speeds on image motion, as well as the lower manoeuvrability and reduced ground visibility with fixed-wing aircraft. The system may also suffer from instability owing to wing flexing. This can be reduced by using aerodynamic camera pods and mechanical compensation to the camera mounts, although not to the extent that is needed for rigorous photogrammetry (Spencer and Hall 1988).

A variety of cameras are suitable for fixed-base photography because each stereopair is acquired from simultaneous firing of two cameras, which means that the recycling speed of the cameras is not a major concern.

### 2.3.2 Timed-interval large-scale photographic systems

This method uses sequential photographs from a single camera to obtain stereo coverage through forward overlap of the photos. Scale can be determined from ground reference points, a foliage-penetrating radar, (Aldred and Hall 1975) or a rapid pulse laser altimeter that provides for discrimination between canopy and ground signals (Aldred and Bonnor 1985). Relative orientation of stereopairs is usually determined from direct measurement of camera tilts, or photogrammetrically when the photo-base-to-flying-height ratio is large enough (Williams 1978).

Timed-interval photography offers greater latitude in scale because the air-base can be varied for different flying heights to maintain an acceptable base-to-flying-height ratio for parallax measurements. This makes it suitable for a wide range of applications at different scales, including regeneration surveys at 1:500, volume estimation at 1:1200, and disease detection at a scale of around 1:5000 or smaller. Other advantages are that it can readily be used in fixed-wing aircraft, resulting in lower costs and, if the cameras are mounted internally, it allows for access to cameras and film magazines during flight.

The instruments required to determine scale and tilts with this system are expensive and require careful calibration and operation to achieve good results. Furthermore, a reconnaissance camera may be required to achieve the rapid recycling rates needed to obtain sufficient overlap for satisfactory stereo-viewing of large-scale photographs taken from low altitudes.

## 2.4 Photo measurement concepts

### 2.4.1 Variable selection

Two of the most important parameters required for a forest inventory are stand volume and the size class distribution of individual trees, usually expressed as diameters. Tree volumes cannot be measured directly on aerial photographs and direct measurement of diameters is either impossible or unreliable. Therefore both parameters must be estimated indirectly from other parameters that can be measured on photographs, such as tree height, crown diameter, crown area, stocking, or measures of competition with neighbouring trees.

Volume estimates based on photo-measurements imply the use of either aerial stand-volume tables or aerial tree-volume tables. Aerial tree-volume tables imply the use of photographs at scales large enough to show individual trees in open stands.

For most species, total tree height has the strongest correlations with both bole volume and diameter (Sayn-Wittgenstein and Aldred 1967; Spencer 1972; Aldred and Lowe 1978; Hall *et al.* 1989 ). This is followed by measures of crown size (often crown area) and measures of competition with neighbouring trees. However, Hall *et al.* (1989) have shown that the extra cost of measuring crown area may not be justified by the additional small benefit to be gained from its inclusion in the volume or diameter estimating function. Aldred and Sayn Wittgenstein (1972) concluded that '*measures of relation to neighbours*' would not prove to be very useful for estimating volume except in special cases.

Initial studies in the jarrah forest attempted to estimate stand volumes from 1:4500 scale photography. It was found, however, that the correlations between stand volume and the usual parameters, stand height and crown cover, were too low to be cost effective. The structure of the jarrah forest was too complex for simple stand volume estimates. Stands of equal height and crown cover could have different volumes depending on the structure of the forest, but insufficient detail could be seen on the photos to be able to count trees or interpret the structure with sufficient accuracy.

It appeared that estimation of timber volumes in the jarrah forest from aerial photography would have to be based on estimates derived from individual trees.

To test this theory, approximately one hundred jarrah trees were measured near Collie to determine the relationship between gross bole volume and tree height. Crown dimensions were not investigated at this stage, because they are difficult to estimate from the ground and ground estimates vary considerably from estimates made on photographs. It was also anticipated that the crown dimensions would be of secondary importance to height because many of the old trees have degenerate crowns that bear little relationship to their current standing volume (Fig. 5).

A strong exponential relationship was found between bole volume and total height, indicating that stem volumes could be estimated from measured tree height as long as suitable photographs could be obtained that showed individual trees (Fig. 6). The derived relationship is :

$$\ln V = a + b \ln H$$

where $\ln V$ = natural log of bole volume ($m^3$)
$\ln H$ = natural log of tree height (m)
a and b = constants

Test photographs at 1:1000 - 1:1500 scale were taken over the Collie forest using a Hasselblad 70 mm camera from a Piper Super-Cub aircraft. A combination of slow camera recycling and a high aircraft speed resulted in a small stereoscopic overlap, i.e. there was a very large base-flying-height ratio. This made it difficult to measure tree-heights accurately, nevertheless, it demonstrated that individual trees could be identified and measured. Based on a further review of Canadian experiences and parallel research at Melbourne University (Spencer 1972) it was decided to implement a twin-camera, fixed-base photographic system.

### 2.4.2 Measurement of tree heights on large-scale photographs

There are three approaches for determining tree heights from aerial photographs; measurement of shadow-length, measurement of displacement on single photographs, and measurement of stereoscopic parallax. The wider application and greater accuracy of the parallax method has led to its exclusive use in large-scale photographic programs. Therefore, it is the only method discussed here.

Parallax is the displacement of one image with respect to

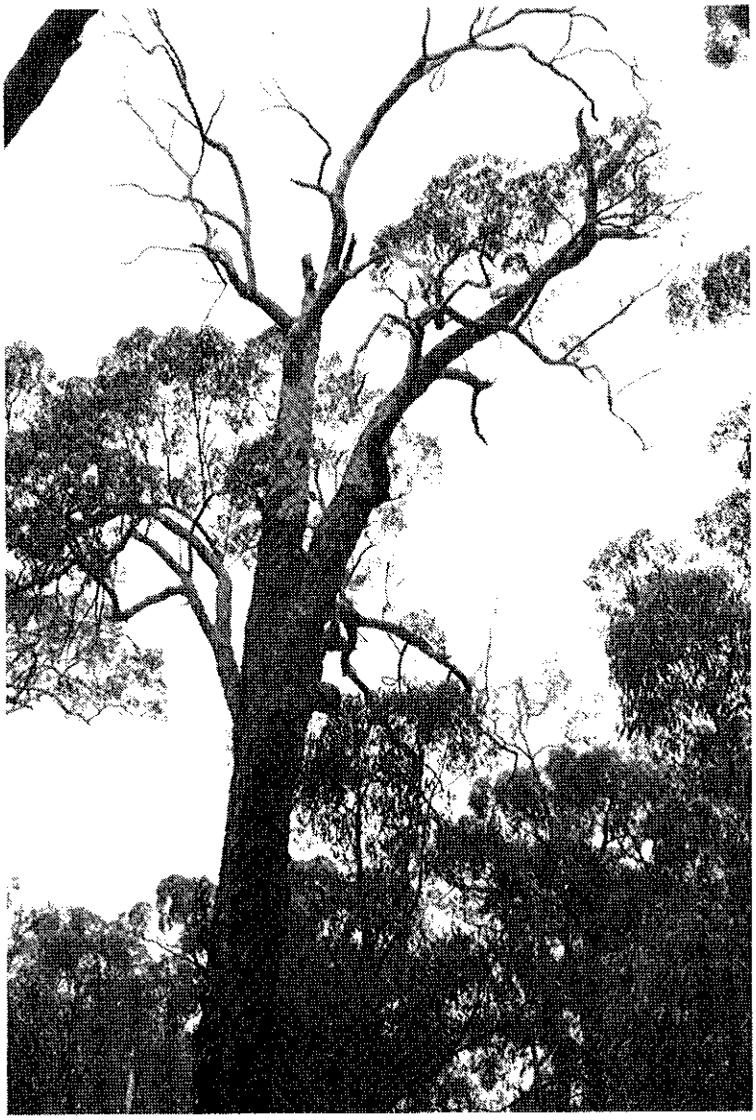


**Figure 5**

Degenerate marri crown. Many old trees have degenerate crowns that bear little relationship to their current standing volume.

another that arises when two objects at the same planimetric position but at different elevations are viewed obliquely. For measurement of heights, parallaxes parallel to the air-base are of most interest.

Requirements for reliable tree-height measurements with the parallax method are :

(i) accurate flying height;
(ii) large differential parallaxes and accurate measurement;
(iii) absence of, or adjustment for, differential tilts;
(iv) absence of wind-sway of tree crowns;
(v) good resolution of tree tops;
(vii) good photographic *penetration* below canopy to facilitate parallax readings at or near the base of each tree or at sufficient ground points to develop a digital terrain model.

With fixed-base photography the flying height (H) can be determined accurately from the photographic airbase; differential parallax can be made large by careful selection of H; differential tilts are eliminated or minimized by preflight alignment of the two cameras; and wind-sway is not a problem because of the simultaneous exposure of the two cameras which *freezes* dynamic scenes. Requirements for resolution of tree tops and photographic penetration below the canopy are essentially the same for both fixed-base and timed-interval photography, and depend on choice of scale, camera, film, lighting, exposure and film processing.

The parallax formula for height determinations is usually stated in the form:

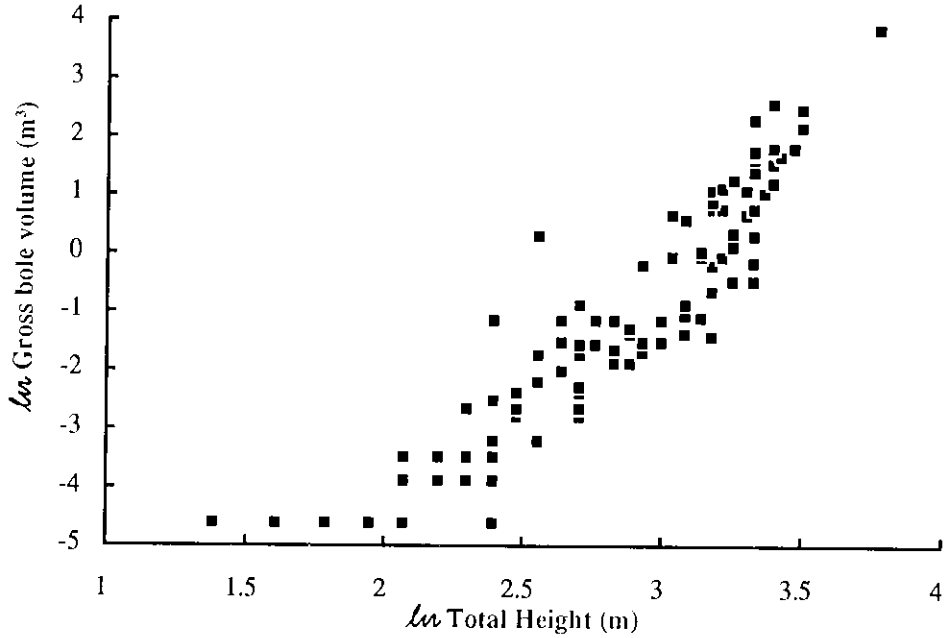


**Figure 6**

Jarrah gross bole volume / total height relationship; 112 observations, $r^2 = 0.8439$.

(1) $h = H_b.dp/(P_b + dp)$

For flat country $P_b$ is equal to the photographic air-base (b).

(2) Thus $h = H_b.dp/(b + dp)$

Making the alternative substitution

$$P_b = f.B/H_b,$$

gives the following equation which can be used for fixed-base photography:

Thus $h = H_b.dp/(B.f/H_b + dp)$,

which transposes to give

(3) $h = H_b^2.dp/(H_b.dp + fB)$

where h = height of tree (m)
$H_b$ = height of the camera stations above the base of the tree (m)
dp = differential parallax (mm)
B = distance between the two camera stations, syn. air-base (m)
b = photographic air-base(mm)
f = focal length of camera (mm)
$P_b$ = absolute stereoscopic x-parallax of the base (mm)

The above three formulae are exact in theory and under perfect conditions of photography and measurement would give the same results (Schut and van Wijk 1965). However, because perfect conditions rarely apply, results will vary.

By transformation of parallax equation (2) it is seen that:

$$dp = h.b/(H_b - h)$$

For conventional small-scale photography where object-heights (e.g. trees) are generally small relative to flying heights, this equation may be approximated by

$$dp = h.b/H_b.$$

Substitution of

$$b = B.f/H_b$$

gives $dp = h.(f/H_b).(B/H_b)$.

This approximation does not apply with large-scale photography because the heights of objects cannot be assumed to be small in comparison with flying heights, hence

$$dp = h.(f/H_b).(B/(H_b-h)).$$

Because of this difference it is apparent that differential parallaxes can be large on photographs of very large scales, even when the air-base is very short and air-base to flying height ratio is small relative to values in conventional photography.

With fixed-base photography, increasing flying height increases overlap and consequently reduces differential parallax for objects of given heights. This is a constraint of the system in contrast with the single-camera system where flexibility in the choice of air-base allows for parallax conditions to be maintained over a range of flying heights, hence scales of photography. The latter system, however, requires very fast recycling of the camera at low flying heights to obtain desired overlaps. Thus, neither system is optimal for all requirements.

Other factors affecting both types of photography include film characteristics, image quality, distortions in the image, and the skill of the interpreter. Focal plane shutters cause distortions in the image which may be significant over the whole photograph, although their effect on tree-height measurement at a point on a photograph appears to be small. The type of film, transparency or print, colour or black and white, also has an influence on the accuracy of height measurements but differences between interpreters make this difficult to quantify.

## 2.5 Sampling design

The sampling design had to meet the objectives of a relatively intense sample over a large area in a short time. Two-phase sampling met this requirement, while providing flexibility as demanded by other constraints.

An important objective of the jarrah inventory was to provide valid volume estimates for any portions of the production forest zones, therefore samples were required at uniform intensity over all areas. Systematic sampling ensured such a uniform distribution and maximized the efficiency of flying, although it was recognized that random sampling would have provided more valid estimates of sampling error. This requirement for uniform coverage, plus the difficulty of obtaining random photo samples, amply justified the use of systematic sampling.

Various assumptions were made regarding the variances and costs of the two phases when estimating the required sampling intensities. Based on existing ground inventory data, it was expected that the coefficient of variation (CV) of gross bole volume from the photo samples would be approximately 70 per cent (i.e. the standard deviation is 70 per cent of the value of the mean). The required number of ground plots depended on the strength of the relationship between the two phases, and this was unknown for jarrah forest. Chehock (1981) stated that the ratio of ground estimate/photo estimate should be predicted to a CV of less than 20 per cent. It was expected, however, that ground estimates of sawlog volume would be less well correlated with the photo estimates of gross bole volume, so it was assumed that the CV of this ratio could be as high as 50 per cent. As the objective was to estimate sawlog volume to ± 25 per cent at 95 per cent confidence for areas of 10 000 ha, it was this figure that was used to determine the appropriate sampling intensity.

From Chehock (1981), the total relative sampling error can be calculated from the two phases as

$$E = \sqrt{E_1^2 + E_2^2} \qquad (1)$$

where $E$ = allowable sample error
$E_1$ = sample error from the first phase
$E_2$ = sample error from the second phase

The sample errors $E_1$ and $E_2$ can also be defined as

$$E = \frac{t.SD}{\sqrt{n}} \qquad (2)$$

where SD = standard deviation
n = sample size
t = value of student's t at the appropriate confidence level (= 2 at 95%)

Substituting equation 2 into equation 1 gave

$$E = \sqrt{t^2SD_1^2 + t^2SD_2^2}$$

Using $SD_1$ = 70% and $SD_2$ = 50%, there was a wide range of combinations of sample sizes which could have been used to obtain a sampling error of 25 per cent for areas of 10 000 ha. It was expected from the literature that the cost of photo plots could be as little as one tenth the cost of ground plots (Lyons 1964), but this was untested in the local conditions. Also, costs were not the only factor in deciding the relative intensities of the two samples. It was desirable to maximize the use of the photographic systems once they were established, and also to ensure that the distribution of the first phase samples was adequate to meet the demands of the later geographic manipulation.

It was determined that an intensity of one photo plot per 50 ha and one ground plot per 500 ha would meet all these requirements. This corresponded to 200 photo plots and 20 ground plots in each 10 000 ha. (Fig. 7). It was planned to alter this intensity, if necessary, based on analysis of early results.

The efficiency of aerial photography is greatest when sample points are arranged densely along flight-lines that are spaced far apart. This, however, produces a very clumped sample and would have compromised an important objective of the inventory. As a compromise, flight-lines were selected at 1000 m intervals, with photo samples at 500 m intervals along each line. This involves 40 per cent less flying time than the same number of sample plots at 700 x 700 m spacing.

Ground samples were then selected as every fifth photo sample on every second line, giving a spacing of 2000 m x 2500 m, which closely approximated the desirable square configuration for maximum uniformity.

Fixed-area plots were chosen in preference to point samples because they are easier to define on the aerial photographs and they facilitate close matching of the ground and photo samples. Circular plots were selected as they involved only the matching of one point, and for a given area involve the smallest perimeter along which mismatches can occur between the two phases.

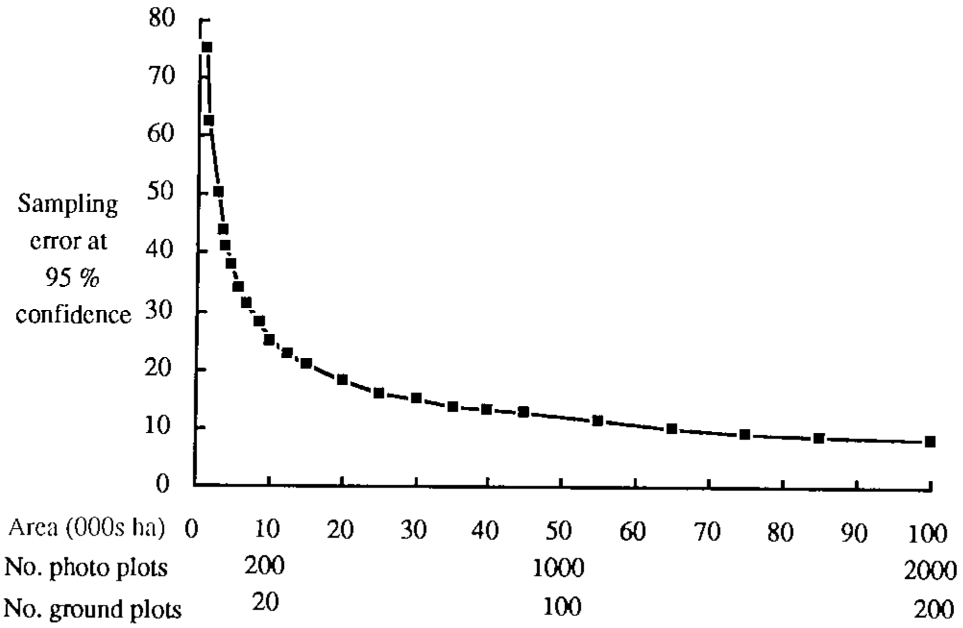


**Figure 7**

Forecast sampling errors for volume estimates derived for discrete areas of forest, assuming systematic plot locations, one photo plot per 50 ha, one ground plot per 500 ha and coefficent of variation as explained in Section 2.5.

# 3 *AERIAL PHOTOGRAPHIC METHODS*

**P.H. Biggs, C.J. Pearce and M.A. Green**

## 3.1 Design of photographic system

A twin-camera fixed-base design was selected after considering the advantages and limitations of single-camera and fixed-base systems in conjunction with the following, equally weighted, considerations:

- time requirements to implement the system,
- availability of a suitable altimeter,
- potential accuracies,
- costs.

The system could be implemented at reasonable cost using available expertise and equipment (Biggs and Spencer 1990). Transverse orientation of the air-base relative to the direction of flight was selected because of its lower requirements for precise camera synchronization, resulting in greater latitude in the selection of cameras (Spencer 1979).

This was especially important if Vinten reconnaissance cameras were to be used as they have focal plane shutters that are very difficult to synchronize.

The restricted choice of flying heights associated with a fixed air-base system was not considered to be a serious limitation for the project because the stereoscopic parallax would be adequate at the scales required and the project was large enough to justify building a dedicated system. On the other hand, it was recognized that implementing the altimeter and tip/tilt recorder required for timed-interval photography would be expensive and difficult because of a lack of experience with such systems in Western Australia.

The booms (Fig. 8) were designed in Perth by Aeronautical Engineers Australia and built by Aircraft and General Welding. They have a braced tripod construction similar to designs used for agricultural sprays in order to minimize flexing during flight which, if present, reduces the accuracy of scale calculations from photo-measurements.

They are mounted on three hard points on each side of a Bell 206 B Jetranger helicopter and are braced to a fourth hard point toward the tail boom. Vibration tests conducted during certification for the Department of Aviation showed that the booms are rigid enough for sharp photography. No major modifications were required to the helicopter apart from strengthening of the upper hard point.

**Figure 8**

Helicopter-mounted equipment. Transverse boom of 7.5 m mounted on a Bell 206B Jetranger supporting aerodynamic pods housing synchronized computer-controlled cameras.

Camera separation on the booms (i.e. air-base) is 7.5 m, with each of the cameras being housed in a Mylar-glass pod for protection from the weather, dust and minor impacts (Fig. 9). The tail-cone of each pod is secured by a quick release nut so that it can be removed quickly to gain access to the cameras for changing film magazines. An electrically driven hatch is installed in the bottom of each pod to protect the camera lenses from dust during take-off and landing. The hatch is opened by remote control during flight. Two types of cameras were used during the course of the inventory, Vinten 492 reconnaissance cameras during years one and three, and modified Hasselblad 500 EL/M cameras during year two.

Mounts for Vinten cameras were designed so that each camera can be bolted directly onto the ends of the booms. This is possible because the booms were designed to have parallel and vertical end plates that are aligned correctly for the cameras (Fig. 10). Once these cameras are installed, they remain in place for the entire photography season, so that their relative orientation remains constant for the whole season. This simplifies the calculation of scales and is less prone to errors.

Mounts for Hasselblad cameras (Fig. 11) were designed so that the cameras can be levelled after installation. This is done by placing bubble levels on the reseau plates and then bolting the cameras into their correct positions. These cameras are removed from the helicopter each day for security and for maintenance. Therefore, the camera angles vary slightly from day to day. In order to check camera orientation in flight, calibration targets are photographed at the beginning and end of each flight. This is satisfactory under perfect circumstances but is subject to error if the targets are missed by the cameras, if the calibration run is forgotten, or if the cameras are adjusted during the day without another set of calibration photographs being taken. The better solution is to leave the cameras in a fixed position for as long as possible.

The aircraft power supply is used to power the cameras, removing the need for batteries in the cameras. The aperture and film numbering of the Vinten cameras was also controlled from inside the helicopter.

## 3.2 Camera selection

Reconnaissance and semi-metric 70 mm cameras were considered for use in the photography (Table 1). Various 35 mm cameras were also considered but the disadvantages of smaller format size outweighed the potential savings in cost. The maximum film capacity of the 35 mm cameras investigated was 250 frames but no data backs were available

**Figure 9**
Camera pod with rear housing removed.

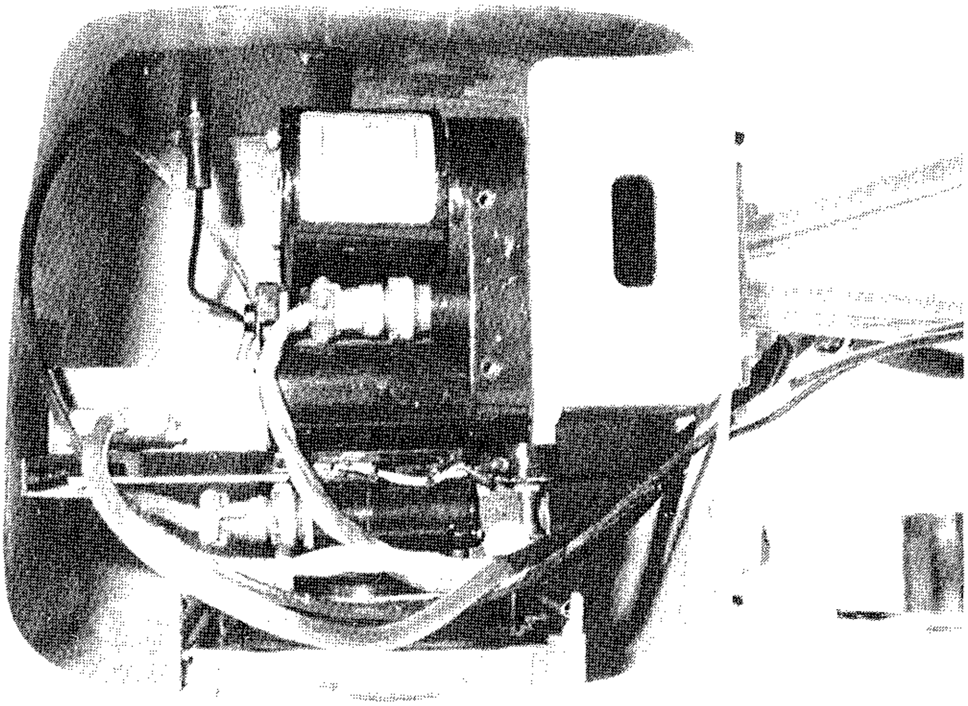


**Figure 10**
Mount for Vinten camera.

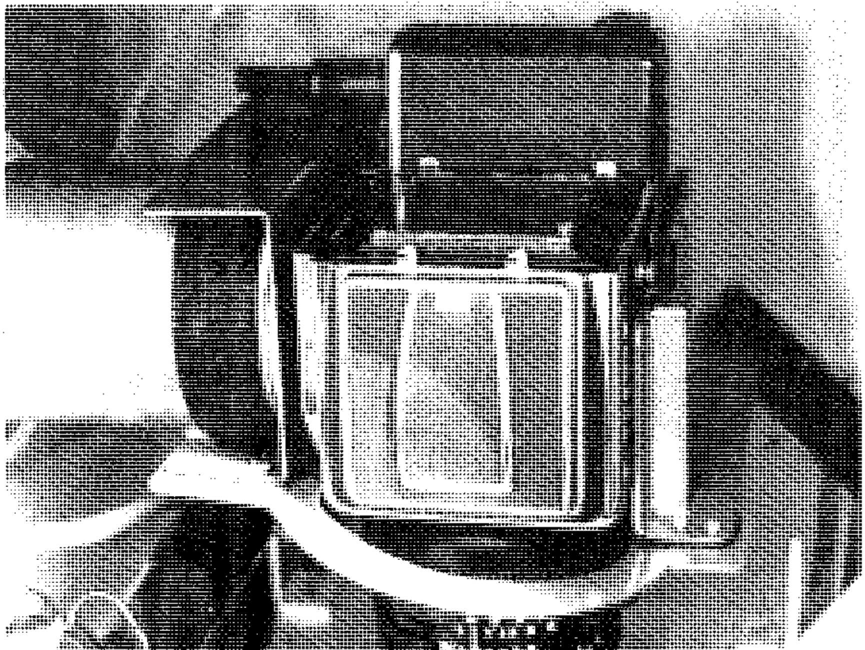


**Figure 11**
Mount for Hasselblad camera.

**Table 1**

Camera selection considerations

| Camera | Shutter type | Shutter speed | Reseau plate | Aperture Control | Data Back | Magazine Capacity | Film Flattening | Approx Cost ($) |
|---|---|---|---|---|---|---|---|---|
| 70 mm PHOTOGRAMMETRIC CAMERAS | | | | | | | | |
| AMI /Bronica SQ/Am. | Leaf | 1/500 | Yes | Automatic | No | 24 | Yes | 15 000 |
| Hasselblad MK70 | Leaf | 1/500 | Yes | Manual | Yes<br>No | 100/200<br>500 | Pressure Plate and reseau | 30 000 |
| Hasselblad 500EL/M | Leaf | 1/500 | No (Custom Installed) | Manual | Yes<br>No | 100/200<br>500 | No (Yes if reseau installed) | 10 000 |
| Rollieflex 6006 Metric | Leaf | 1/500 | Yes | Automatic | No | 170 | Vacuum back | 15 000 |
| 70 mm RECONNAISSANCE CAMERAS [a] | | | | | | | | |
| Vinten 492 | Focal Plane | 1/1000 | No | Remote | Yes | 500-1000 | No | 30 000 |

(a) Modern reconnaissance cameras were investigated by the Forests Department in 1984 for application in dieback photography. It was found that most were designed to be hand-held for marine surveillance, or were designed for jet fighter aircraft. Older cameras such as the Hulcher have been used for forestry photography and would be an alternative to the Vinten.

for such magazines. Bulk 35 mm transparency film would have cost as much or more per square mm of image to purchase and process as 70 mm transparency film.

Reconnaissance cameras, such as the Vinten, were designed for military surveillance and are characterized by their robust construction, large film capacity, remote operation and fast shutter speeds. Their lenses, however, are not generally of metric quality, although they can be exchanged for lenses of better quality, and they have focal plane shutters that cause distortions in images taken from a moving platform.

Semi-metric 70 mm cameras, on the other hand, have high quality lenses and intra-lens shutters to minimize image-distortion and provide for accurate photomeasurements. They also have reseau plates that provide fiducial marks for precise referencing purposes and flatten the film during exposures. These cameras have evolved from standard 70 mm studio cameras and are therefore usually of light construction and have a small film capacity.

The choice between the available cameras took account of shutter speed, potential for accurate measurements, film capacity, aperture control mechanism, availability of film numbering/data back, robustness and cost.

None of the available cameras met all of the requirements for the project, but the Hasselblad MK70 camera was considered to be the best technical option. It has a high photogrammetric standard, plus film numbering and a moderate film capacity with the DM 100/200 magazine which gives 200 frames. The cost of purchasing two cameras plus a number of magazines (minimum of six) and two lenses was, however, beyond the budget for the project. Furthermore, its limitation of 200 frames per magazine would have required more time for reloading, resulting in greater flying costs.

Vinten 492 reconnaissance cameras with 500 frames per magazine, 100 mm focal length lenses and a film numbering facility were already owned by the Department and had previously been used successfully to acquire large-scale aerial photographs for detecting jarrah dieback disease (*Phytophthora cinnamomi*) over large areas (Bradshaw and Chandler 1978). Although it was recognized that their photo-measurement quality is diminished because of distortions owing to their focal plane shutter and reconnaissance lens, reports from various Canadian users have shown that they can still be used to obtain satisfactory tree measurements (Sayn-Wittgenstein and Aldred 1967; Aldred and Lowe 1978; Titus and Morgan 1985). Therefore, it was decided to use the Vinten cameras, initially at least, until a better solution could be found.

Subsequently, large capacity magazines were acquired for the Hasselblad 500 EL/M cameras, which allowed for trials with these semi-metric cameras and gave the opportunity for more precise and detailed measurements using an analytical plotter. In cooperation with Mr Bruce Montgommery at Curtin University of Technology, reseau plates were installed in the Hasselblad cameras (Fig. 12) to provide fiducial marks for analytical photogrammetry. This was done by fabricating an aluminium frame which fitted into each camera body. A flat glass plate with crosses etched onto its surface (a calibration plate from the Adam MPS-2 analytical plotter) was bonded into the aluminium frame, bringing the surface of the glass plate into contact with the film plane in the camera magazine. Film was pulled through the modified camera, with a spring balance and the magazine in place, to ensure that the film did not bind on the glass plate, yet with the plate sufficiently close to the focal plane to focus correctly and to help flatten the film.

The cameras were calibrated by photographing target arrays (Fig. 13) and using software at Curtin University of Technology (Fraser 1980).

The cameras are electronically actuated in flight at the required spacings using a laptop computer coupled to a sophisticated navigation and flight recording system (Biggs *et al.* 1989).

## 3.3 Flight planning and photography

### 3.3.1 Flight planning

The first step in planning the photography was to identify the areas to be included in the inventory. Initially this was done on 1:500 000 computer plots that were generated from digital mapping information on multiple use and conservation forest areas. The multiple use areas were then divided into 29 *cells*, each of 150 000-200 000 ha, which were identified on the Department's 1:50 000 map series and later digitized into the GIS. These cells are a manageable size for planning and executing the photography as each cell takes about a week to photograph.

The next step was to use the GIS to create a flight plan, drawing upon the computer file of reference points, called way-points (Fig. 14). Most flight lines were orientated east-west at 1.0 km spacings, with stereopairs of

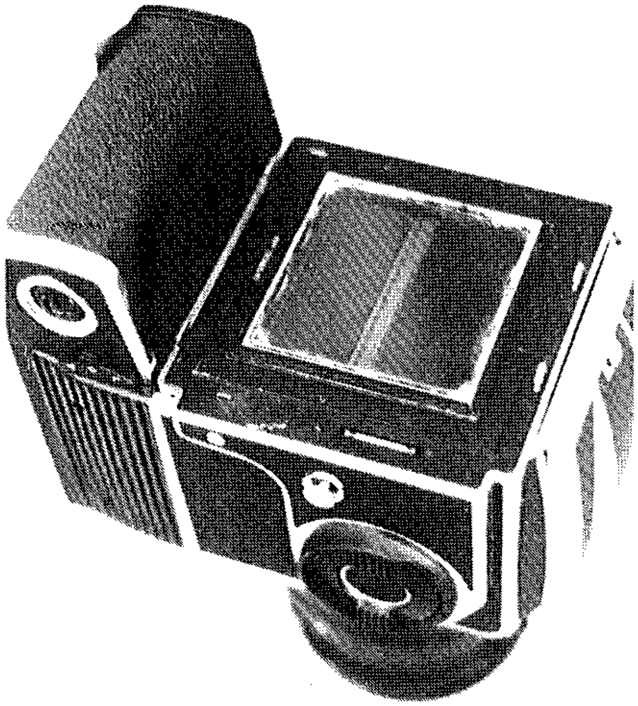


**Figure 12**
Hasselblad 500 EL/M with reseau plate installed.

**Figure 13**

Target array at Curtin University of Technology used for lens calibration.

photographs planned for 0.5 km intervals along each line. The east-west flight direction transects the major topographic relief, hence the main gradient of forest quality, and gave the longest (and most efficient) flight lines for most cells. Some cells, however, were flown north-south. Use of a grid locking system ensures that flight paths commence and end on even 500 m values. Interactive editing of the parallel flight lines is undertaken to remove unwanted areas and to check that all way-points were entered correctly.

The coordinates of each start and end point of each flight line are then extracted using application software and stored in a computer file for later entry as way-points to a GPS in the aircraft. Initially, a manual technique was used to determine the flight paths owing to timing constraints, but the method is now semi-automated using the GIS.

Completed flight maps are useful for planning other aspects of the program. For example, the GIS can provide flight lengths and the number of photo points, thereby permitting the calculation of film requirements and hence the need for landing areas to change film, as well as flying times and fuel requirements for planning appropriate fuel dumps in addition to the main bases.

Prior to flying missions, the owners of adjacent private properties are notified by mail to seek approval to fly over their land at low altitude. Initially, this task was undertaken by exhaustive searching of Local Government records, but it is now being automated by generating a distance buffer around each cell and using this as a spatial window into the State's Land Information System. At a cost of $0.10 per land parcel, data depicting owner details and address are then extracted as a computer file, which is used to generate mailing lists.

### 3.3.2 Photography

During flight, the navigator sets a course along each flight line using the Trimble 1OX GPS control unit while checking the course on flight-line maps (Fig. 14). The GPS receiver then provides continuous displays that enable the pilot to navigate along each flight line (Fig. 15). As each flight line is being flown, the laptop computer reads the aircraft's position from the GPS every second, from which it calculates the distance travelled and fires the cameras at 500 m intervals via an interface built by Protek Electronics Pty Ltd. It then records the geographic coordinates for each stereopair on its disk, along with the status of the satellite constellation, the aircraft's altitude as approximately

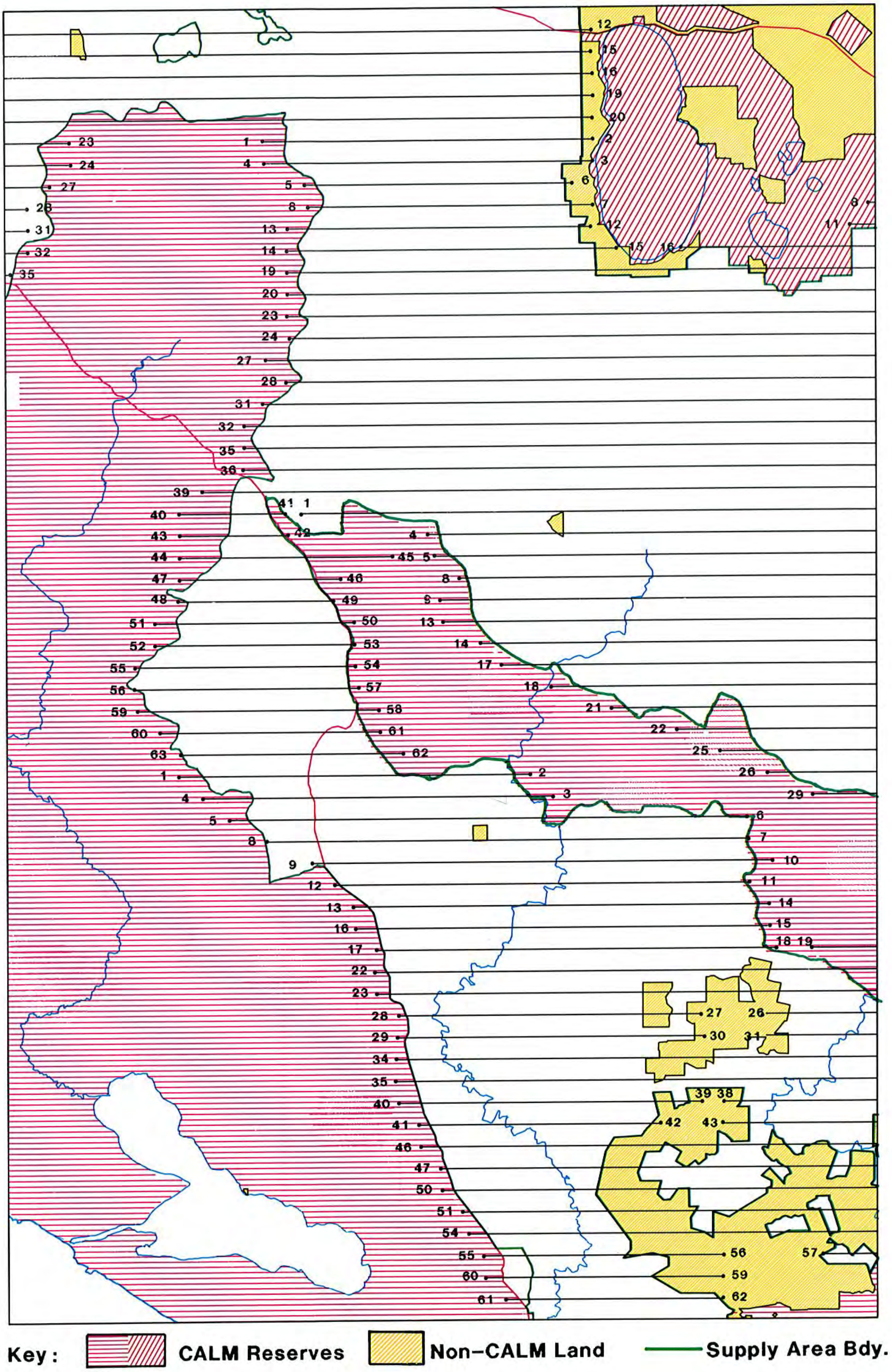
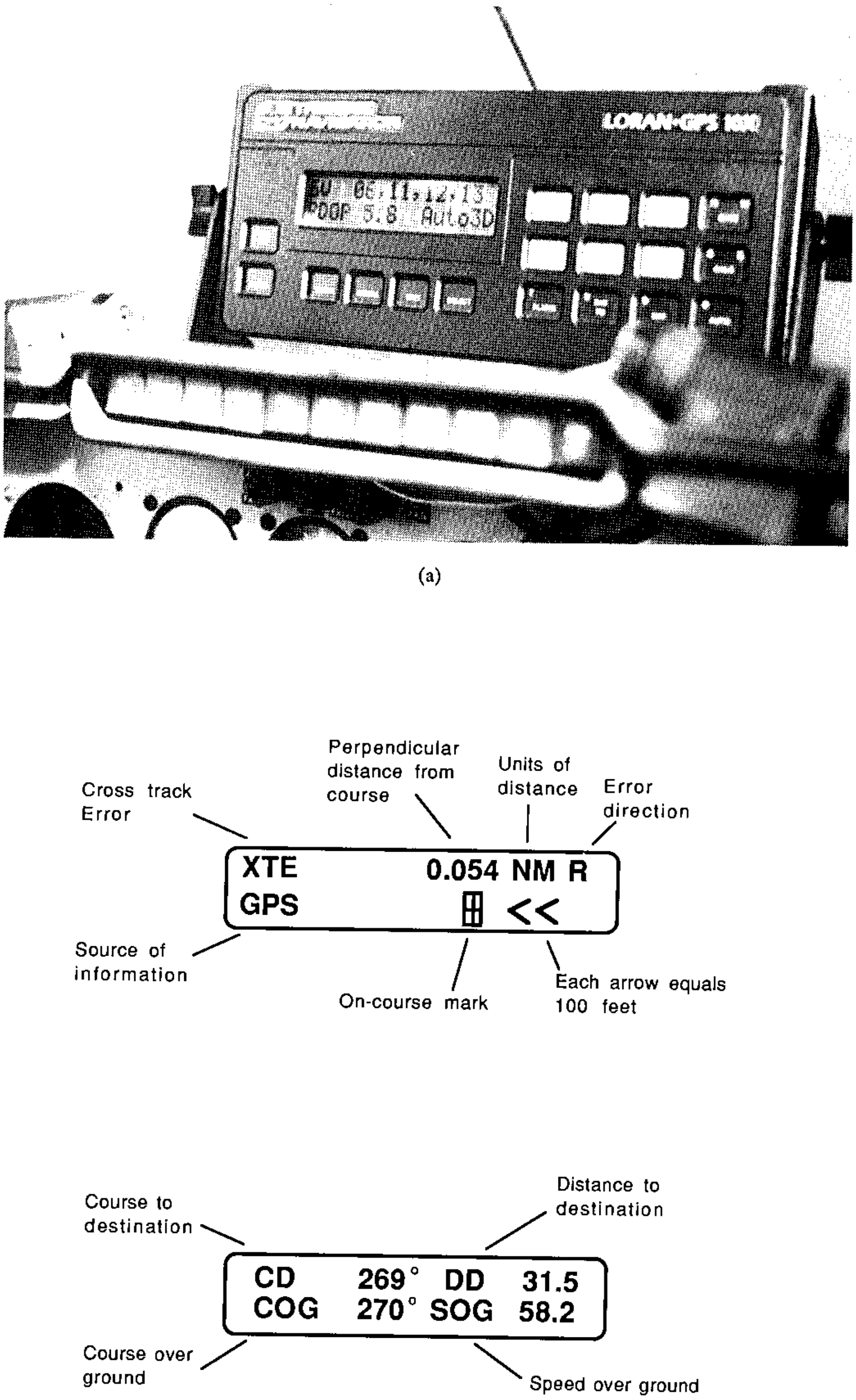


**Figure 14**
Example of flight line maps.



(a)

(b)

**Figure 15**

Example of Global Positioning System (GPS) receiver displays.

(a) shows the position of the GPS panel in the cabin and (b) displays data registered on the panel.

determined by a radar altimeter, and the frame number (Table 2).

As a cross-check, the camera operator records the numbers of each completed flight line in a log book, together with the number of the frames on each line. The name of the computer file in which the location data are stored is also recorded.

The inter-relationships between major components of the navigational and camera-control systems are illustrated in Figure 16; Figure 17 shows their layout in the aircraft and Figure 18 displays each unit.

The inflight positional data are subsequently transferred via a floppy disk to the Department's GIS, which is used to plot the photo-locations onto maps of suitable scale for administration (1:250 000 and 1:50 000) (Figure 19) and for relocation of selected photo-plots in the field for ground measurements (1:25 000) (see Figure 23). Photo and ground sample data are later attached to the positional data in a database that enable processing for the determination of sample volume estimates for any areas defined within the GIS. An example of a stereopair used for photo-measurement is given in Figure 20.

Photographs are acquired during summer under high overcast (i.e. shadowless) or full sunlit conditions. Hotspot was not found to be a problem on these photographs, so photography was able to continue through the middle of the day. Estar base Kodak Aerochrome MS 2448 colour transparency film was used, or Kodak Ektachrome if this was unavailable. These films give high resolution for measurements and good colour rendition for species interpretation. They are also cost-effective owing to their single-stage processing. Timing of photography is also affected by visibility of the satellites forming part of the GPS (Fig. 21). This varied throughout the project as more satellites entered the constellation.

Exposures are determined from a Sekonic lightmeter with a remote readout inside the cabin. The meter is attached below the aircraft in a cylindrical mount designed to restrict its angle of field to the coverage obtained with the 100 mm focal length lenses. All exposures are at 1/500 seconds, resulting in image motion of approximately 60 microns at a ground speed of 60 knots (30 m per second). Although a shutter speed of 1/1000 second is available on the Vinten cameras (but not the Hasselblads), which would reduce image motion to 30 microns, the slower shutter speed is used to give more choice of apertures so that photography can be continued under cloud. A flying height of 100 m ± 20 m above the tree tops is used, resulting in contact scales of around 1:1000 - 1:1500.

Films are processed in 30 m rolls by Irvin Datacolor of Perth. Roll pairs from the two cameras are processed together to eliminate colour differences owing to differences in processing conditions. The films are then

**Table 2**

Example of output from the navigation system. Each line is a separate record showing " Cross track position" (GGXP) and satellite status (GSS) from the GPS reciever, altitude from the radar altimeter and frame number from the computer

| | Time | Latitude | Longitude | Satellite Status | Altitude | Frame No. |
|---|---|---|---|---|---|---|
| GGXP, | 012217, | 3344.827,S, | 11529.534,E, | GSS,A,3,11,12,06,13,004.8: | 334 | 87001 |
| GGXP, | 012417, | 3345.235,S, | 11529.270,E, | GSS,A,3,11,12,06,13,004.8: | 274 | 86003 |
| GGXP, | 012433, | 3345.212,S, | 11528.940,E, | GSS,A,3,11,12,06,13,004.7: | 289 | 86004 |
| GGXP, | 012449, | 3345.201,S, | 11528.618,E, | GSS,A,3,11,12,06,13,004.7: | 348 | 86005 |
| GGXP, | 012503, | 3345.217,S, | 11528.303,E, | GSS,A,3,11,12,06,13,004.7: | 337 | 86006 |
| GGXP, | 012518, | 3345.219,S, | 11527.984,E, | GSS,A,3,11,12,06,13,004.7: | 363 | 86007 |
| GGXP, | 012531, | 3345.213,S, | 11527.664,E, | GSS,A,3,11,12,06,13,004.7: | 368 | 86008 |
| GGXP, | 012646, | 3345.837,S, | 11527.223,E, | GSS,A,3,11,12,06,13,004.7: | 213 | 84010 |
| GGXP, | 012705, | 3345.811,S, | 11527.507,E, | GSS,A,3,11,12,06,13,004.7: | 266 | 84011 |
| GGXP, | 012724, | 3345.771,S, | 11527.811,E, | GSS,A,3,11,12,06,13,004.7: | 304 | 84012 |
| GGXP, | 013707, | 3348.363,S, | 11527.757,E, | GSS,A,3,11,12,06,13,004.4: | 314 | 4014 |
| GGXP, | 013722, | 3348.340,S, | 11527.439,E, | GSS,A,3,11,12,06,13,004.4: | 344 | 4015 |
| GGXP, | 013737, | 3348.349,S, | 11527.120,E, | GSS,A,3,11,12,06,13,004.4: | 357 | 4016 |
| GGXP, | 013752, | 3348.357,S, | 11526.803,E, | GSS,A,3,11,12,06,13,004.4: | 392 | 4017 |
| GGXP, | 013808, | 3348.361,S, | 11526.480,E, | GSS,A,3,11,12,06,13,004.3: | 356 | 4018 |
| GGXP, | 013824, | 3348.367,S, | 11526.157,E, | GSS,A,3,11,12,06,13,004.3: | 338 | 4019 |
| GGXP, | 013934, | 3348.877,S, | 11525.428,E, | GSS,A,3,11,12,06,13,004.3: | 355 | 6021 |

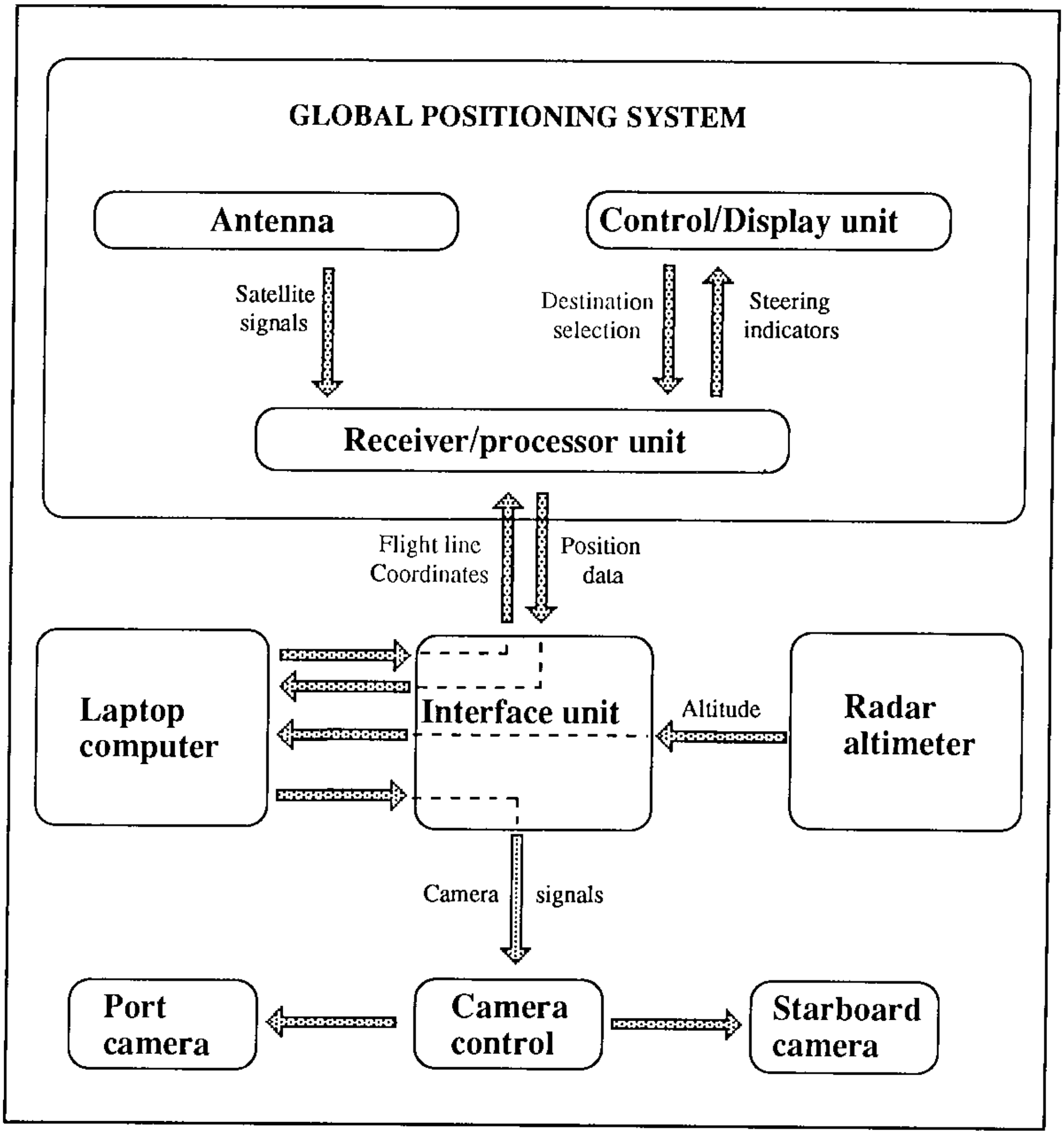


**Figure 16**
Components of integrated navigation, camera-control, and flight recording system.

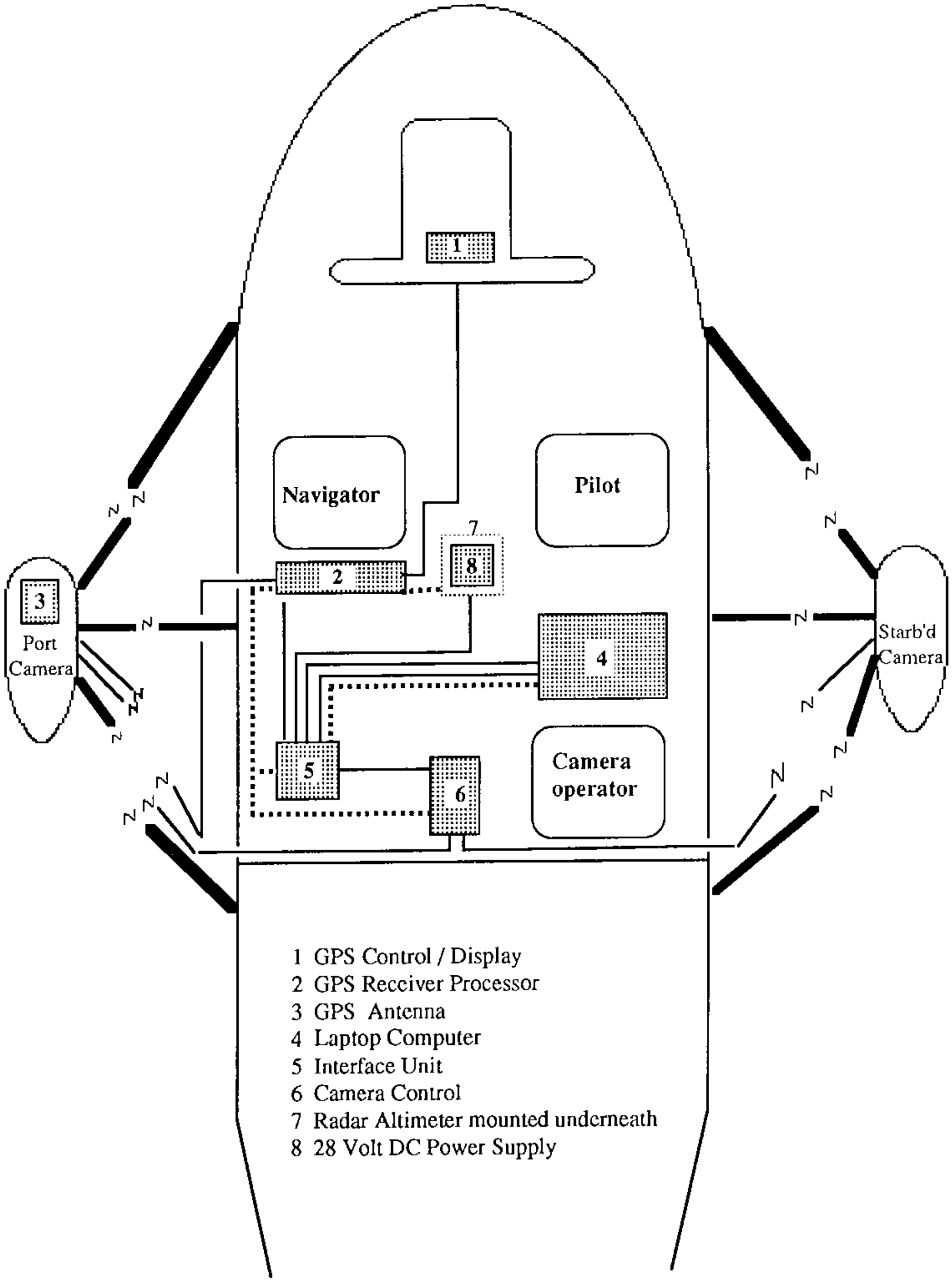


**Figure 17**
Layout of navigation system components.

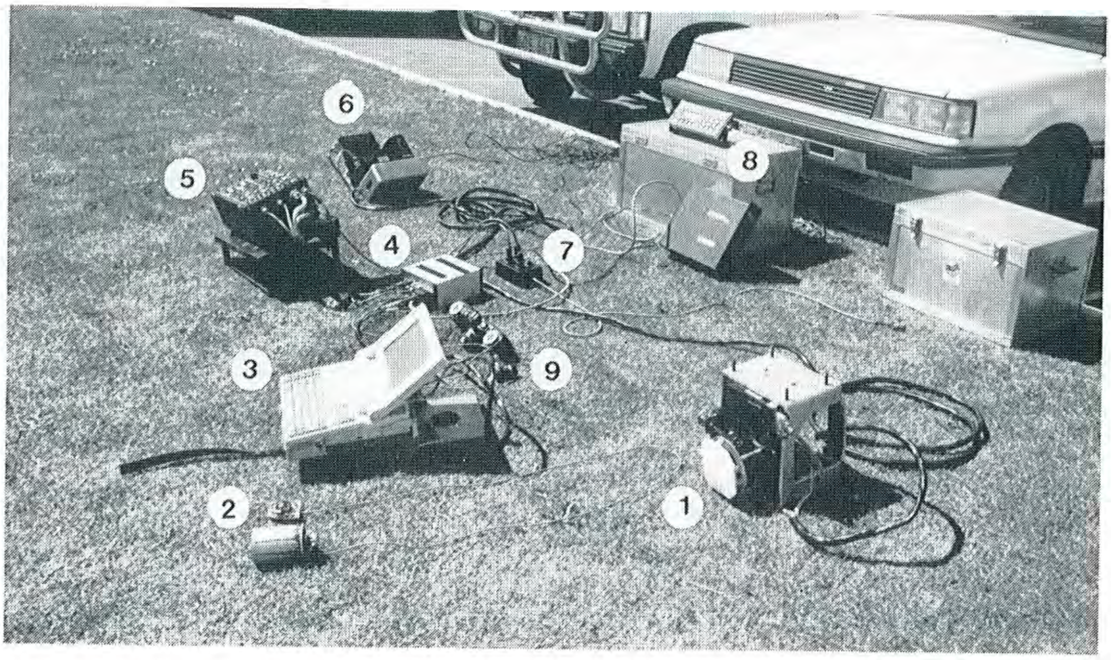


**Figure 18**
Major components of the navigational and camera systems.
1. Starboard camera 2. Light meter 3. Laptop computer 4. Interface unit
5. Camera control 6. Port camera 7. Power distribution board
8. GPS receiver (below) and control-display unit (above) 9. Tracking camera

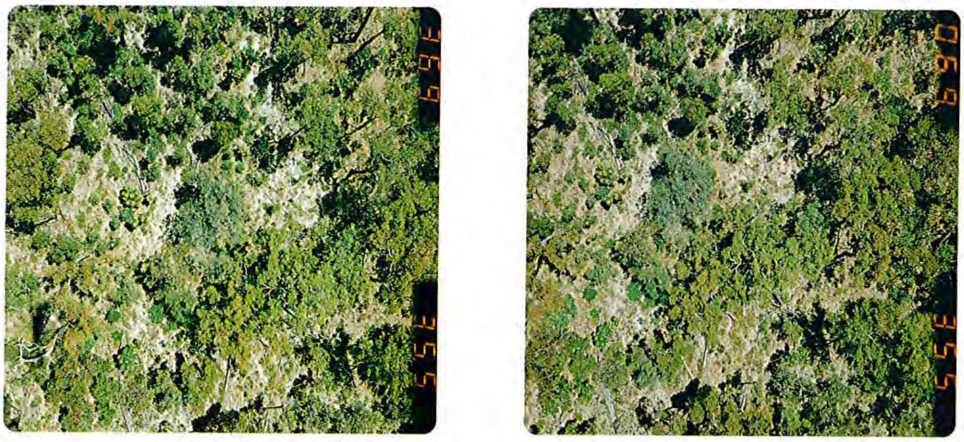
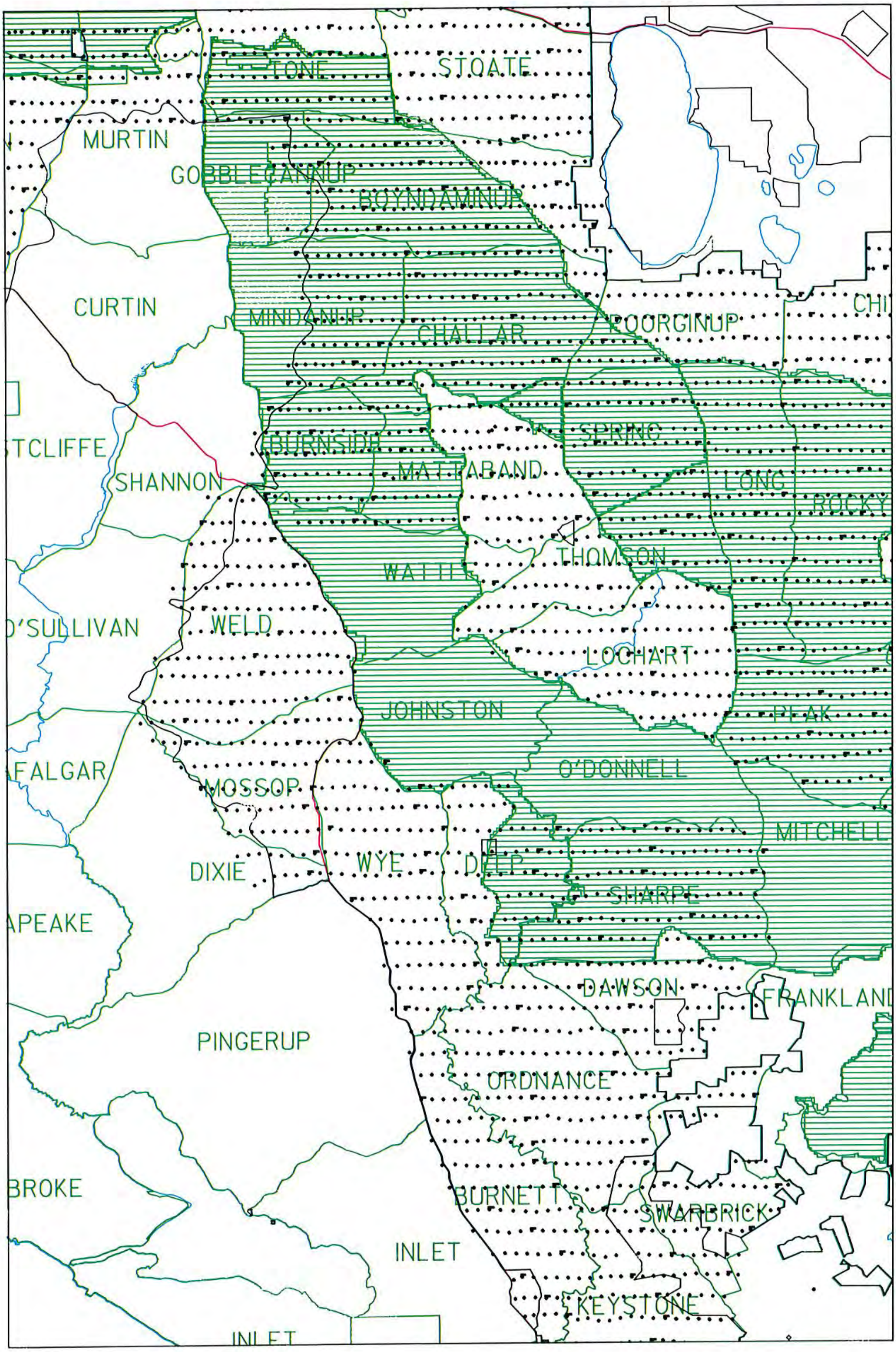


**Figure 20**
Sample pair of stereoscopic photographs.



Key: •••••• Photolocations ▤ Disease Risk Area

**Figure 19**

Example of photo-location map from ARC/INFO Geographic Information System based on positional data from the Global Positioning System as recorded by the on-board computer.

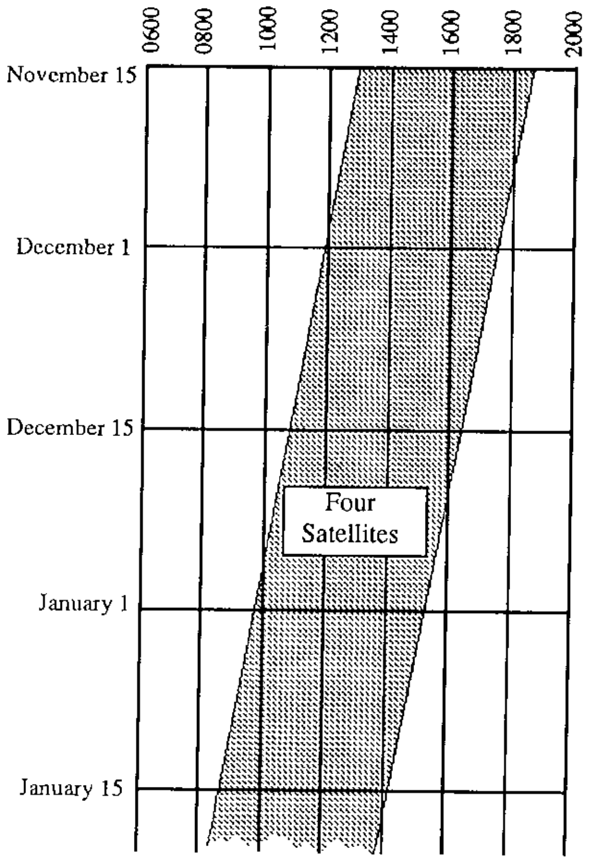


**Figure 21**

Global Positioning System. Time of the day when four satellites were available for accurate positioning - November 1988 to January 1989.

annotated by reference to the log book and location maps before individual frames are cut from each roll for storage as stereopairs in plastic vertical file pockets ready for interpretation. For security they are stored in a fireproof safe (Fig. 22).

## 3.4 Flight-line mapping and plot location

The locations of each photo-point are recorded as co-ordinates on the laptop computer. These data are later transferred to the Department's VAX mainframe computer system where they are processed into the GIS. By displaying photo-location data with the planned flight path data, it is possible to make a visual assessment of the success of the photographic coverage. In the display, graphic symbols define each photo-location, with frame numbers being displayed against every tenth location (Fig. 19).

Photo locational maps are then prepared for ground navigation and administration purposes, as follows :

(i) where 1:25 000 digital mapping coverage is available, computer plots are generated consisting of specified base themes together with photo point information;

(ii) a plot on clear film is generated together with a 1:25 000 map sheet layout (graticule) and map number for referencing.

**Figure 22**

Photo security involving storage in vertical file in a fire-proof safe.

Using an ammonia-based dyeline process, this overlay is positioned on the Department's appropriate 1:25 000 Australian Map Grid map sheet and a diazo film copy is produced. Owing to the roller process of this method, a linear stretch between the medium is evident and is compensated by allowing over registration at the beginning equivalent to half the calculated total stretch. An alternative method is to use a flat vacuum frame technique, with arc lights, to eliminate stretching.

Plot locational maps are also produced at 1:50 000 and 1:250 000 scale with land tenure information depicting the production and conservation areas, freehold lands and other non-Department lands for administration and planning use.

The reliability of the mapped photo locations depends on the accuracy of the GPS receiver (± 25 m), errors in the base map (± 25 m at 1: 25 000) and the registration of the two by paper overlay (up to 50 m errors). A further source of error can result from photographic tip and tilt.

Plots are located in the field by simple survey using a hip-chain and compass. The distances and bearings to plot locations are scaled off the 1:25 000 location maps (Fig. 23) using identifiable features such as track intersections, and reference tree as reference points. This introduces another source of error of uncertain magnitude. Plots are usually less than 1000 m from a track, although some plots are several kilometres from an access road, especially in areas of restricted access because of disease risk regulations. Such surveys are therefore prone to errors of variable magnitude but are probably within 25 m. As a result, very few of the photo plots are found exactly where expected.

Experience shows that half of the plots are found within 50 m of the expected position, with 90 per cent being within 100 m (Fig. 24). This is sufficient to find the general vicinity of each plot, with the exact plot centres being located from tree to tree navigation on the large-scale photos (Fig. 25). The remaining 10 per cent of plots can be up to 300 m out of position and difficult to find. Many of these problems are caused by errors in the GPS, resulting from photographs being taken during periods of the day when the satellite constellation is incomplete. These times should be avoided.

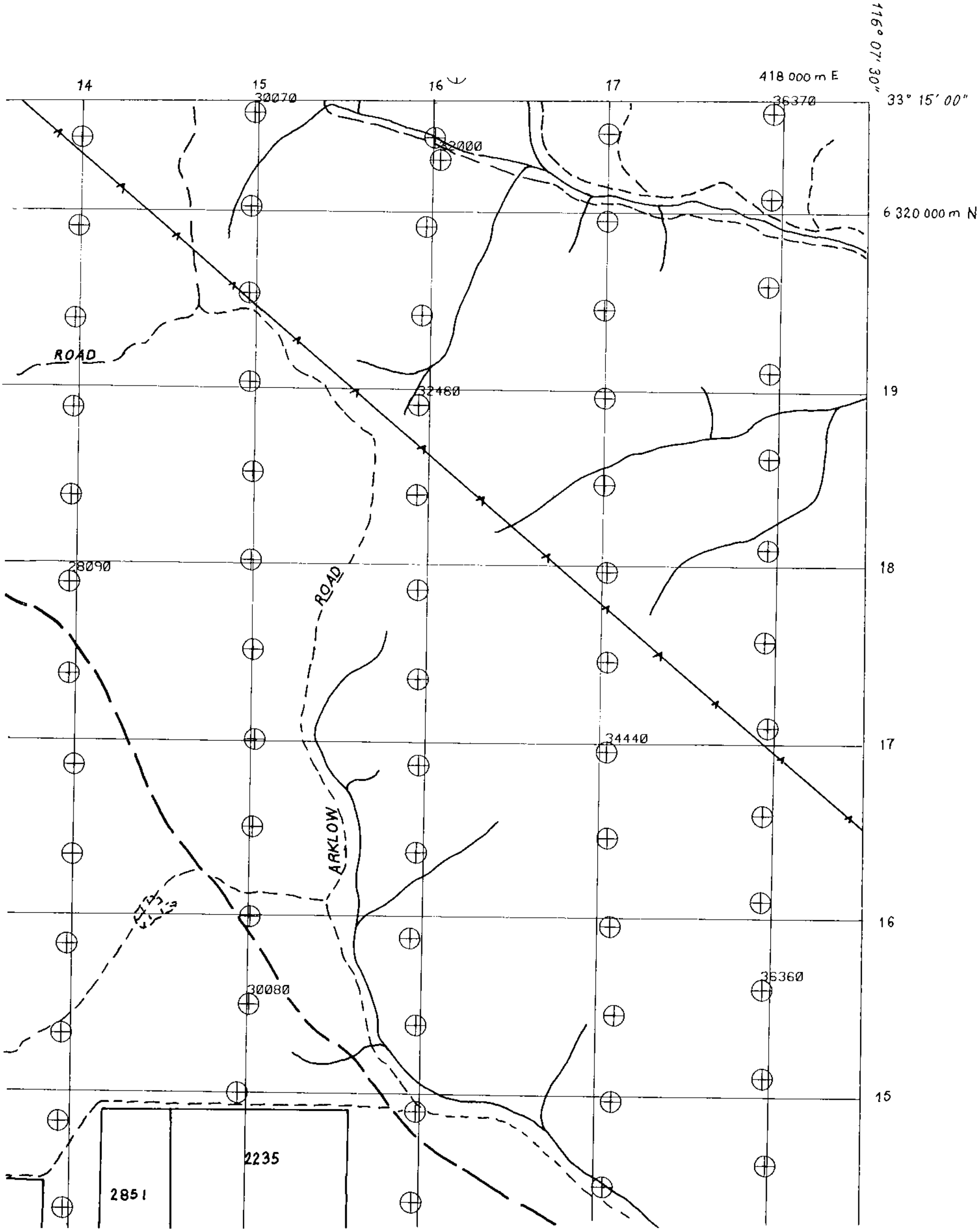


**Figure 23**
Sample Geographic Information System output of photo-locations at 1:25 000 scale as used for field navigation to ground plots.

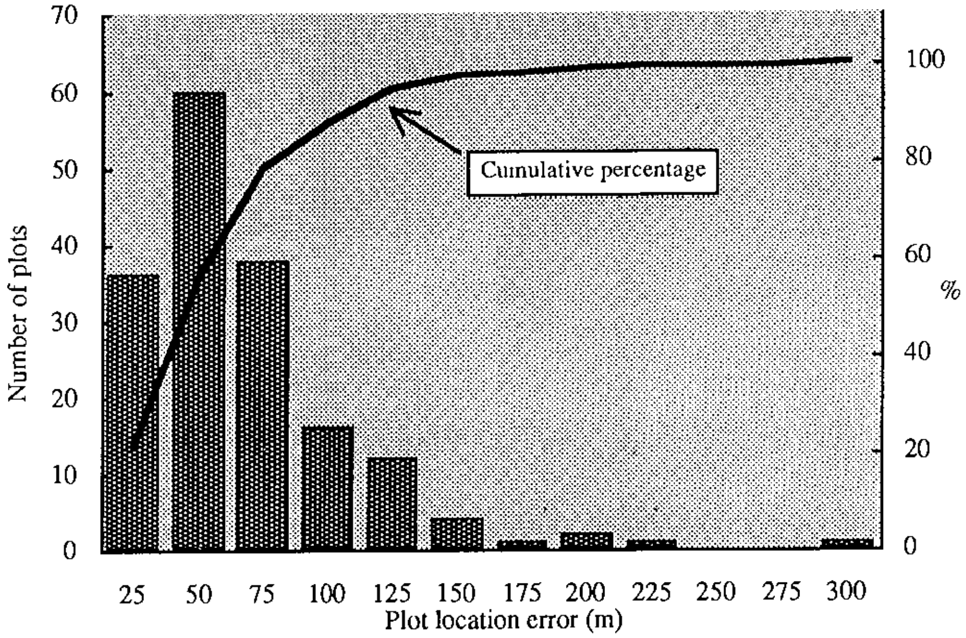


**Figure 24**
Ground plot location error. Frequency distribution and cumulative frequency percentage of plot location errors (m) for a sample of plots.

**Figure 25**
Ground plot location. Ground plots were located using the photos viewed on a portable light board, to identify features and navigate to the plot centres.

# 4 PHOTO-MEASUREMENT METHODS

**P.H. Biggs and S.M. Quain**

## 4.1 Determining photo-scales

With fixed-base photography, two cameras are mounted in parallel on a rigid boom at a fixed and known separation and are fired simultaneously to obtain stereo photographs. The photographic representation of the air base is the photo base, which in this case varies with the scale of the photography. At low flying heights the photobase is large, whereas at high flying heights it is correspondingly smaller. The formula expressing this relationship is :

$$b = B.f/H$$

where $b$ = photo base (mm)
$B$ = actual air-base (m)
$f$ = focal length of camera (mm)
$H$ = flying height above the ground (m)

For example, with a boom of 7.5 m, a flying height of 100 m and a focal length of 100 mm, the scale of photography (f/H) is 1:1000 and the photographic air-base is 7.5 mm. At 500 m above the ground, the photo scale is 1:5000 and the photo base is 1.5 mm.

As it is not possible to guarantee that the cameras are perfectly parallel in flight, it is necessary to use calibration targets to determine exact flying heights and, if necessary, to calculate a linear regression of photo base versus the reciprocal of flying height to determine the relationship between them.

Using this procedure for the Vinten photography (Fig. 26) gives the following derived flying height function :

$$H = 1 / (0.00318 + 0.00133\ b)$$

where $H$ = flying height (m)
$b$ = photo base (mm)

Hasselblad photography is a little more complex because daily reinstallations of the cameras cause slightly different relative orientations. Therefore, in order to determine the relationship between flying height and photo base for each day's photography, it is necessary first to calculate the camera orientations by reference to calibration targets.

The flying height of a stereopair can be calculated as :

$$H = Bf/(b + f\tan\theta) \qquad (1)$$

The value $f\tan\theta$ can be calculated from the photographs of calibration targets by rearranging equation 1.

$$f\tan\theta = Bf/H_C - b_C \qquad (2)$$

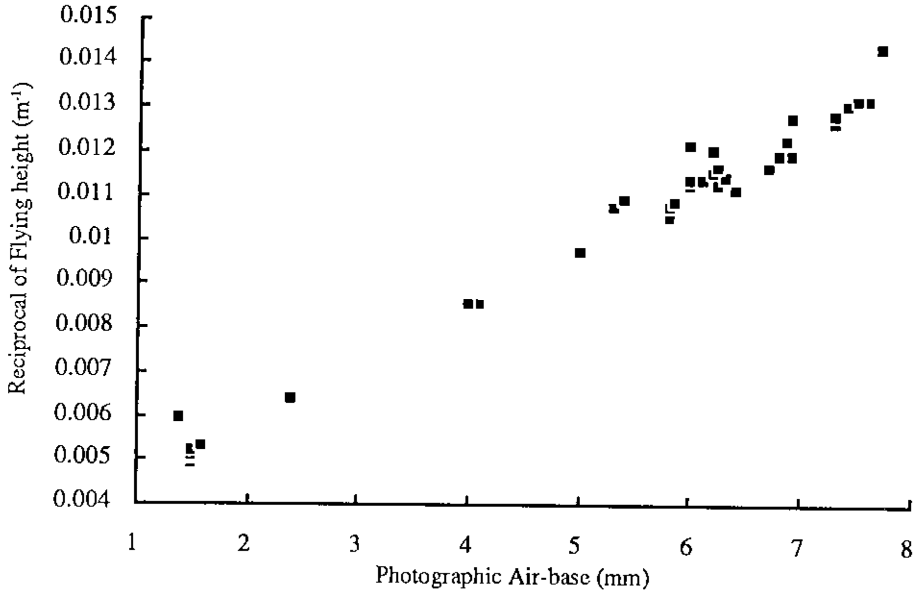


**Figure 26**

Flying height function. Reciprocal of flying height determined from ground-truth, was regressed against photographic air-base to develop a relationship for use in calculating the scale for photo-measurements. (Vinten photographs, 34 observations $r^2 = 0.988$.)

but $f/H_c = l_{pc}/l_{gc}$ (3)

so $f\tan\theta = (B\ l_{pc}/l_{gc}) - b_c$ (4)

Substituting equation 4 into equation 1 gives :

$$H = Bf/((b-b_c) + B\ (l_{pc}/l_{gc})) \qquad (5)$$

where $H$ = flying height (m)
$H_c$ = flying height of calibration stereopair (m)
$B$ = airbase (m)
$b$ = photo-base (mm)
$f$ = focal length (mm)
$\theta$ = angle of convergence or divergence (degrees)
$b_c$ = photo-base of calibration stereopair (mm)
$l_{pc}$ = length of calibration target on photo (mm)
$l_{gc}$ = length of calibration target on ground (m)

## 4.2 Photo-measurement equipment

To obtain the maximum advantage from estimating timber volumes from aerial photographs, the measurement equipment should not only be capable of accurate measurements, it should also be quick to use. If possible, the instrument should have a facility to correct for distortions in the photography, such as from tip and tilt and lens distortion.

Equipment developed for the measurement of large scale photographs exhibits innovation and variety in terms of capabilities, cost, and speed of operation (Spencer and Hall 1988). The simplest systems for measuring height consist of a stereoscope and parallax bar, sometimes with an encoder for semi-automated recording of measurements.

Operational forest inventories, however, involving hundreds or thousands of large-scale sampling photographs, require better, more expensive instruments, preferably with built-in facilities for parallax measurement, tilt adjustment, and the automated recording and processing of coordinate data. These requirements have led to customized systems based on Helava's analytical plotter concept developed at the National Research Council of Canada (Friedman *et al.* 1980).

Analytical plotters use mathematics and computers to solve the relationships between photographic image coordinates in two dimensions and ground coordinates in three dimensions. They are, therefore, mechanically simpler and more compact than analog plotters and can readily accommodate the effects of different focal lengths, film formats, lens distortions, and shrinkage. Their major advantages are that they provide straightforward, semi-automated procedures for relative orientation and recording of digital data. They also allow the operator to read, record, and store ground or other coordinates and to recall it at any stage with the computer, which provides for immediate calculations and analysis.

The locally manufactured ADAM MPS-2 small format analytical stereo digitizer was favoured for these reasons (Fig. 27). However, the amount of distortion in the Vinten photography caused by the focal plane shutter could not be easily accounted for in the analytical instrument without large amounts of ground control, and that without correction,

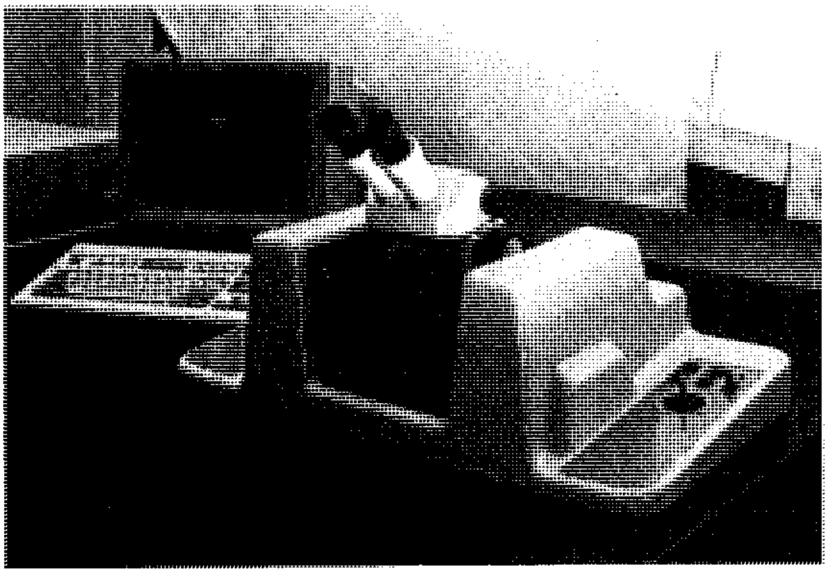


**Figure 27**
Adam MPS-2 analytical stereodigitizer.

relative orientations and parallax measurements could not be performed satisfactorily. This made the MPS-2 unsuitable for photographs from the Vinten cameras, but it was possible to measure photographs from the Hasselblad cameras.

As a result, alternative analog instruments in the form of modified Zeiss Stereotopes (Fig. 28) and Zeiss Jena Interpretoskops are being used to measure tree heights on the Vinten photographs. Modifications to the Stereotope facilitate the use of transparencies instead of prints. Although neither of these instruments is fitted with an encoder for the automated recording of parallax measurements, they are each supported by a microcomputer that accepts parallax readings keyed in by the interpreter and calculates and records tree heights.

The scale of each photo-pair, as described in Section 4.1, is calculated from a measurement of the photo base and a predetermined regression of photo base with flying height. This regression is checked by reference to calibration targets that are photographed at the beginning and end of each flight. The procedure estimates flying height to within ± 3 per cent of the true values at 100 m. The photo-base is determined from a simple procedure that involves measuring the difference between two corresponding images in a stereopair and their respective photo edges (Fig. 29) (Lyons 1964; Spencer 1979).

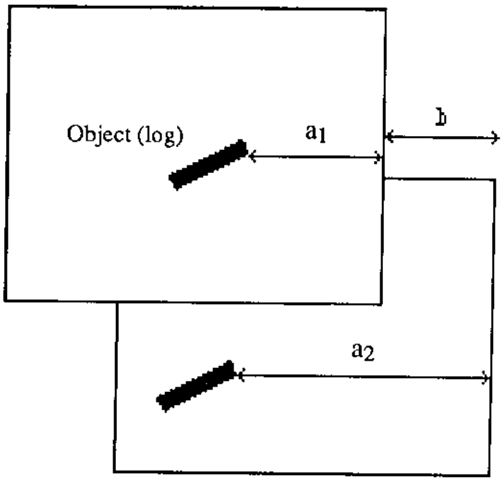


**Figure 29**
Measurement of photographic air-base(b) on 70 mm transparencies: $b=a_2-a_1$.

## 4.3 Selection and training of photo-interpreters

Photo-interpreters are selected for their ability to measure tree heights photogrammetrically. Experience in identifying tree species and forest types is also desirable, but as experienced forestry staff were not available for this part of the project, it has been necessary to implement a training

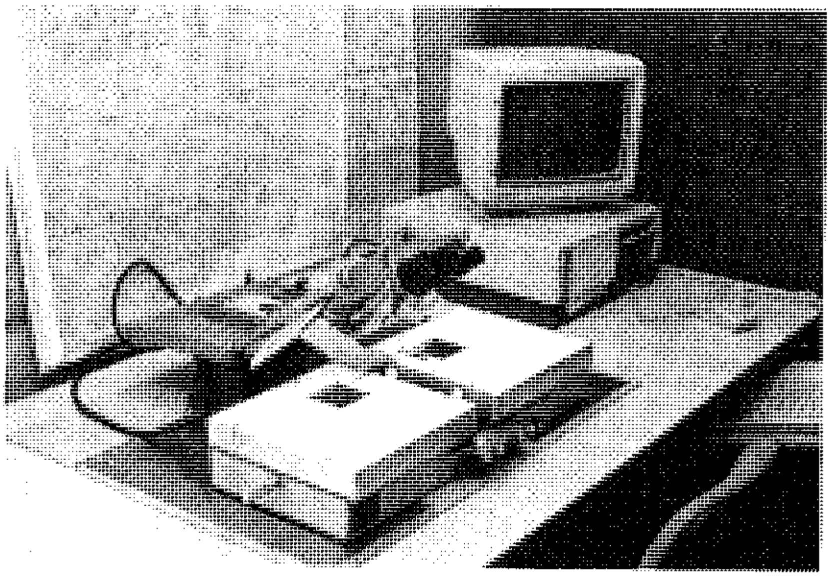


**Figure 28**
Zeiss Stereotope stereoplotter.

program in forest photo interpretation. Most staff employed in this area were either recent graduates or tertiary students in surveying or cartography.

Initial training involves one month's work in the field with ground assessment teams to gain experience in identifying tree species and stocking from the ground, and to develop a background knowledge of the forest. This is followed by one week of intensive training on species interpretation and stocking determination from aerial photographs, plus several days of training on tree height measurements.

Practice and evaluation then follow and interpreters do not start production work until they have obtained satisfactory test results, requiring a standard error of photo height measurement of less than 2 m and a species interpretation success rate of better than 75 per cent.

Each interpreter works on a single cell of photography at a time, with each cell being divided into smaller areas (subcells). Work on each cell begins with a reconnaissance of each subcell as a means of training the interpreter in the particular characteristics of that forest type and colour differences with different films.

## 4.4 Species identification

Tree species are differentiated on the basis of their geographic location and landscape position, the shape and size of the tree, branching pattern, colour, flowering and associated vegetation (Fig. 30, Table 3). As two major species, jarrah (*Eucalyptus marginata*) and marri (*E. calophylla*), account for some 80 to 90 per cent of the trees in the jarrah forest, the interpretation process is simplified.

**Table 3**

Factors used in species identification

| Species | | Identification Keys |
|---|---|---|
| Jarrah *(Eucalyptus marginata)* | Crown | • dark shiny green<br>• leaves appear brown at times |
| | Branches | • red brown, gentle angles |
| | Flowers | • cream - early summer |
| | Location | • mid slope to ridge top |
| | Similar species | • pole sized trees similar to marri |
| Marri *(E. calophylla)* | Crown | • olive green, yellowish at times<br>• cauliflower appearance on pile sized trees |
| | Branches | • grey brown, twisted, sharp angles<br>• fine dead branches common<br>• often bent down by weight of capsules |
| | Flowers | • cream - later summer |
| | Location | • low to mid slope, less on ridge tops |
| Blackbutt *(E. patens)* | Crown | • olive green lighter than marri<br>• structure similar to jarrah |
| | Location | • gullies, moist sites |
| Wandoo *(E. wandoo)* | Crown | • structure & colour similar to jarrah but appearing very dark at times |
| | Branches | • and bole white to grey-yellow |
| | Location | • low rainfall zones |
| Karri *(E. diversicolor)* | Crowns | • spreading, very tall when mature<br>• regrowth in uniform, even aged patches |
| | Branches | • white |
| | Location | • high rainfall zones, gully sites in jarrah inventory area |
| Other eucalypts | | |
| Bullich *(Eucalyptus megacarpa)* | | • gully sites, white branches, |
| Flooded gum *(Eucalyptus rudis)* | | • larger creeks and rivers |
| Non-eucalypts | | |
| Sheoak *(Allocasuarina fraseriana)* | | • spreading crowns, grey branches<br>• light olive green, but brown when flowering |
| Banksia *(Banksia spp)* | | • large leaves in circular patterns large cylindrical flowers |
| Paper bark *(Melaleuca spp)* | | • gully sites, white boles and branches |
| Woody pear *(Zylomelum occidentalis)* | | • large ovate leaves, dense crowns white flowers, common in Collie area |

Shadows are sometimes an additional aid to interpretation because they can give a different perspective of the crown shape and structure and they can be a help in counting the number of stems in clumps.

Colour is of great value in interpretation but it cannot be used alone to separate species because colours vary considerably between different sites, as well as with different stages of flowering and fruiting and with different batches of film. Wandoo (*E. wandoo*), karri (*E. diversicolor*) and bullich (*E. megacarpa*) can be identified by their white bark (eg. Fig. 31).

Flowering is a characteristic that can be useful for separating species (Fig. 32) on small areas but its value varies widely over time and location. Where evidence of the stage of flowering at the time of photography is detected during a cell reconnaissance, it can only be used as a diagnostic feature in the relevant portions of that cell. Location, site and associated vegetation are used initially in conjunction with other observations during the cell reconnaissance to determine which species might be expected in each area. Other clues include the structure of the forest, symptoms of dieback, jarrah leaf miner (*Perthida glyphopa*), gumleaf skeletonizer (*Uraba lugens*)and management activities. When difficulties are experienced in the photo-interpretation, checks are made in the field.

## 4.5 Photo-measurement procedures

All photo plots within multiple-use State forest are measured, except plots within areas that are being logged, or that have been logged since the photographs were taken.

The first step is to measure the photo base of each stereopair using a glass scale graduated to 0.01 mm. This is done, as previously described, by identifying a point, preferably on the ground, which is visible on both photographs and measuring the distance from that point to the corresponding edges of each photograph. The difference between these measurements is the photo base (Fig. 29). This method, first suggested by Lyons (1964), avoids the tedious tasks of marking and transferring principal points.

The second step involves identifying the species and measuring the heights of all trees taller than 10 m that fall within a 20 m (0.125 ha) radius of the centre of the stereo overlap. This circular plot is defined by a transparent template positioned under the right-hand photograph (Fig. 33). A range of templates, in 1mm radius gradations, is available to match the plot size approximately to the scale of each photograph. The analysis program calculates the exact scale and equivalent ground radius to ensure that the 'blow up' expansion factor for volume per hectare is used.

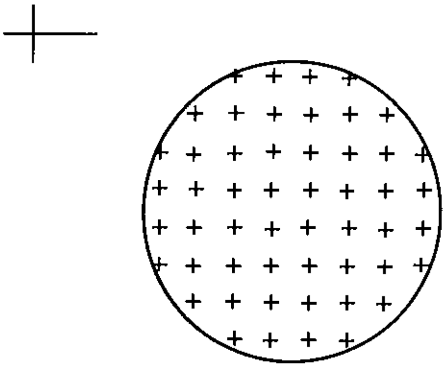


**Figure 33**

Photoplot template showing grid pattern to aid systematic measurement of all trees.

Photographs are scanned on a systematic pattern, with each tree being numbered, interpreted according to species, and measured for total height using the parallax method. A computer program is used to prompt the operator to record the appropriate photo data and to calculate tree heights.

## 4.6 Performance monitoring

Once a month, every interpreter is required to complete a performance test involving species identification and tree height measurements on a number of sample plots for which the heights and species have been checked in the field. A different set of photographs is used for each test to avoid the possibility of memory bias.

The following analyses are then made on the test data :

- mean error (photo-measured height-ground measurement);
- ratio correction factor (photo-measurement / ground measurement);
- standard deviation of the mean error;
- species interpretation accuracy;
- visual check on consistency of the height measurements.

The test results are used to monitor interpreter performance over time and to identify any problems. They are also used to calculate correction factors to be applied to each interpreter's measurements. Each plot is coded for the interpreter who measured it and the appropriate correction factor is included in the file to adjust the calculations in later processing. Typical results for species recognition are shown in Table 4a. Accurate species interpretation will affect the volumes estimated for species-specific products, but not the total volume.

Stem numbers for each species also affect the volume estimation and a series of test plots is used to check stocking accuracy. Finally, the easiest component to check is heighting accuracy, where the photo measurements are compared with ground measurements (Table 4b and Fig. 34).

**Figure 30**
Example of jarrah/marri crowns.

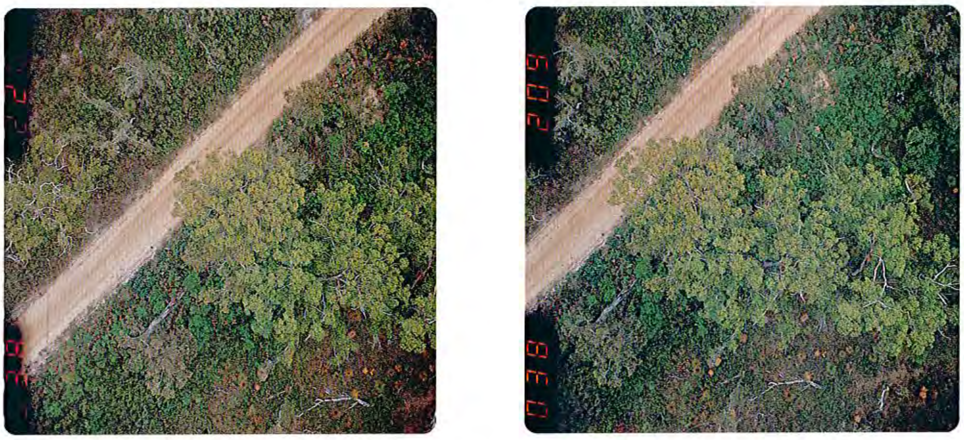


**Figure 31**
Example of white bark on karri.

**Figure 32**
Example of marri in flower.

**Table 4a**

Species interpretation tests - all interpreters, January to October 1989

| Ground truth | Photo interpretation | | | | | |
|---|---|---|---|---|---|---|
| | Jarrah | Wandoo | Blackbutt | Marri | Non-Eucalypts | Total |
| Jarrah | 533[a]<br>91.27<br>89.43 | 0 | 0<br>0.00<br>0.00 | 46<br>7.88<br>26.59 | 5<br>0.86<br>7.46 | 584 |
| Wandoo | 1<br>100.00<br>0.17 | 0 | 0<br>0.00<br>0.00 | 0<br>0.00<br>0.00 | 0<br>0.00<br>0.00 | 1 |
| Blackbutt | 2<br>28.57<br>0.34 | 0 | 5<br>71.43<br>100.00 | 0<br>0.00<br>0.00 | 0<br>0.00<br>0.00 | 7 |
| Marri | 54<br>39.17<br>9.06 | 0 | 0<br>0.00<br>0.00 | 124<br>69.27<br>71.68 | 1<br>0.56<br>1.49 | 179 |
| Non-eucalypts | 6<br>8.57<br>1.01 | 0 | 0<br>0.00<br>0.00 | 3<br>4.29<br>1.73 | 61<br>87.14<br>91.04 | 70 |
| Total | 596 | 0 | 5 | 173 | 67 | 841 |

(a) Values in each cell are respectively frequency, row per cent and column per cent.
For example the figures show that of 584 jarrah trees, 533 (91 per cent) were correctly interpreted as jarrah, 46 (8 per cent) were interpreted as marri and 5 (1 per cent) as other species (errors of ommission). In total, 596 trees were interpreted as jarrah of which 533 (89 per cent) were corrently identified while 63 were actually other species, mainly marri 54 (9 per cent) - errors of commission.

**Table 4b**

Height measurement tests - all interpreters January to October 1989

| | |
|---|---|
| Mean height - photo | 19.27 m |
| Mean height - ground | 19.65 m |
| Difference (mean error) | -0.38 m |
| Standard deviation of mean error | 1.71 m |
| Ratio Correction factor | 1.025 m |

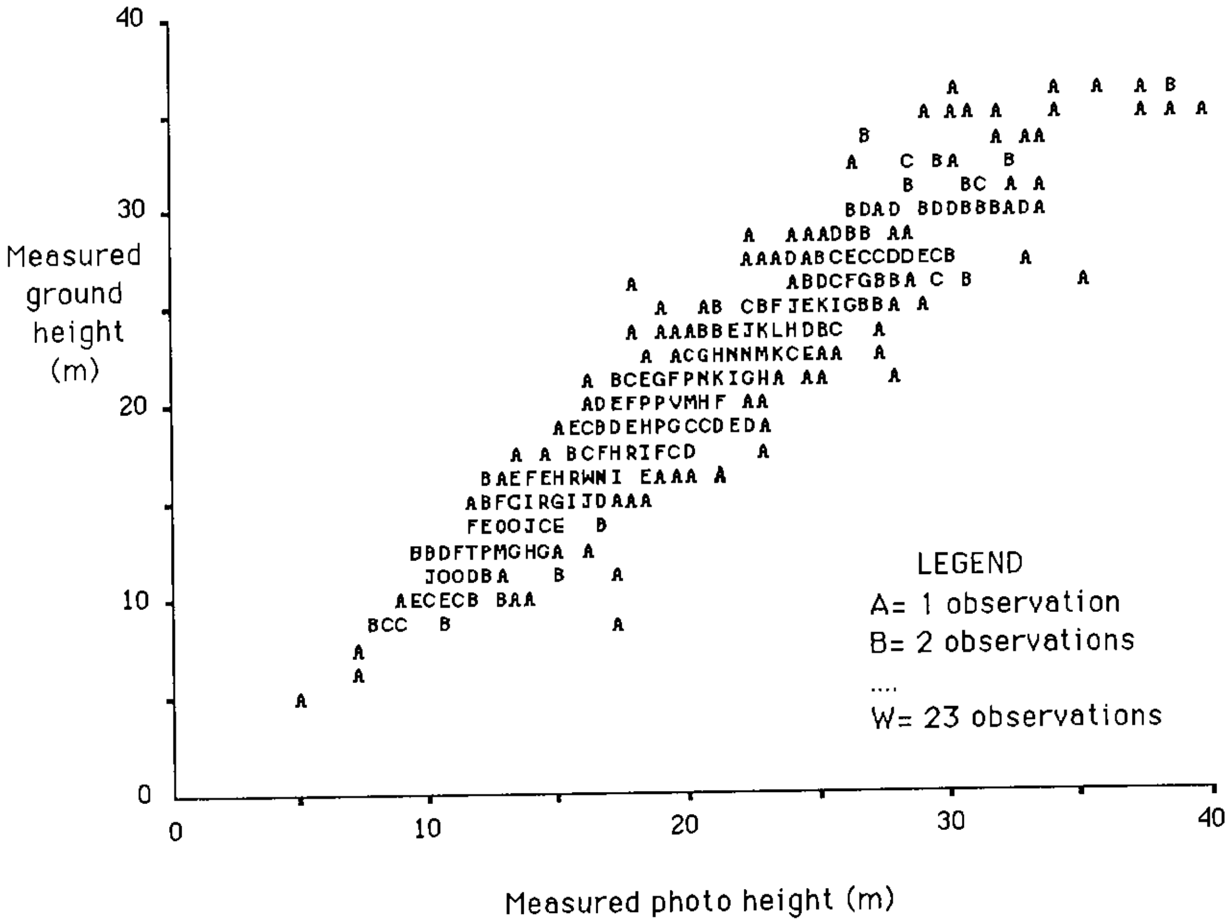


**Figure 34**

Comparison of tree heights measured from the ground and from aerial photos.

# 5 *GROUND-MEASUREMENT METHODS*

**G.J. Strelein and W.J. Boardman**

## 5.1 Selection of ground samples

As described in Section 2.5, a 10 per cent second phase ground sample was chosen to provide a satisfactory sampling error, considering the size of the area, the sample size, and the likely types of management enquiry. Every fifth plot on alternate flight lines was selected to obtain a uniform distribution of ground samples.

Plot position maps were overlaid onto the Department's coloured 1:50 000 scale operational plans to identify the relevant plots. Smaller areas of other land-uses such as recreation or conservation areas, plantations and private property are excluded from selection.

Similarly, areas of imminent logging or mining are excluded, but are programmed for reassessment after the operations are complete. If a plot could not be located in the field, then the next stereopair along the flight line was used as a replacement.

## 5.2 Locating ground samples

An index of second phase ground plots is provided to the ground crews, together with the Australian Map Grid coordinates for each plot and the corresponding large scale 70 mm stereopair. In addition a map of the photo points, produced via the intergraph system at 1:25 000 scale and overlaid onto the Department's Topographic series (Fig. 23), is provided to show detailed information on tracks and other features to assist in field navigation to each plot.

These maps are the initial means of navigating to the vicinity of each sample plot - usually to the nearest road or track feature that can be used as a reference point. Distances and bearings to each plot are scaled off the map and measured by rally-type trip meters, where appropriate, or hip-chain and compass.

The Trimble GPS receiver from the photography operations was also mounted on vehicles and used in areas with few reference points and poor map detail for new tracks. Hand-held GPS units were also used. This equipment was only useful in the latter stages of the field program when the satellite constellation was almost complete, providing better signals for ground reception in forest areas.

Once the assessment crew has navigated to the approximate location of each plot, it then examines the photographs stereoscopically to identify the precise location of the plot on the ground using features such as individual tree shape and size, stag-headed trees, logs, understorey plants. The plot centre is defined as the centre of the relevant photo overlap. The transparencies are viewed using an Abrams 2X/4X lens stereoscope and a white translucent sheet of perspex to provide diffuse natural back lighting (Fig. 25).

Experienced assessors generally locate the sample point within ten minutes, although the task is more difficult in some forest types with dense featureless canopies. If a plot cannot be found it is substituted by the next along the flight line. Where featureless forest types are likely to be extensive, with few tracks for referencing, as in the higher quality southern forests, an additional tracking camera is also used to provide an overview of the area. This camera has a wide-angle lens and gives stereoscopic images centred on the sample points to show a larger area of forest to assist the ground navigation.

## 5.3 Ground measurements

### 5.3.1 Choice of measurement variables

Since the ground samples are the second phase of the inventory, their purpose is twofold. Firstly, they are used to correct any errors in the first phase photo-estimation of volume and species composition and secondly, they provide additional information on timber quality and dimensions to facilitate partitioning of gross volume estimates into quality and size classes.

To satisfy the first requirement, it is necessary to record the trees by species and to measure appropriate dimensions for calculating volumes. A volume relationship requiring measurements of the stem diameter and height at crown break together with diameter at breast height (d.b.h.o.b.) of 1.3 m and bark thickness (b.t.) is used. The point of crown break used in this function has to be described explicitly to cater for wide variation in branching habits (Appendix I).

The above measurements also provide the data for analysing piece sizes, an important consideration in conjunction with quality data for determining types of products.

The methods used for wood-quality assessments are very different from the routine assessment procedures and are described in Section 5.4. Because of time constraints these measurements are restricted to bole wood, but it is recognized that a separate, additional inventory of crown wood will be required at a later stage when demand for this resource increases.

The major species (Appendix III) are measured down to 15 cm d.b.h.o.b; all other species are measured down to 25 cm. The minimum of 15 cm diameter over bark equates approximately to 10 cm under bark, which is likely to be the lower limit for most products.

Other attributes recorded include silvicultural class : e.g. old-growth/regrowth; condition: standing/fallen, live/dead; and status, which describes the general size and quality class of each tree. Additional factors cover assessments of forest health, damage owing to fire, insect, disease, and regeneration stocking.

### 5.3.2 Ground measurement procedures

Circular 0.125 ha full plots of 20 m radius and 0.03 ha sub-plots of 10 m radius are laid out and marked as the first stage of measurement. Circular plots were selected to minimize difficulties in matching the photo and ground plot boundaries.

Trees less than 25 cm d.b.h.o.b. are measured only on the smaller subplot because of their greater numbers. Similarly, measurement of small logs and species of little commercial potential are restricted to the subplot. Other adjustments to further improve efficiency involve eliminating measurements and quality assessments on some classes of trees, such as trees of small diameter, trees of very poor form, and large trees with a high proportion of defects.

Lower bole diameters are measured with a steel tape, bark thickness with either an ice-pick or needle-syringe type gauge. Heights and upper stem diameters are measured using a Spiegel Relascope.

The major plot measurement procedure relates to the assessment and description of timber quality in each log, live and dead tree. This step is time-consuming because every defect and wood type along each bole is categorized according to type and size (circumference or cross-sectional area), with the bottom and top heights of each affected section being recorded.

To make the resource data more versatile, some abnormalities not normally regarded as defects are recorded, such as wild grain and eccentricity, as they may become significant in the future when specifications could be revised.

Observations on forest damage and regeneration stocking require a relatively small part of the plot measurement time, which in total varies from 0.5-1.0 days (including travel) depending on the number of trees, their size and condition (Fig. 35). Details of the plot measurement specifications are given in Appendix II.

### 5.3.3 Recording methods

Most of the early recording was onto special paper sheets that can be used in light rain, but the method is inefficient because it requires subsequent entry and validation for computer analysis. Consequently, portable computers have been investigated for direct recording. Husky Hunter computers were available in the Department and have been programmed for direct field recording with much of the validation carried out as the data is entered (Fig. 36), but other machines are being evaluated.

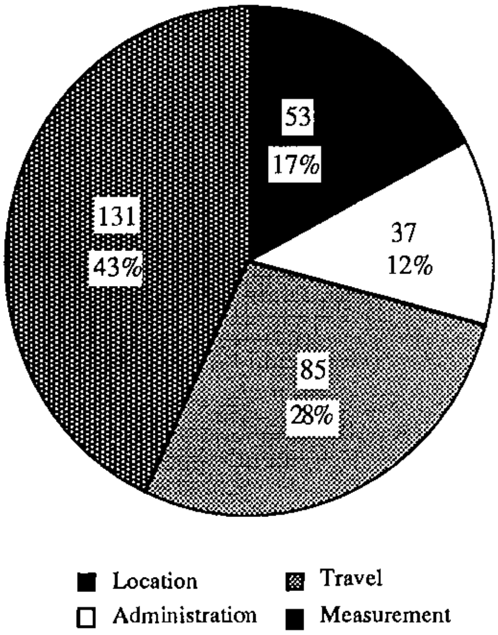


**Figure 35**
Time allocation for ground plot establishment (minutes and percentages) for a sample of ground plots during the early stages of the program. Times and proportions are affected markedly by forest conditions and the assessor's experience. This trial included two plots that could not be found, despite considerable searching.

Using the Husky Hunters, the assessor keys in the records for each plot and may accumulate data on a few plots before downloading it to the main computer system. It is then given a final validation check for errors that are difficult to detect with the Husky system. Any corrections are made by the assessment crews to help them improve their recording procedures.

## 5.4 Quality assessment

Describing quality characteristics, including defects and attributes, rather than assessing trees for specific products, is a relatively new approach that is being employed because specific *product* requirements are subject to rapid change in today's wood utilization industry. It is an approach designed to allow for changes in the types or amounts of specific defects permissible in each product, as well as the possibility of new products coming onto the market in future years.

The system requires the description of a range of wood qualities (see Appendix IV) and their magnitude (See Appendix V) that can then be analysed according to product-specifications by computer modelling techniques. Figure 37 shows a simplified flow diagram of the sorting process.

For sawn products, the modelling process rebuilds the tree to look at interactions and the relative positions of positive

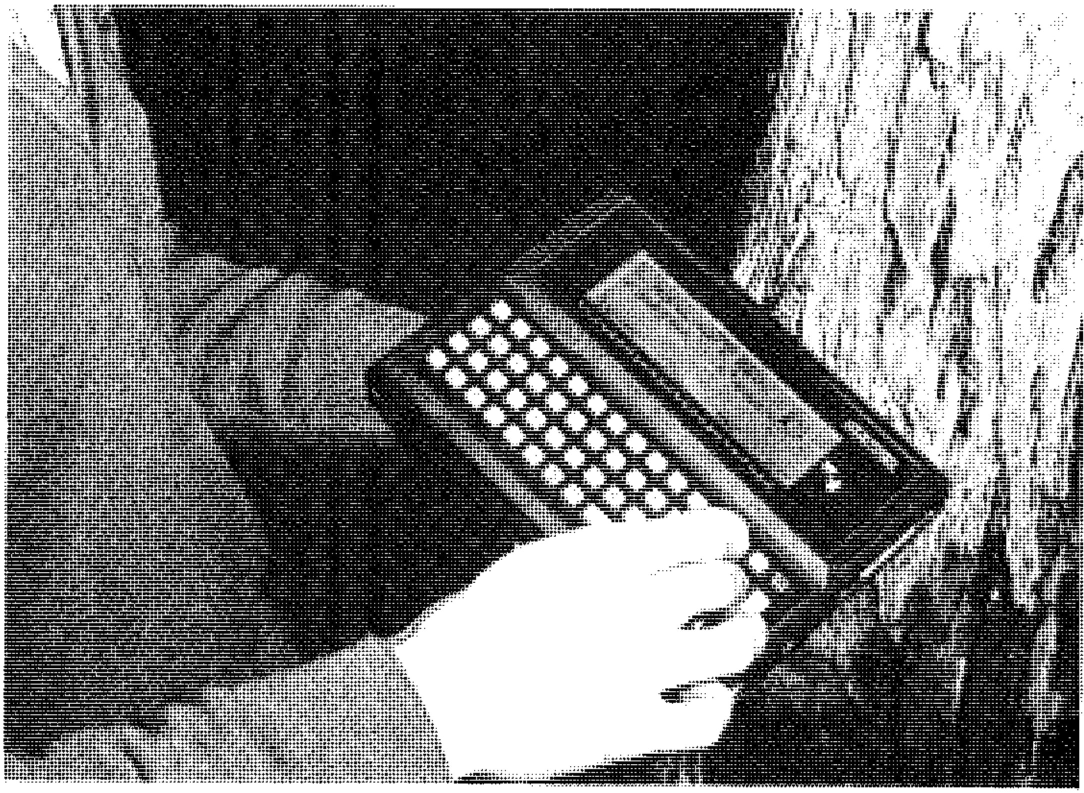


**Figure 36**
The Husky Hunter portable computer in use in the field..

and negative characteristics. For bulk products, such as chipwood and charcoal, the modelling process simply considers the usable cross-sectional areas required for a log to qualify.

In the actual assessment of quality there are basically three types of features; surface features that can be described easily, internal conditions such as rot or termite attack, and shape. Assessment of some surface features is very straightforward and only requires a description of the proportion of the circumference and the length that is affected, plus the quadrant. Other features, however, such as overgrowths or borer holes, have associated internal defects that are hidden. The internal defects are dealt with in the sorting process by including a conservative allowance for them in the specifications for the product.

Sawing trials are being conducted to try to develop a stronger correlation between external indications and their internal expression (Fig. 38). These form part of a wider program aimed at developing better understanding of relationships between utilization potential and basic resource availability and quality.

## 5.5 Product types

Products are defined very loosely as the aim was to design a flexible system that would allow for the calculation of product types to meet various specifications. A table of permitted features, and conditional features, together with their limits, formed the basis for programming the sorting of different product qualities (Table 5).

If the values of conditional features change, then the limits are also changed in the software. If the conditional or permissible features change, the software can again be changed to add or delete from the list and the sorting becomes more or less complicated as a result. The aim is to develop the sorting process so that the product specifications become part of the input, thereby providing planners with a means for evaluating resource availability in relation to tighter or looser specifications.

Part of the product specification has to include priorities for sorting. For example, a high quality log would be suitable for many uses but it can only be used once and the priorities can markedly alter the yields for specific products.

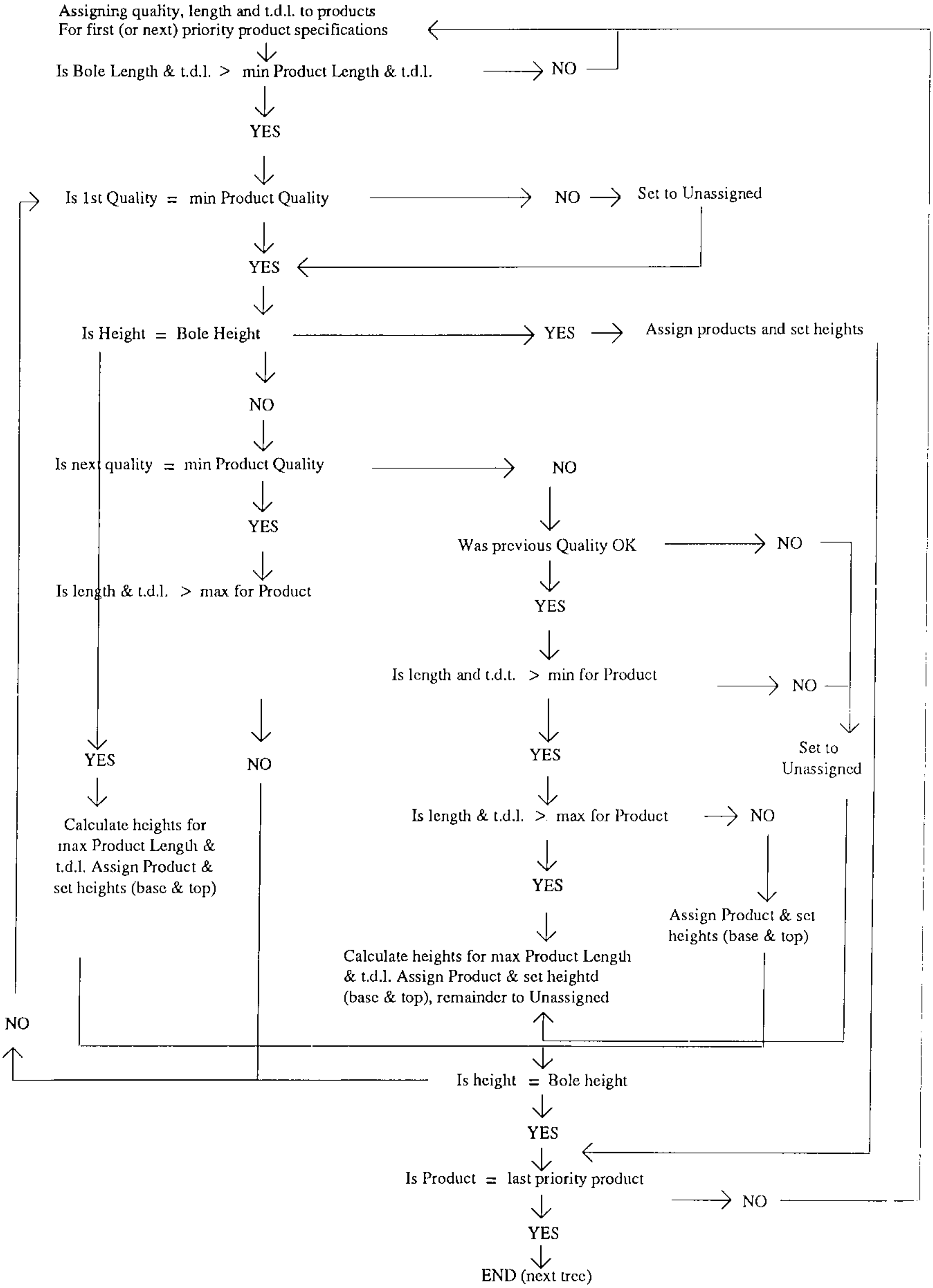


**Figure 37**

Quality Sorting Program. This Figure represents a simplified flow diagram of the quality sorting program to determine products and calculate piece-size diameters and lengths.

**Table 5**

Current specifications used in product sorting - sawlogs.

| | | |
|---|---|---|
| **Sawlogs** | First Grade A1, A2 | Second Grade B1, B2 |
| **Codes** | Short E | Small J |

**Tree Description** (See Appendix II)

| | Status | Form | Silviculture | Condition | Species |
|---|---|---|---|---|---|
| Acceptable | 1,2 | 0-2 | 1-6 | 1,4 | 1-4 |

| **Size** | A1 | A2 | B1 | B2 | E | J |
|---|---|---|---|---|---|---|
| t.d.l.u.b. (cm) | | | | | | |
| Min | 25 | 25 | 25 | 25 | 25 | 15 |
| Max | 999 | 999 | 999 | 999 | 999 | 25 |
| Length (m) | | | | | | |
| Min | 3.0 | 2.1 | 3.0 | 2.1 | 0.75 | 2.1 |
| Max | 999 | 3.0 | 999 | 3.0 | 2.1 | 999 |

**Qualities** (See Appendix II)

| | |
|---|---|
| Acceptable | CW, CU, IL, LM, L, EM, E, F, X |
| Unacceptable | Q, IP,DP, DM, HP, HM |
| Non-Millable | HB, HU, H, BU, B, O, SH, T, R |

| Min. % Millable | A1 | A2 | B1 | B2 | E | J |
|---|---|---|---|---|---|---|
| | 50 | 50 | 30 | 30 | 50 | 95 |

Conditional (Maximum)

| | Wind | Dryside Multiple | Overgrowth Multiple | Checks | Branch Multiple | Branch Unsuitable Multiple | Circularity | Gum | Gum Multiple | Bend/ Multiple |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 14 | 2 | 2 | 5 | 2 | 1 | 35 | 30 | 3 | 8 |
| B | 14 | 3 | 2 | 5 | 2 | 2 | 35 | 30 | 3 | 8 |
| E | 14 | 2 | 2 | 5 | 2 | 1 | 35 | 30 | 3 | 8 |
| J | 14 | 1 | 0 | 0 | 1 | 0 | 10 | 10 | 1 | 0 |

Multiple Sweep* and Kink (max) (*Single Sweep and Kink - special cases where deviation calculated)

| t.d.l. (max) | A | B | E | J |
|---|---|---|---|---|
| 300 | 1.5 | 1.5 | 1.5 | 1.0 |
| 500 | 5.0 | 5.0 | 5.0 | 1.0 |
| — | 7.5 | 7.5 | 7.5 | 1.0 |

**Figure 38**

Correlating external log characteristics and internal defects. Sawing trials were carried out at CALM's Wood Utilization Research Centre at Harvey, W.A., to correlate external characteristics and internal defects.

At this stage the sorting programs are intended to handle six grades of sawlogs, plus chipwood and charcoal logs, but they are to be expanded to include roundwood products such as poles and fencing materials.

## 5.6 Validation procedures

Validation of ground plot data is performed by processing the data with software written specifically for the project. Data collected on portable computers is subjected to basic checking in the field to ensure that all fields are entered with relevant symbols and that all related fields are matched.

The main validation program continues running after an error is discovered to find related errors so that the data can be corrected in a single editing session. Data are again validated after this editing to ensure that none of the errors was missed and that no new errors have been introduced. Supervisors and assessors are involved in the validation process to give direct feed-back on any misconceptions, bad habits or tardiness.

Not all validation messages indicate real errors, as there are often warnings that a value exceeds the expected range and should be checked. In the interests of efficiency, symbols are used to highlight error types. For example, if a tree-record is in error then it is printed on one line with the appropriate symbol printed below it in a relevant record-field.

# 6 DATA INTEGRATION AND ANALYSIS

C.J. Pearce, W.J. Boardman and M.A. Green

## 6.1 Geographic Information System

Every item of data collected in the jarrah inventory, whether from the aerial photographs or from ground-based measurements, is tied to a geographical location. The locations of the measured plots, provided to an accuracy of 20 to 30 m by the GPS, form a more or less uniform rectangular grid of points over the area covered by the inventory. They therefore form the basis of a quasi-continuous map of the resource parameters measured. Such data is handled, and related to other spatial data (in particular other maps), by a geographic information system (GIS).

At the commencement of the jarrah forest inventory, the Department already possessed a pre-existing GIS, or rather the software and hardware tools which go to make up such a system. It also had a large database of thematic map data in digital form, covering the area of the inventory, as well as some high precision digital maps related to tenure and the forest management plan. The task required for the jarrah inventory was to adapt the existing GIS tools to meet the data storage, processing and reporting requirements of that project.

The existing GIS facilities consisted of three main components: Intergraph, a sophisticated proprietary computer-aided mapping and graphics facility; ARC/INFO which is another proprietary system for computer-assisted mapping and map analysis; and FMIS, a forest management information system developed in-house. The Intergraph is used for high precision map input, editing and storage, and for derivative map production. ARC/INFO is intended for spatial analysis (such as buffer generation, or polygon intersection) and some map product generation, and FMIS is a grid-based map overlay system for forest resource inventory and area statements. For the jarrah inventory project, all three components are required, in a way which links them together more closely and systematically than has been necessary in the past.

In the following subsections we describe the requirements imposed on the GIS by the jarrah forest inventory and the overall system design adopted to meet these requirements.

### 6.1.1 System requirements

It is convenient to discuss the requirements under three main headings: data storage, data analysis and processing, and output or reporting. The essential requirement for data storage is that all the measurement data, with its associated geographical location, is linked to a graphical representation of that location. That is, the three types of data collected - navigational data, photo-measurement data and ground-measurement data - must be stored in a database which links to a graphics design file showing the locations of the photo plots. This is necessary in order for the measurement data to be selected and accessed in relation to other, external, map data or map representations. The system must also be able to store such external reference maps, which themselves may be linked to other databases. Examples of such maps include topographic map and cadastral boundaries, as well as numerous thematic maps relating to forest type, treatment, operations, and Departmental administrative boundaries. Much of this information already exists in the Intergraph and FMIS data bases.

The processing requirements, however, are more demanding and less easy to predict in the long term.

Firstly, the system must have full data editing, updating and archiving facilities, and must provide a secure linkage between the three different types of stored measurement. It must also have the means of transferring graphical data (the 'reference maps' referred to above) between different components of the system (such as FMIS and ARC/INFO) and of combining any graphical data in one component of the system with graphical data provided from some other component.

It must be able to carry out polygon overlay between different reference maps, based on the database or 'attribute' values associated with the polygons (such as the actual year of logging associated with logging history polygons). There must be the means for generating 'buffers' or 'zones', either along linear features or about points, so that the buffers form new maps which may be overlaid with the measurement data. It must also have digital terrain modelling capabilities, so that conditions on slope or elevation, for example, may be imposed when interrogating the data. The central processing requirement, however, is to be able to select all measurement plots within a window defined by a reference map (generated in any way required), and to extract and make available all data from the database applying to those plots. This capability is necessary in order for the resource to be estimated within any pre-defined area.

Finally, it is essential that the data stored in the measurement databases should be accessible (following selection by plot identifier) to FORTRAN programs for analysis and statistical reporting.

The reporting requirements lie in the areas of both graphical output and statistical or tabular statements.

First there are maps required, showing the principal points of photos against a topographic background, at scales of 1:250 000 (for planning purposes) and 1:25 000 (for use in navigation by ground-measurement crews). When interrogation takes place, a map showing the window of interrogation, again with a suitable topographic background for reference, is needed. Following more elaborate interrogations, it may be necessary to generate a high quality map showing a succession of interrogation windows, together with some kind of shadowing, colouring or symbols to indicate resource levels. A perspective view of a three-dimensional representation of the resource level or 'elevation' may also be desirable.

The system must be capable of outputting tabular resource information in virtually any form which may be requested. Since the processing requirements dictate that the measurement data should be accessible to FORTRAN programs, there should be no restriction on the type of statistical summaries which may be compiled by direct extraction from the database. In particular, the system must be capable of generating input files for a statistical analysis package. Another form of output would be an FMIS resource statement, made possible by creating an FMIS 'theme' (or map) of resource density through the use of the digital elevation model facility.

### 6.1.2 System design

The design adopted for handling the processing of the jarrah forest inventory data consists basically of a set of GIS modules (some pre-existing) and the interfaces between them.

There are five main modules, plus a number of smaller ones intended mainly for data validation, housekeeping and so on.

The central module, in which much of the geographical processing takes place, is ARC/INFO, shortly to be supplanted by ARC/SQL. This system is used for all data storage (in the ORACLE database) and data management. It also contains the graphical representation of the principal points (in an 'ARC coverage'). The generation of the final form of the geographical window of interrogation also takes place in ARC/SQL, as is the intersection between the array of principal points and the window polygon or polygons, in order to generate the set of photo plots within the window.

The generation of the window of interrogation may also involve two other modules: Intergraph and FMIS.

The role of FMIS is to provide that component of the interrogation window which depends on forest thematic maps such as forest type, cutting history, administrative areas and so on.

Intergraph is used to store and supply topographic features, such as roads, or towns, which may be used to define buffers of exclusion or zones for inclusion. In addition, the Intergraph can provide tenure and management-plan map information. The Intergraph is also employed to produce the principal point maps following the aerial photography, and may be involved in the final production of resource maps for management.

The next major module is the product allocation program. This takes a list of products, in a priority order, and allocates those products to the ground-measured plots within the interrogation window. It also reads the relevant photo-measurement data, and generates a composite data file for input to the statistical program, which is the final main module. This process is described in detail in Sections 6.2.2 to 6.2.5.

In addition to the above, special software has been developed to provide efficient and easily operated interfaces between the main modules, so that data may be passed rapidly between them with minimum intervention.

## 6.2 Processing Geographic Information System and resources data

### 6.2.1 Processing Geographic Information System data

Once the data are in the system, and have been validated, the processing sequence follows a downward path through the flow diagram in Figure 39.

The first stage is the definition of the area to be interrogated for resource - the window. The specification of this area will in general involve themes from FMIS, topographic information from Intergraph, and buffer generation within ARC/INFO. First, a multiple map overlay is carried out in FMIS to generate a composite map which represents the area satisfied by a subset of the constraints defining the interrogation window. The composite is then transferred to ARC/INFO and a coverage created. Similarly, the appropriate topographic and cultural features (such as roads, rivers, place names or sawmill location) are transferred from Intergraph to ARC/INFO and the required buffers, or zones, created. A polygon overlay is then carried out to intersect any such buffers with the composite map from FMIS to generate the final window for interrogation.

The second stage is to select the sample plots which lie inside the interrogation window. This is achieved by using the point-on-polygon operation in ARC/INFO, and then generating a list of the identifiers of those plots which lie within the window.

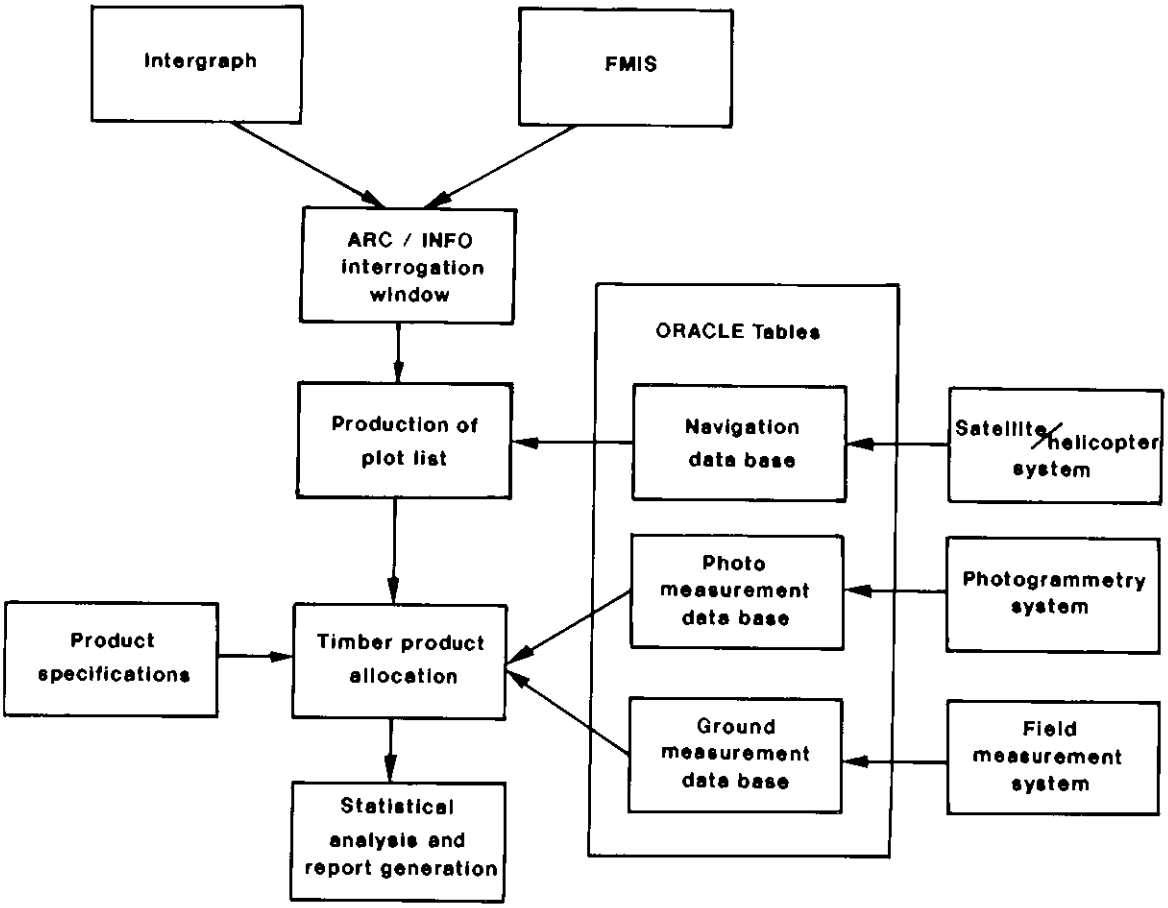


**Figure 39**
Flow diagram for processing Geographic Information Systems data.

The third stage is to extract and process the measurement data within the window. This is carried out by a program described in Section 6.2.3, which takes the list of plot identifiers, and uses it to read from the ORACLE database all the photo measurements and ground measurements of the plots within the interrogation window.

The program searches for and allocates the required products based on the ground measurement data, and constructs an input file for the statistics module. The latter combines the measurement data and generates the summarized resource statement which is required.

The final processing stage is the construction of a map, showing the window of interrogation, tabulation of resource level information, and topographic background. This currently takes place on the Intergraph, but may in future be done with ARC/INFO.

### 6.2.2 Processing photo-measurement data

Photo data are collected either directly from the Adam Technology MPS-2 analytical stereodigitizers or via a data entry program running on a personal computer from the parallax measurements on the stereotopes or interpretoskop. These systems include initial validation of the data, which is followed later by more extensive cross-checking.

The parameters recorded for each plot are the plot identifier (which is linked to the location coordinates), photo scale, plot diameter, plot type (full plot or half plot on a forest boundary) and land cover (e.g. native forest, exotic species, water body, mine). Individual tree parameters include the tree species and its silvicultural class (regrowth or old-growth) as well as the tree height. Plot data are checked against navigational data and cadastral boundaries to ensure that the coverage of the photo samples is correct and that there are no duplications or omissions.

An empirical formula, obtained by linear regression (Section 2.4.2), is applied to each tree height to determine gross bole volume. A correction factor is applied to the tree height estimate if it is known that the interpreter's measurements are significantly biased. The volume estimates are then added to the ORACLE database. When ground data are later added to the database, a ground-measurement flag is set to indicate the double sample plots.

### 6.2.3 Processing ground plot data

The ground plot data contain all of the information describing the wood qualities in each sample tree. The data for each tree are assessed by computer programs to derive the estimates of volume for each of the various product types. The product specifications are not fixed, but can be varied for each run of the program, and the order in which the products are computed can also be changed to match changing priorities in the market.

In the computer assessment, each tree is assessed in turn for the products within it. First the tree is tested to see if it is potentially suitable based on species, diameter at breast height, bole length or condition. The most valuable product is looked for first (based on the user's priorities) and assigned wherever possible. Then the next most valuable product is sought and assigned, if possible, where no other product has already been assigned. This process continues until the tree is completely assigned or until all desired products have been considered, in which case any remainder will be assigned as waste.

To reduce the computational load, each product is defined in terms of acceptable, conditionally-acceptable or unacceptable wood quality types. Most computation time can therefore be devoted to conditionally-acceptable quality types. For these types, a large quantity of defect would disqualify the corresponding section of log from consideration. For example, an acceptable quality is a burl, a conditional quality is rot, and an unacceptable quality is attack by pinhole borers(*Atractocerus kreuslerae*).

For a conditional quality measured as a cross-sectional area, whose quantity is not too large to be unacceptable on its own, there are two considerations to be made when determining acceptability. First, the quality (defect) could occur in a quadrant different from other defects below (Fig. 40); as such it would effectively add to these other defects (qualities) when assessing the suitability of the entire length being considered for assignment to the product. Second, it could be coincident so that there is no increase in cross-section resulting.

If the sum of the various areas exceeds a permitted maximum (such as 50 per cent cross-sectional area) it would disqualify the section from consideration. Where a section is unacceptable, then, if there is sufficient length below, the product would be assigned to that length.

After failure owing to too large a quantity by itself in one section, or through non-coincidence with other qualities, checking would begin again above the failed section. In the case of defect in non-coincident quadrants, the lowest section being considered would be omitted in case it is out of alignment with those above it. This would be done by adjusting the lower height to be at the top of the omitted section. Then the checking process would start over again (Fig. 41).

Some conditional qualities are more difficult to accommodate than others. In particular, these include sweep and bend. In the case of bend there can be an upper limit to acceptability. Where the maximum is reached and, if there is sufficient length below, then that length can be assigned and checking can recommence above the bend.

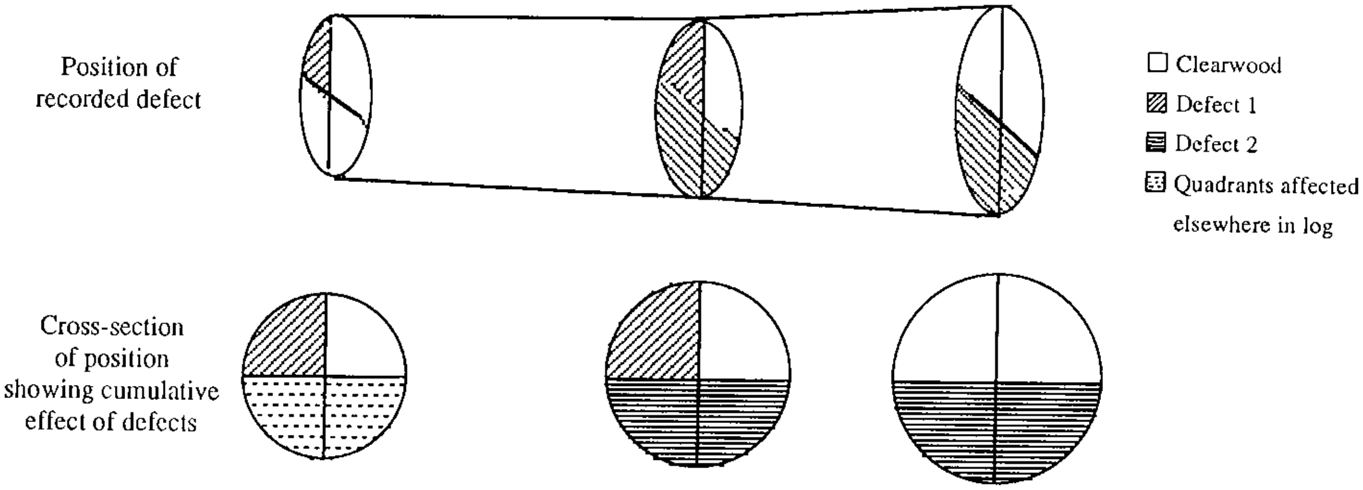


**Figure 40**
Combined effect of defects in different sections of the same log.

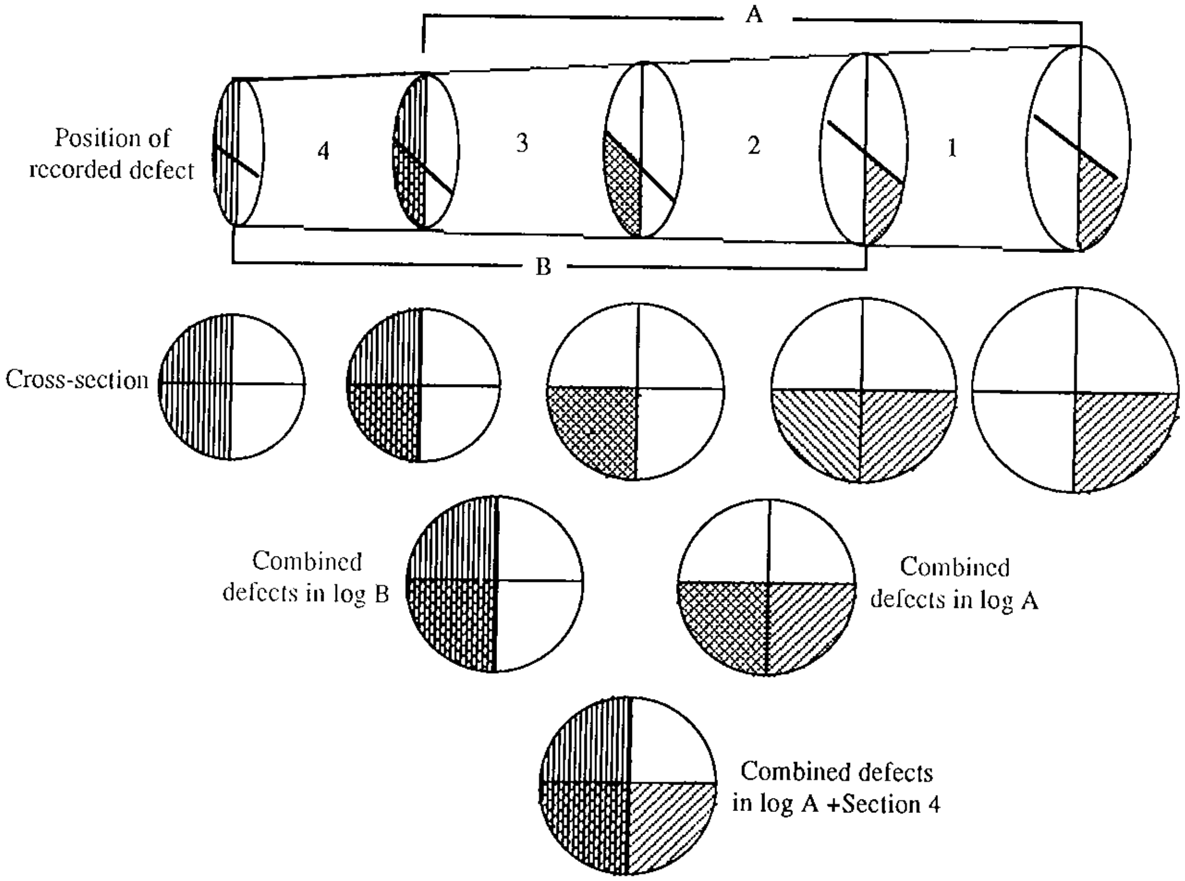


**Figure 41**
Combining acceptible sections to optimize product allocation. If a maximum cross-sectional area of 50 per cent is allowed, then section 4 is unacceptable to Log A since the combined area of defect would be 75 per cent. If Log A is not long enough then Log B (and above) will be considered and section 1 demoted. If log A is long enough then it will be assigned and checking will begin from the beginning of section 4, unless section 4 is unacceptable for reasons other than non-alignment of defects - in which case processing would recommence from the end of section 4.

Where there is insufficient length below and the angle of the bend is not too great, the product can extend into the bend until the minimum cross-sectional area is reached, including lower defects. The direction of the bend in relation to the position of other conditional qualities can also be a factor.

In the case of sweep it may be possible to have some shorter lengths of a product within the sweep section. Once again it is necessary to combine the effect of the sweep with other defects in determining the length available for consideration. Sometimes products can be assigned with just a part within the sweep. There is no requirement to assign a product below the sweep so, unless there is a length restriction, the greatest length possible is the desired goal.

Each ground plot tree is assigned a stratum value consistent with the same rules used to assign trees to strata in photo-plot measurement. The strata are based on plot size differences and variations in volume calculation for the various species and for old-growth (which differ in shape). All product volume calculations for the tree are then assigned this stratum value. Since fewer strata are required than are available after interpretation of photographs, rules are applied to photo-plot stratum values to coalesce relevant strata into the same strata as the ground tree strata. The product volumes are accumulated into a total for the tree. By including the *waste* sections, this provides an estimate of gross bole volume.

### 6.2.4 Volume estimations

For the ground plot data, log volumes are estimated using the integral of a formula used to estimate the diameter 'D(h)' at a height 'h' given the diameter at breast height (d.b.h.), the diameter at crown break (d.c.) and the crown break height. The formula was originally derived for karri but it is accurate for other species as long as the diameter at crown break is measured, and not estimated by a taper function.

To calculate the volume $V_{12}$ of a log within a karri bole of crown diameter $D_C$ (cm), d.b.h.o.b. $D_B$ (cm), Height to Crown $H_C$ (m) from height $H_1$ (m), up to height $H_2$ (m) :

$$\text{d.o.b.}(H) = D_C + X_a.(\theta.\gamma + \beta) \quad \text{in cm}$$

where H is such that $0 < H = \text{or} < H_C$ in m

$$X_a = D_B - D_C$$

$$\theta = A_\phi + \phi.\phi 1\,(A_1.H_C - A_2.D_B)$$

where $A_\phi \approx 0.811$, $A_1 \approx 0.434$, $A_2 \approx 0.25$ (from Karri Volume Table)

$$\tau = (H_C - H)/(H_C - 1.3)$$

$$\beta = (1 - \theta)\, e^{-\zeta(H - 1.3)}\,;\ \zeta = \lambda / D_B$$

where $\lambda = 75.0747$

$\rightarrow$d.o.b.$(H) = a - bH + c\,e^{\zeta H}$ in cm

where $a = D_C + \chi.\Phi.H_C$
$b = \chi.\Phi.$
$c = \chi.\psi$

and $\chi = D_B - D_C$; $\Phi = \phi/(H_c - 1.3)$ and $\psi = (1-\phi)e^{-\zeta(1.3)}$

$$\text{d.u.b.}(H) = (\rho).\ \text{d.o.b.}\ (H) \quad \text{in cm}$$

$$= a^1 - b^1 H + c^1 e^{-\xi H}$$

$$V_{12} = R\left\{\begin{aligned} & a^2(H_2 - H_1) - (ab)\left(H_2^2 - H_1^2\right) \\ & + \left(\frac{b^2}{3}\right)\left(H_2^3 - H_1^3\right) \\ & + \left(\frac{2bc}{\zeta^2} - \frac{2ac}{\zeta}\right)\left(e^{-\zeta H_2} - e^{-\zeta H_1}\right) \\ & + \left(\frac{2bc}{\zeta}\right)\left(H_2 e^{-\zeta H_2} - H_1 e^{-\zeta H_1}\right) \\ & - \left(\frac{c^2}{2\zeta}\right)\left(e^{-2\zeta H_2} - e^{-2\zeta H_1}\right) \end{aligned}\right\} \quad \text{in m}^3.$$

where $R = (\pi/40000)\,\rho^2$

At the butt end, standard stump heights are used. These are 0.2 m for regrowth trees and 0.4 m for old-growth. Thus any volume calculation below breast height (1.3 m) would also be reasonably accurate since there is only a small length for the estimated diameter to diverge from the true value. The relationship is less accurate in the butt swell region.

There are some precautions, however, which must be made for trees of very small bole. Where the bole length is 1.3 m or less, then the formula for a cylinder is used with diameter equal to the diameter at crown break. The volume of a cylinder is also assumed in the case of logs on the ground where the midpoint diameter and length are measured directly.

Where the bole is less than 2 m but more than 1.3 m and the diameter at breast height over bark is small at less than 300 mm, then a conic formula is used for volume calculation. The diameter over bark at crown break and diameter at breast height over bark are the parameters used along with the upper and lower heights of the log section.

Once the sorting process has determined the bottom and top heights of a section to be assigned to a product, these heights are used to calculate its volume. The volume is then added to that stratum for that species/product.

Volumes are then entered into a statistical system that was developed in-house to process the double sampling estimates and the outputs are generated using SAS programs on the Department's VAX SAS system.

Total volumes are estimated using the double sampling for ratio estimation (Cochran 1977). With this method, the mean volume per hectare of gross bole volume or product volume is defined by :

$$\bar{V}_T = \bar{v}_G / \bar{v}_P * \bar{V}_P$$

where $\bar{V}_T$ = total volume per ha ($m^3ha^{-1}$)
$\bar{v}_G / \bar{v}_P$ = ratio of ground measured volume divided by the photo measured volume for the same photo plots.
$\bar{V}_P$ = the mean volume per hectare predicted from all photo plots ($m^3ha^{-1}$).

Each tree on ground or photo plot measurements is categorized as old-growth or regrowth. This may be used to modify the volume function if the analysis indicates sufficient improvement in the volume model. Old-growth trees have reached their maximum height and continue increasing in diameter, but there is a large variation in the resulting volume. Regrowth on the other hand increases in diameter with height.

Variations in the relationship occur with forest quality. In poorer forest, bole height is a smaller proportion of total height than in good quality forest. Attempts were made to use *top height* of the plot to determine this, but investigations revealed that the sample size of the plot (20 m radius) was often insufficient to reflect a true top height of the site. Many areas of forest are also cut over and the resultant regrowth has not reached its potential height and too few veterans are present. Consequently, the forest areas have been stratified into quality classes and recorded in the GIS. The photo plot position information is used to determine which volume function is used for a particular plot.

### 6.2.5 Outputs

The jarrah inventory system has been designed as an interrogation type database, though routine resource summaries can be generated. Routine summaries can be made on the basis of current product specifications and values. The real value in the system, however, is the ability that it gives to re-run the data to test options. These options might include changing the amount of defect allowed when evaluating resources availability, or changing priorities to see the effects on supply and revenue.

Such interrogations are often area-specific, hence the need to link the resource data to the Department's GIS. Using this facility an area of interest can be specified by categories, such as management or land-use type, within a boundary or specified distance or any combination thereof (Fig. 42).

The ground and photo-plots within such an area are extracted from the database and run through the sorting routine and calculation process. Outputs consist of various degrees of detail from species/product combinations by strata to total volume summaries, with associated error estimates. The volume summaries can be supported by map products highlighting the areas involved.

Because the inventory has been designed to answer specific questions relating to the resources contained in defined areas under specified utilization criteria, logically the major outputs will be maps showing specified areas accompanied by tables of volume data and description of the utilization criteria.

One map, for example (Fig. 43), might show the boundaries of the *interrogation* area, plus all of the areas which have been excluded from the volume statement, such as private property, conservation areas, road, river and stream reserves, areas currently being logged, areas logged since measurement, and other areas excluded for various purposes, such as bauxite mining. Another overlay or map might show the distribution of samples in the area (Fig. 44).

Tables of volume estimates that might be required could show, for example, volumes of products within various species, silvicultural and condition classes with an accompanying key to explain the criteria used to define each of the products (Table 6).

Accompanying each table could be a statement of risk showing the probabilities associated with resource commitments at various levels (Fig. 45).

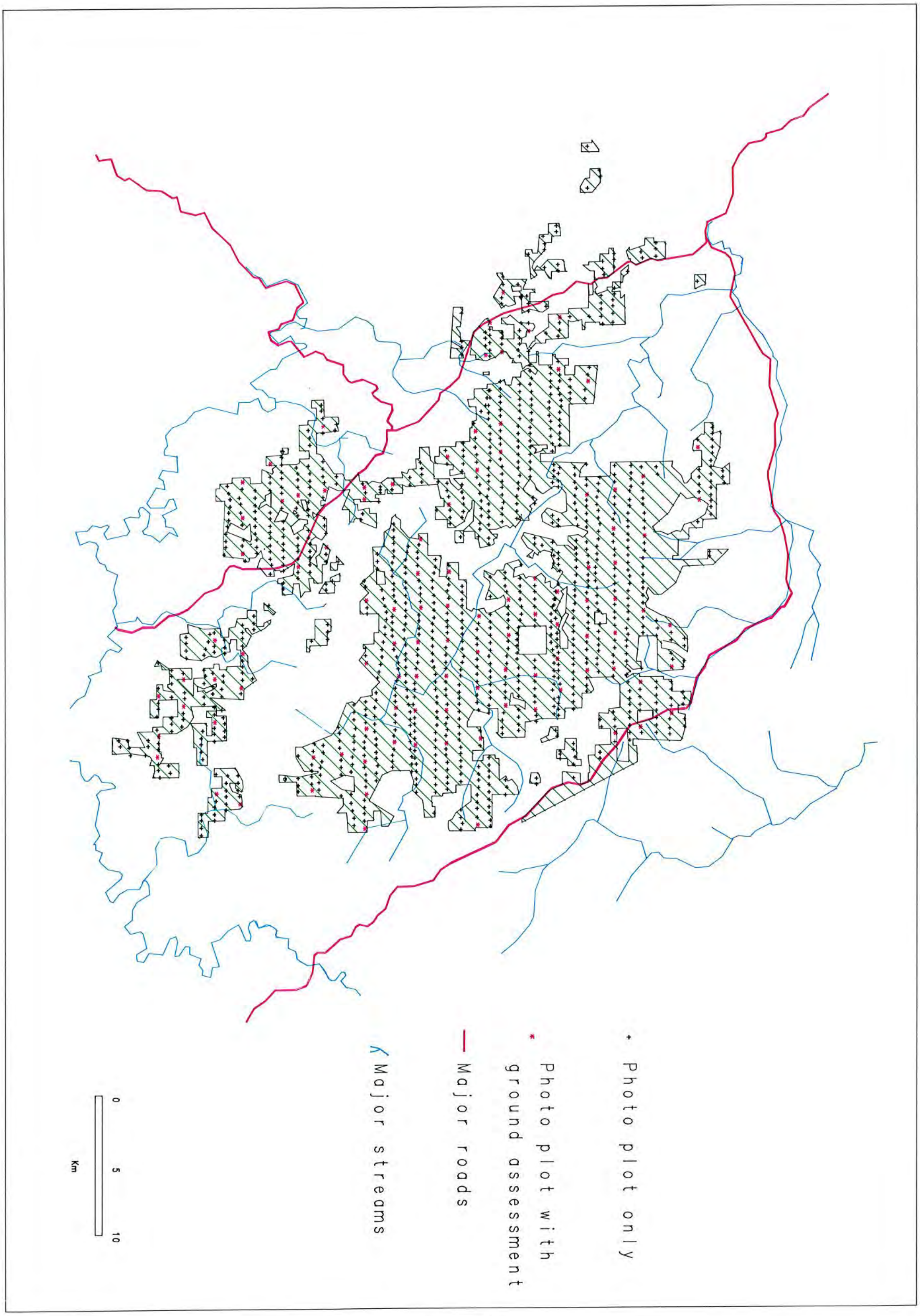


Figure 42
Map showing State forest and sample points.

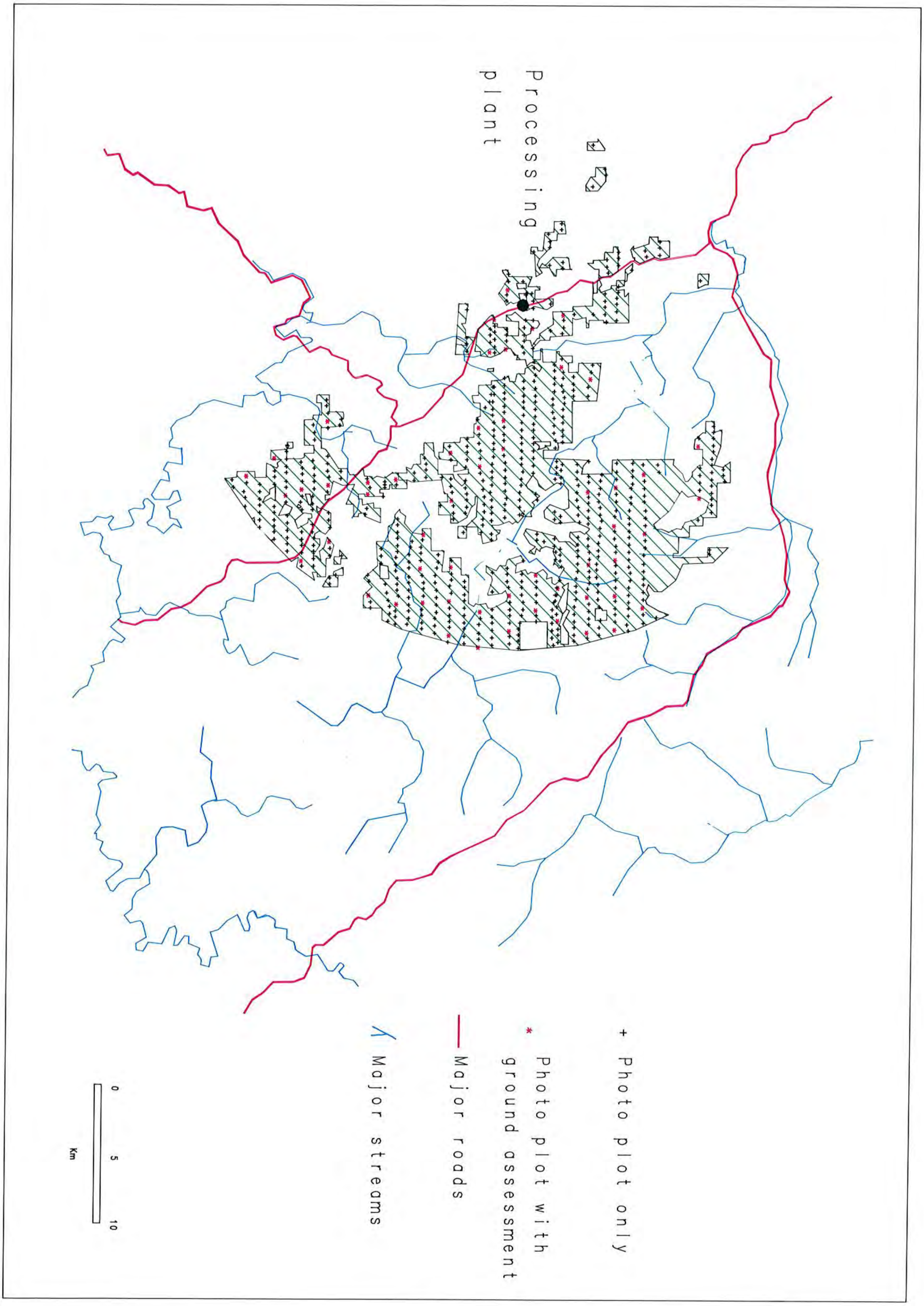


**Figure 43**
Sample points and State forest within 20 km of a processing plant.

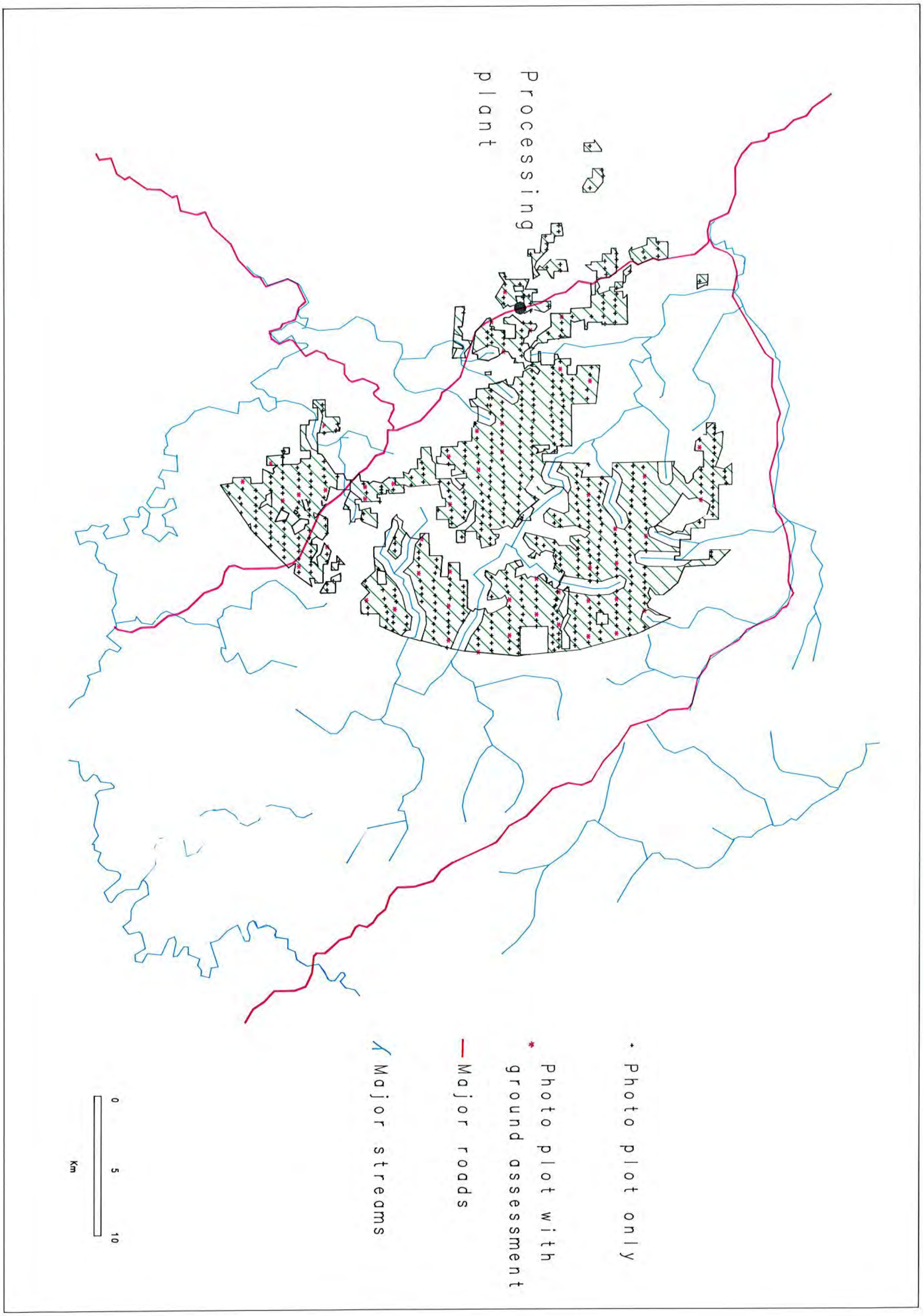


**Figure 44**

Sample points and State forest within 20 km of processing plant but not within stream buffers.

### Table 6a

Volume output statement.
Hypothetical example of volume output per hectare by species, silvicultural class and product grade

| | Sawlogs | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1st Grade | 2nd Grade | 3rd Grade | Chip wood | Power Poles | Fence Timber | Industrial Firewood | Waste | Total |
| **Live standing trees** | | | | | | | | | |
| Jarrah old-growth | 10 | 5 | 11 | | | | 7 | 8 | 41 |
| Jarrah regrowth | 3 | 3 | 4 | | 0.5 | 0.5 | 4 | 3 | 18 |
| Jarrah crop trees | 4.5 | 3.5 | 9 | | 2 | | 1 | 8 | 28 |
| Marri old-growth | | | 1 | 20 | 1 | | | 8 | 30 |
| Marri regrowth | | | | 10 | 1 | | | 9 | 20 |
| Wandoo | 1 | 1 | 2 | | | | | 2 | 6 |
| Blackbutt | 0.5 | 0.5 | | | | | | 1 | 2 |
| Other species | | | | | | | | 14 | 14 |
| Subtotal | 19 | 13 | 27 | 30 | 4.5 | 0.5 | 12 | 53 | 159 |
| **Dead wood** | | | | | | | | | |
| Jarrah | | | | | | | 50 | 20 | 70 |
| Marri | | | | | | | | 20 | 20 |
| Wandoo | | | | | | | | 10 | 10 |
| Blackbutt | | | | | | | | 5 | 5 |
| Other species | | | | | | | | 5 | 5 |
| Subtotal | | | | | | | 50 | 60 | 110 |
| Total | 19 | 13 | 27 | 30 | 4.5 | 0.5 | 62 | 113 | 269 |

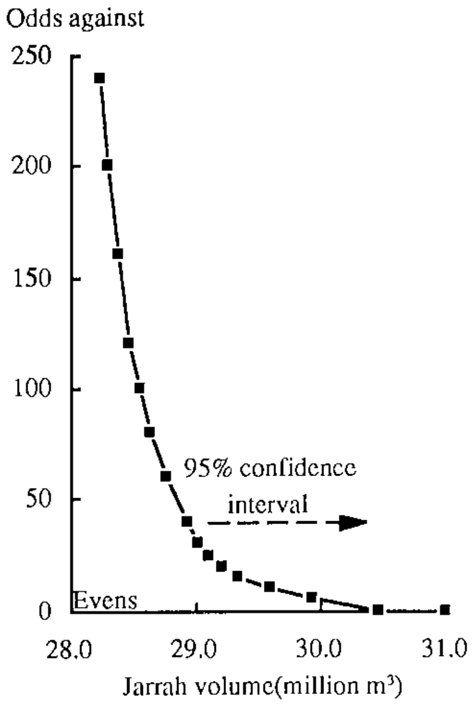
### Table 6b

Key to product specifications

| | Minimum length (m) | Minimum top diameter (mm) | Sweep percentage (max) | Percentage defect sectional area | Other special constrants |
|---|---|---|---|---|---|
| Sawlogs | | | | | |
| 1st Grade | 2.1 | 250 | 3 | 50 | No pinhole borers |
| 2nd Grade | 2.1 | 250 | 4 | 70 | No pinhole borers |
| Small | 2.1 | 150 | 0 | 5 | |
| Short | 1.0 | 250 | 3 | 50 | |
| Chipwood | 2.1 | 100 | 5 | 70 | 0% charcoal |
| Poles | 9.5 | 150 | 1 | 10 | |
| Piles | 11.0 | 200 | 1 | 10 | |
| Industrial rounds | 1.8 | 60 | 3 | 10 | |
| Industrial firewood | 1.0 | 100 | 5 | 80 | 0% termites |

**Figure 45**

Statement of risk in volume estimation. For jarrah gross bole volume (alive) the odds against the resource being less than a given level are, for example, 200 to 1 against the jarrah resource being less than 28.3 million m$^3$



# 7 *EVALUATION AND FUTURE DEVELOPMENT*

**G.J. Strelein and P.H. Biggs**

## 7.1 Evaluation

### 7.1.1 Photographic quality

Throughout the project there have been few problems with the exposure and processing aspects of photographic quality, though initially there were problems owing to incompatibility between the photography and analytical measurement equipment. These problems related to the lack of precise fiducials and problems associated with image distortions caused by the focal-plane shutters in the Vinten cameras. Expensive fully calibrated metric cameras are required to overcome these problems.

There were also some early occurrences of excessive image motion owing to excessive speed and large variations in scale, owing to turbulence and/or insufficient control of flying height, which made photo-measurement difficult. These problems have been reduced by using the GPS receiver to display the ground-speed to the pilot, by using the radar altimeter to help control flying height within tighter specifications, and by avoiding turbulent conditions.

Some loss of clarity was also noticed in the second season's photography when reseau plates were fitted to the Hasselblad cameras, which affected focusing but not to the extent that it affected measurement accuracy.

Photographs were taken in poor light on occasions to maintain production. One day photography was attempted with about two eighths cloud to judge the impact on photo quality, but the photographs taken in shadow were too dark because the Hasselblad cameras were used and they do not have remote aperture adjustment. This result highlights the advantage of remote aperture control on the cameras.

### 7.1.2 Navigation systems

The GPS navigation system provided accurate data on plot locations which facilitated an efficient link between the ground and photo samples and other geographic information. The precision of the plot locations was discussed in Section 3.4.

The main difficulty encountered with the GPS navigation system was the availability of the satellites. This restricted photography to the months of December, January and February in the first season, and limited the actual hours of the day during which photography could be carried out. This problem, however, is slowly disappearing as more NAVSTAR satellites are launched. It is expected that within a few years three-dimensional (i.e. 4 satellites) GPS navigation will be possible continuously.

The GPS navigator was cheap to run, since no ground transponders were required, as was the case with the microwave systems used previously within the Department. In addition, the positions obtained from the GPS unit were in latitudes and longitudes rather than coordinates referenced to local base lines. This made the connection of photo location data with existing map data very straightforward.

Once the satellite constellation is complete, then field crews will be able to use hand-held GPS receivers to relocate sample plots throughout the year. This will overcome the problems experienced in registering the plot positions with existing printed 1:25 000 scale map sheets.

### 7.1.3 Photo and ground measurements

Photo measurements are constantly monitored for errors using a combination of regular field visits by the interpreters, plus monthly trials of height measurements and species interpretation.

These tests show that the standard error of height measurements is ± 1.7 m ($p=0.68$) compared with ground measurements and that species interpretations are correct 85-90 per cent of the time. These tests are used to determine the average bias in height estimation for each interpreter so that their measurements can be corrected to ground standards.

Ground measurements are monitored by regular remeasurement of a series of four sample plots. Analysis of these measurements shows that the variability of volume estimates between assessors is much less than the variability between plots (Fig. 46). Assessment of logs is much more variable compared with standing trees which could be attributed to the fact that logs are often severely burnt and rotten, making consistent measurements of length and diameter more difficult than on standing trees.

To evaluate the accuracy of volume estimations in relation to actual yields, two trial areas were subjected to intensive photography at 500 m x 100 m intervals and ground sampling at 500 m x 500 m intervals. These areas are being logged to obtain removal data for comparison with the sample estimates.

In the absence of these data, the only tests possible are comparisons between photo estimates and ground estimates. From one cell of photography 1202 photo plots and 100 ground plots (20 ground plots not measured owing to logging), it is evident that the estimates of gross bole volume from photographs underestimates the ground volume. A variety of factors have been identified as

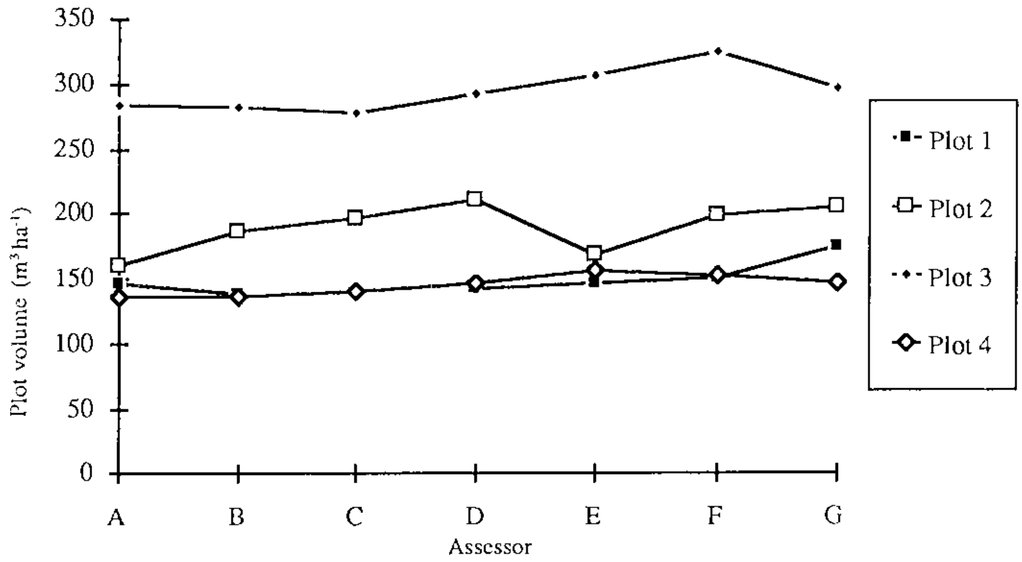


**Figure 46**

Variability between assessors compared with variability between plots.

contributing to this problem. The most common factor is the omission of trees from the photo estimates where crowns are close or interlocking and appear as one tree.

On several of the plots investigated, it has also been found that crown damage is common among large trees in some areas. In these cases the trees are relatively short but contain large bole volumes (Fig. 47). These trees are difficult to account for in the estimation process, but they can have a significant impact on results as shown in Figure 48. This demonstrates the relationship between the photo and ground estimates of gross bole volume.

From the example given, the estimate of gross bole volume from the double sample has a standard error of 4.1 per cent compared with 5.7 per cent from ground sampling only. The double sample involved 330 person days of work. To achieve a similar result from ground sampling would require 195 ground plots, nearly twice the number involved in the double sample: 195 ground plots would involve 380 person days, 18 per cent more than the double sample.

A full economic analysis of the method is not possible until more results are obtained, but it appears from these data that significant savings in labour and time are being made using aerial photo sampling.

### 7.1.4 Geographic Information System design and application

There are two questions to be considered when evaluating the GIS design: first whether the type of interrogation envisaged will be adequate to satisfy the information requirements of the end users, and second, whether the apparatus put in place to perform such interrogation can do so with sufficient speed and by enough different operators to be useful.

The first question will be answered only when the system has been in use for some time. The answer will almost certainly be *no*, as new possibilities become apparent for answering more complicated management questions and dealing with 'what-if' queries.

The second can be tested once there is sufficient data in the database for realistic interrogations to be tackled. Possible success criteria could be:

(i) a definition of window possible, based on geographical description;

(ii) generation of resource by products, in priority order;

(iii) facility for data to be corrected and updated routinely;

(iv) tabulations of resource figures available within, say one day of interrogation being received.

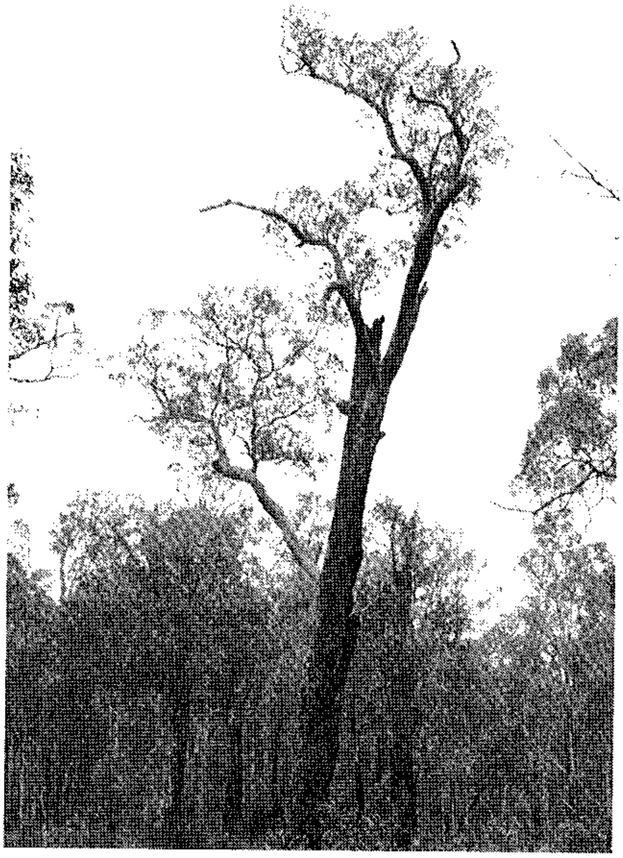


**Figure 47**
Crown broken out of large veteran.

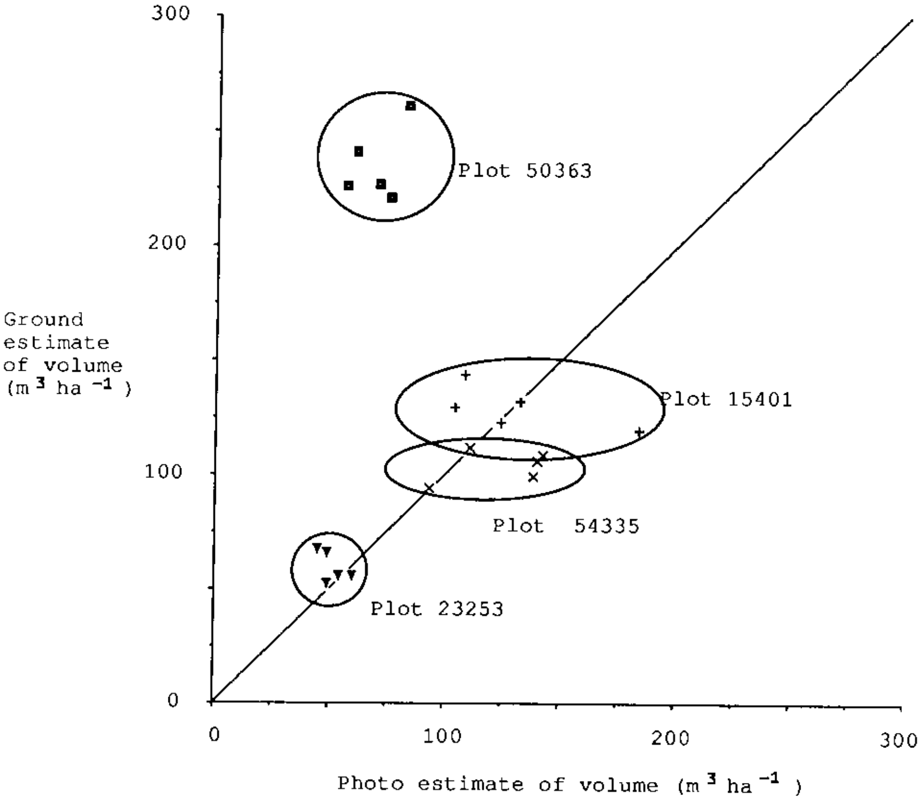


**Figure 48**
The effect of crown damage on photographic estimates of volume.
Plot 50363 was affected, the other three plots were not.

## 7.2 Costs

Data from two years of plot measurements have shown that photo samples obtained using large scale photography cost approximately one-tenth that of ground plots (Table 7). To derive the cost per plot, the fixed costs were apportioned out over the expected number of samples to be obtained to complete the initial assessment.

These costs will change slightly with different circumstances but in both cases, the variable costs are the major factors, and these will change little. In the case of the ground plots, the computer programming cost is high owing to the requirements of the quality assessment software. With the photo plots, the cost for the stereoscopes would be higher if all the instruments were purchased new. In this case, we are grateful to the West Australian Maritime Museum, the Department of Land Administration and The University of Melbourne for the loan of their stereotopes, which significantly reduced the cost of this project.

It should also be noted that more information was collected on the ground than from the photos. From Figure 35, it can be seen that an average of 131 minutes were spent on plot measurement. If gross bole volume only were assessed, and no wood qualities, this time could drop by at least half, reducing the total time per plot to 240 minutes, and the variable costs to $277. If the computer programming for quality sorting were not involved, then the total cost for the ground plots could be as low as $284 per plot. It may be more meaningful to compare this figure with the $38 per photo plot to obtain similar information.

## 7.3 Future developments

### 7.3.1 Continuous forest inventory

Data on growth and future predictions of short and long term yields are essential requirements for scientific forest planning and management. These requirements are usually met by establishing and measuring permanent sample plots within the forest at regular time intervals - called continuous forest inventory. Application of ground-based measurements to permanent sample plots is very expensive and slow and some times results in inconsistencies between successive measurements that result in costly rejection of results. Therefore, better measurement and recording systems are required.

Aerial photogrammetry, especially using photographs at very large scales, warrants closer attention in light of the recent technological advances described in this report. Their distinguishing characteristic is that they can provide a detailed permanent record of ground-quality measurements at the time of each measurement for quantifying and modelling growth and yield. These measurements could

Table 7

Costs of ground and photo plots.

| | Ground plots (2600 samples) | Cost per Plot ($) | Photo plots (26 000 Samples) | Cost per Plot ($) |
|---|---|---|---|---|
| Fixed costs | Field equipment | 4 | Photo equipment | 2 |
| | Computer programming | 23 | Measurement equipment | 2 |
| | | | Computer programming and development salaries | 4 |
| | | 27 | | 8 |
| Variable costs | Salaries - crew | 195 | Salaries - aircrew and administration | 2 |
| | Salaries - administration | 50 | Helicopter hire | 7 |
| | Accommodation and travel | 96 | Film purchase and development | 3 |
| | Consumable equipment | 3 | Navigation and mapping | 1 |
| | Data processing | 8 | Accommodation and travel | 1 |
| | | | Salaries - measurement | 16 |
| | | 352 | | 30 |
| Total | | 379 | | 38 |

include tree spacing and height, crown dimensions such as depth, area, and volume, and measurements for digital terrain modelling and three-dimensional modelling of trees and stands.

### 7.3.2 Applications to other forest types

The methods of large-scale aerial photography and geographically linked processing have the potential to be applied in many different forest types. For example large-scale photography procedures were developed in Canada in mainly coniferous forests, so the methods should be applicable in pine plantations in Australia. Indeed, Spencer (1972) has already demonstrated the potentials for applying large-scale photography over pine plantations in Victoria.

Thus, the advantages of this inventory system (particularly locational information and efficiency) prompted consideration for use in other inventories. The main areas of application would be for inventories in pine plantations, eucalypt plantations, karri regrowth and karri old-growth.

Measurement of the greater heights occurring in karri old-growth stands may be near the limits of the current photographic system geometry (see Section 2.4.2) but should still be achievable by experienced photo interpreters. Because of similar variability in forest type and log defects, the sampling intensities of the two phases would probably be similar and similar log quality assessment would be required.

In karri regrowth and other eucalypt plantations, however, the system is likely to be more accurate and straightforward. With young eucalypts the height/volume relationship would be much stronger, requiring a lower intensity sample. The lower level of defect and smaller range of potential products would also mean that the second phase ground assessment could be made much simpler and faster.

One problem in these young eucalypt stands is the high crown cover densities which both obscure the ground and create darker conditions below the canopy, both of which can make height measurement difficult. Fortunately, there is little species variation in these stands so that species interpretation is not a problem and the canopy can be overexposed to allow better exposure below the canopy. The other alternative is to photograph under more limited full cloud conditions. These options are currently being tested.

The photomeasurement software does have a simple terrain model so that it is not necessary to see the base of each tree unless the ground is very uneven. The terrain model could be developed to handle more uneven surfaces, requiring ground readings only in open patches to establish the model. Tree height measurements then only require an additional reading at the top of each tree.

The second problem is where dense understorey obscures the ground, thereby making it difficult to obtain ground readings. Although this may sometimes be a problem in karri old-growth, it is almost always a problem in the regrowth forests where the understorey is usually 2 - 5 m tall, depending on age and site. Nevertheless, it is possible to measure heights above the scrub and then to add an allowance for scrub height to determine total tree heights.

In pine plantation inventories the height/volume relationship should be strong in stands with similar silviculture, thus requiring a lower second phase sample. Furthermore, as plantations are generally more uniform than native forest, the overall sampling intensity could be lower, although this would usually be negated by requirements for higher precision.

With current silvicultural practices in pine plantations, dense canopies would cause measurement problems on high quality sites prior to first thinning. Conversely, as the level of defect in pines is relatively low, the second phase ground measurements could be made very efficiently.

The wood quality assessment methods developed for the jarrah inventory have potential applications in other forest types where the patterns of utilization are changing because of the decreasing availability of old-growth resources. The concepts are also applicable to plantations where computer models based on taper functions and minimum diameter specifications are already used around Australia to predict grade recoveries. The addition of other quality data, covering factors such as sweep, branching, and forks, are merely extensions to these approaches.

Finally, the linking of inventory data with other geographic data through the use of a GPS and a computerized GIS has potential application in all forest types. Put simply, GIS provide forest managers with the tools required for more powerful and flexible planning of multiple forest resources.

### 7.3.3 New Geographic Information System developments

The incorporation of inventory data into the Department's corporate database and linking them to the GIS means that inventory results need no longer be a bewildering array of tables. Instead, the results can be accessed in a form that is 'presentable' and specific to areas relevant to a particular enquiry.

The inventory system will be made sufficiently user-friendly to allow dispersed interrogation at intelligent workstations in regional offices through the Department's extensive computing network. With plans for colour plotters at each regional centre, the GIS components of the system will be used for the production of high quality resource and planning maps.

Apart from tables of results and simple maps of the 'window' area, facilities are being developed for presentation of the data as elevation models of resource density. These would be three-dimensional graphic representations of volume data displayed over a background of topographic and management information.

A resource-seeking technique could also be developed in which the system searches the inventory data to determine an area from which a specified resource could be obtained. Spatial constraints would include haul distances and road networks classed according to road standards and economic factors.

The link to GIS will help to identify resources within different management categories, such as road and stream reserves and visual management areas. The effect of buffers of different sizes on the available resource could be modelled using the GIS.

As these applications are introduced, new possibilities will undoubtedly arise as management becomes more intricate and formally constrained.

### 7.3.4 Camera system developments

There is potential for significant improvement to the camera system described in this document and in the literature. To obtain the best quality photographs for detailed mensuration using analytical photogrammetric instruments, it is clear that metric cameras are required. The nature of aerial photography, however, places extra demands on the design of such cameras.

Especially for fixed-base photography, where the cameras are inaccessible during flight, the film capacity needs to be large (500 frames) and the aperture shonld be controllable from within the aircraft. Frame numbering (data imprinting) is necessary for efficient handling and cataloguing of the thousands of frames generated in a project of this size. Where the cameras are controlled by a computer/navigation system, as in this project, it is desirable for the film numbering unit to accept data directly from the computer, so ensuring exact correspondence between the computer records and film annotation.

Developments with forward motion compensation make it feasible that 230 mm (9 inch x 9 inch) cameras could be used for photography at this scale in a sequential, single camera arrangement with altimeter and tip/tilt recorder. The size and cost of the cameras would make them unsuitable for fixed-base photography. The advantages would be the increased area available for sampling at a given scale, but the benefit from this would depend on the application.

Video or CCD (charged couple device) cameras also have potential for future large-scale photography missions. Such cameras could reduce the cost of photograpby by removing the dependence on film, and open the way for automated measurement systems. These types of cameras are being implemented into industrial close-range photography (Fraser 1988) but in tightly controlled environments with regular targets which permit the use of image recognition to automate the digitizing procedure. It may be some time before this technology can be used in forest mensuration.

### 7.3.5 Refined photo-measurement systems and methods

To acquire the large quantities of photo measurements required in an inventory of this magnitude, it is imperative that the measurement systems are fast and efficient. This has only been partly achieved in this project by the computer programs written to accept parallax readings from the photo interpreters and calculate the tree heights. The next stage would be to fit encoders to the stereoscopes which would enable direct digital entry of readings to the computer without the operator having to look up from the image. X and Y encoders, as on the Zeiss Stereocord (Brun 1972), would also permit the digitizing of crown perimeters and other variables of interest.

The optimum solution with today's technology would be to implement analytical stereo digitizers (analytical plotters) which could correct for distortions in the camera lenses and could support more complex computations during the photo measurement process. This is slowly being achieved with the Adam MPS-2 instruments. Custom software has been written to model the gronnd surface in the sample plot, and to calculate the tree heights as the difference between the digitized tree tip and the ground model below it. The 20 m plot radius is also displayed on the computer screen, and a warning given to the operator if they move outside the plot area.

This is an improvement over the template method currently used with the older instruments, as it ensures that the plot radius is exactly 20 m. The most difficult step in implementing the analytical plotters is to ensure that the orientation of the photographs is calculated correctly from the fixed-base arrangement without reference to ground control. This needs to be done with the minimum orientation time since each photo pair involves only 30 minutes of measurements. Significant time must be spent with the programmers from the manufacturing company to ensure that all the requirements are met.

### 7.3.6 New applications of large scale photography and Geographic Information Systems

The potential applications for this photography are large - from simple stocking counts for regeneration and planting surveys (e.g. Hall 1984) to more complex measurements and interpretations for evaluating such things as site quality, growth, logging residues, fuel conditions (e.g. Morris 1970), species diversity and abundance, habitat characteristics, conservations values, stream conditions, erosion rates. Particularly in combination with the analytical machine, efficient measurement of many parameters in two or three dimensions is possible from the large scale photographs.

The linkage and processing of such photo data with geographic areas using GIS technology provides a powerful tool for wider application by resource planners and managers.

# 8 CONCLUSIONS

## 8.1 Inventory design

The jarrah forest inventory was designed to provide detailed, flexible information quickly over 1.4 million ha of forest. The method employed double sampling with large scale aerial photographs and ground measurements in combination with a GPS receiver and a GIS for referencing and processing data respectively. Because of the known positions and uniform distribution of sample plots, GIS analysis could provide estimates of timber volumes and other parameters for any area of forest under any set of constraints. This factor, coupled with new techniques that were developed to estimate log products under varying log specifications, provides a very powerful planning tool.

## 8.2 Aerial photography and photo-mensuration

The system selected for this project used twin 70 mm cameras attached to a boom which was mounted transversely on a helicopter. This system avoided errors owing to wind-sway, minimized errors from camera mis-synchronization, and was quick to implement. It also provided an effective method for obtaining the sampling photographs at 1:1200 scale required for detailed interpretation and measurement.

The GPS used for flight-line navigation and photo-positioning also proved highly successful, making it possible to place flight-lines accurately at 1000 m intervals with photo-samples at 500 m intervals along each line.

Coordinate data from this system, when subsequently entered into a GIS, was used to produce maps which enabled ground assessment teams to relocate the double sample points for remeasurement.

Vinten and Hasselblad 70 mm cameras were tested in the project, but the Vinten cameras were superior in spite of some photogrammetric virtues of the Hasselblads. However, owing to the focal-plane shutters of the Vinten cameras, their photographs could only be measured using simple stereometers, whereas analytical photogrammetry was possible with the Hasselblad photographs. Nevertheless, problems relating to camera-calibration, equipment and software limitations negated these values in this project. Although the use of optical mechanical stereometers for measuring Vinten photographs was comparatively slow and tedious, they gave results of acceptable precision. Automated recording of parallax readings with these instruments would enhance their efficiency.

Colour transparency film was very effective for species interpretations and tree-height measurements, resulting in 85 per cent of species interpretations being correct and tree height measurements with a standard deviation of 1.5 m.

Tree-height was an effective index of stem volume, although problems arose in large trees with damaged crowns. Generally, correlations of tree height with stem volume were within the range of R = 0.7 - 0.8, with values greater than 0.7 being necessary for the double sampling approach to be more efficient than ground-only sampling in this type of forest.

## 8.3 Ground measurements

The ground measurements on a 10 per cent subsample of the photo plots provided data for adjusting the photo-estimated timber volumes and for partitioning these volumes into different log grades using assessment of wood qualities and defects. Furthermore, the computer program (PRALL) used to allocate products from the assessed quality information also provided a means for predicting volumes for new log specifications, or for entirely new products not considered at the time of assessment.

The versatility of the quality assessment procedure has already been proven, because new products and different standards occurred during the course of the project. The product sorting process will be monitored and fine-tuned over time using results from actual logging operations and direct assessment of product volumes.

Analysis of the ground and photo samples showed that photo measurements generally under-estimated the total gross bole volume, hence the need for adjustment through the double sampling scheme.

## 8.4 Data integration

Systematic sampling facilitated with the use of the GPS, when coupled with a GIS, provided a very powerful planning tool. For example, in this project all photo and ground sample data were stored in an ORACLE database, along with the coordinate locational data for each plot obtained from the GPS. This database enables the linkage of volume statements with geographic information, thereby providing great facility for generating resource information. For example, output may be defined from a supply area within a specified distance from a sawmill, which in turn can be modified to incorporate exclusions such as road, stream, or conservation reserves.

Once such areas are defined in the GIS, the system extracts only those plots that are relevant to the 'window' for statistical analysis. This provision allows for extra flexibility in the inventory because new resource statements may be derived if and when the management constraints are changed. Furthermore, map production based on the GPS coordinate data was very efficient and effective at both the large scale (1:25 000) and small (1:250 000) scale required for tactical and strategic planning purposes respectively.

## 8.5 Project evaluation

The jarrah inventory project has demonstrated a very successful combination of efficient, modern systems for inventory, supported by an enthusiastic interdisciplinary project team. The system of large-scale photography provided excellent photographs for the inventory, but opportunities for future refinements have been identified. The GPS navigation system provided for very efficient in-flight navigation as well as accurate and efficient relocation of double samples on the ground and the linkage of sample data with geographic information. Furthermore, with the cost of photo plots being a tenth of the cost of ground plots, the methods achieved a considerable cost saving.

An additional major success was achieved with the ground-measurement and analysis procedures, which provided great flexibility through the methods of quality assessment and GIS integration of data. These procedures have made it possible to obtain accurate inventory estimates under conditions where both the standards of log utilization and constraints imposed on management may change. This factor, coupled with remeasurement of sample plots after cutting or major disturbance, should ensure that the inventory remains useful well into the future.

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# *APPENDICES*

# Appendix I

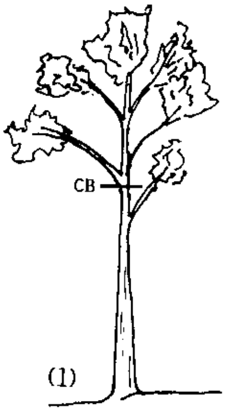
## Procedures used to determine crown break

1 General

The first healthy branch forming part of the main crown, and

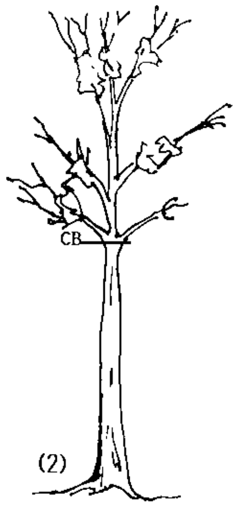
(i) extends as far or further than any branch above it, and

(ii) has a healthy growing tip.



2 Trees with unhealthy or over mature crowns

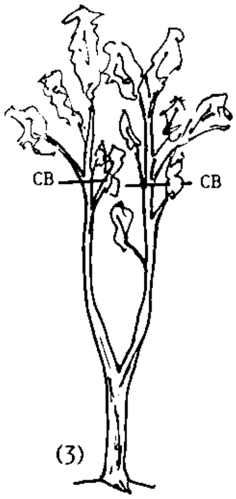
Where the crown is unhealthy or dying owing to factors such as disease or age, crown break may be at the first major branch, regardless of its condition.



3 Forks

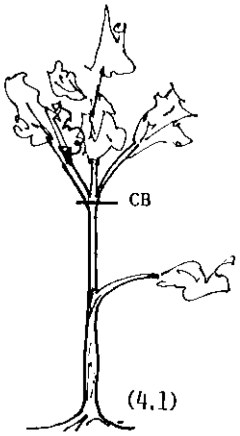
Forks generally do not constitute crown break. A fork is where two (or more) equally vigorous leaders take the place of a single bole. Each leader has its own, individual crown break.

For the purposes of this inventory, the diameter of the smaller leader should be at least 80 per cent of the diameter of the larger leader and both should be approximately vertical. In other cases, the larger leader may be called the bole and the smaller leader a branch (which is then not assessed).

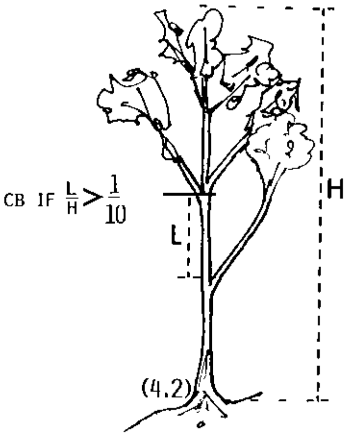


4 Where the main stem continues

4.1 In the case illustrated, the first branch is not part of the main crown. Crown break is therefore at the second branch.

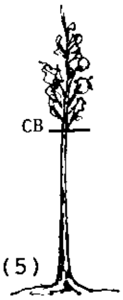


4.2 In this case, the first branch does form part of the main crown, however the 'bole' continues straight and vertically above it. Look then at the next branch which satisfies all the rules outlined above. If the distance between the first and the second branches is greater than 10 per cent of the total tree height, this section can be included in the bole and crown break is at the second branch.



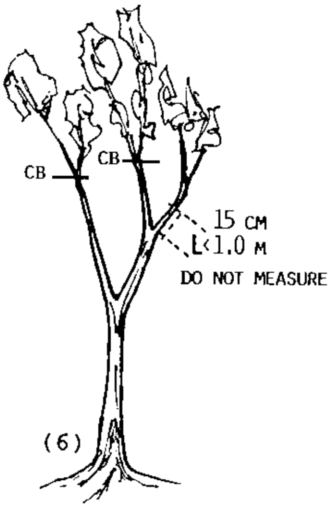
5 Saplings

Crown break may be hard to define in saplings and vigorous poles. For this inventory, crown break may be at the first green branch.



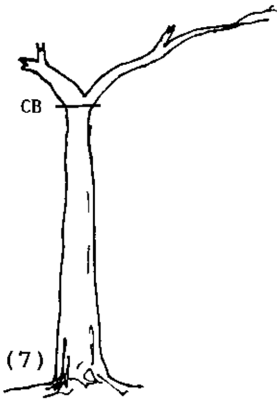
6 Diameter limits on multiple forks

Where a leader is smaller than 15 cm d.o.b., or tapers to this size within 1.0 m of the fork, it should not be assessed or measured. Any leader larger than this should still be assessed all the way to crown break.



7 Dead trees

Dead standing trees will obviously not have live branches. In many cases the branches will have broken off. Use judgement in each case to estimate crown break based on the remaining evidence.



# Appendix II

## Ground plot procedures

## 1. General Information

| | |
|---|---|
| Recording on CLM 129<br>*(See page 76)* | please use soft pencils, e.g. HB.<br>alpha codes are left justified, numeric codes are right justified. |
| Date | |
| Assessor's name | we need to know who was responsible. |
| Block name | |
| Tie point | a relocatable point (Ref tree or junction) to start the plot tie. |
| Plot and Sheet | number for this plot. |
| Tie information | include sufficient detail to allow the plot to be relocated quickly in the future. |

## 2. Plot Header

Record all header data on the first sheet for each plot only, or denote as 'Not for punching' on subsequent sheets.

| | |
|---|---|
| Cell number | as shown on the Cell Map. e.g. C02 |
| Plot number | as shown on the plot map, e.g. 156023 |
| Assessment type | use the following codes for Resource Plots, depending on the type of dendrometer.<br>RN - Narrow band Spiegel relascope<br>RW - Wide band Spiegel relascope<br>RT - Telerelascope |
| Half plots | use prefix H in column 10 for half plots |
| Block number | use the standard block codes |
| Plot size | use the radius space for circular plots and the length and width space for rectangular plots.<br>All resource plots will be 20 m radius unless specified. |
| Date | month and year, e.g. 0188 for January 1988. |

| | | 0 | 1 | 2 | 3 |
|---|---|---|---|---|---|
| FD | Fire damage | Nil | Light | Moderate | Severe |
| DBK | Dieback | Nil | Uninterpretable | Understorey only affected | Overstorey affected |
| Reg.1° (+) | No. within 10 m radius | 0 | 1-15 | 16-30 | 31 + |
| 2° (*) | | 0 | 1-15 | 16-30 | 31 + |
| | | | (Inadequate) | (Marginal) | (Adequate) |
| LM | Leaf miner | Nil | Light | Moderate | Severe |
| GLS | Gum leaf Skeletonizer | Nil | Light | Moderate | Severe |

(+) Regeneration stocking of the primary or preferred species (e.g. jarrah, wandoo, blackbutt).

(*) Regeneration stocking of the secondary species (e.g. marri).

Count the ground coppice and saplings within a 10 m radius of the plot centre. Ground coppice should have a lignotuber about 5 cm or more in diameter and 5 - 15 cm long. Saplings are stems from 1.5 m tall and up to 14.9 cm d.b.h.o.b. Record this number as class 0, 1, 2, or 3.

Plot and subplot percentages - leave blank for standard jarrah inventory plots.

This section will only be used if there are variations from the standard (see below), in which case you will be given the information required to fill out the form.

## 3. Plot establishment - Circular plots

Survey as close as possible to the plot position using the 1:25 000 plot map.

Locate the plot centre from the 1:1000 stereopair. Mark this point on the photo for later interpretation use. Mark the centre point on the ground with a 25 mm square wooden peg. This peg may be removed once the plot is finished.

If there are no trees in the plot e.g. flats or unmapped cleared areas and trial plots, the plot is still recorded and noted as having 'Nil Trees in Plot' and why.
Identify all trees in the plot and subplot by measuring the distance from the plot centre peg with a 30 m tape. Measure the horizontal distance or correct for slope to individual trees using tables when the slope exceeds 8° . The plot must cover the correct horizontal area (i.e. an ellipse on the slope).

All trees must be IN or OUT, there is no facility for borderline trees. This requires accurate measurement of the tree distance. Place the ZERO end of the tape on the centre line of the tree and read the distance at the middle of the plot centre peg. The tree is in if the distance (with slope correction) is 20.0 m or less (10.0 m on subplot trees).

## Half Plots

Half plots may be required when the plot centre falls inside the forest area being inventoried but part of the plot falls in an area mapped as other land. That is, if the area is cleared for example but not mapped then it should be included in the plot. If the area is mapped but shown as other land eg; private or reserved or pines, then a half plot is established along a line through the plot centre parallel to the boundary of the area being inventoried. The bearing of this line should be noted in the tie details and marked on the photo for later interpretation use. (Record H in column 10 of header.)

## 4. Tree assessment and subplot sizes

| d.b.h.o.b. (cm) | % | Radius (m) | Species | Status | Assessment |
|---|---|---|---|---|---|
| 25 + | 100 | 20 | Major | 1 | Complete |
| 25 + | 100 | 20 | | 2 | Main defects |
| 25 + | 100 | 20 | | 4 | Main defects |
| 25 + | 100 | 20 | Minor | 2 | Main defects |
| 25 + | 100 | 20 | Other | 5 | d.b.h.o.b. and dendrometry |
| 15-24.9 | 25 | 10 | Major | 2 | Main defects |
| 15-24.9 | 25 | 10 | Major | 3 | Form code, d.b.h. & dendrometry |
| 15-24.9 | 25 | 10 | Major | 4 | Main defects |

See Appendix III for the list of major, minor and other species.

*Tree number*

Number successively from 1 on each plot.
If a number is missed or subsequently deleted do not record it on the form.
When a tree record carries over the next sheet repeat only the tree number, no d.b.h.or other details.

| **Silvicultural class** | | | |
|---|---|---|---|
| | 1 | Old-growth | -unclassified |
| | 2 | | -mature |
| | 3 | | -overmature |
| | 4 | Regrowth | -unclassified |
| | 5 | | -potential crop tree |
| | 6 | | -non-crop tree |
| | 7 | Unclassified | - logs |

*Definitions*

Old-growth are large-boled veterans older and often larger than most of the regrowth trees, unless the whole stand is old-growth (uncut) or all regrowth. Actual diameters will depend on the site quality, time since cutting and vigour of individual trees but old-growth would generally be above 50 cm d.b.h.

Mature old-growth has a vigorous crown and is still putting on reasonable increment.

Overmature old-growth has a crown which is deteriorating owing to age and the tree is putting on little or no increment.

Potential crop trees meet the specifications for a crop tree under silviculture guidelines. i.e. a codominant with a good crown and at least 3 m of bole free of defects which would preclude its use as a sawlog.

For the 'unclassified' codes (1, 4, 7) : 7 should be used for logs; 1,4 should be used for minor and other species, dead trees or any other cases where selection of crop trees or crown condition is not relevant or indeterminate.

***Condition***

Fallen dead trees are usually windthrows, where the d.b.h and crown break can be measured and the tree volume table used. Logs are sections of bole where breast height and crown break cannot be identified and so a log volume table is applicable.

Tree condition
1 Standing alive
2 Standing dying
3 Standing dead
4 Fallen alive
5 Fallen dying
6 Fallen dead
7 Logs

***Status - Tree status***

1 Marketable or potentially marketable trees, major species only. These trees receive the full quality assessment.

2 Low quality trees with major defects affecting utilization on 3 or 4 quadrants or 75 % + of sectional area for 50% or more of the bole length.

Record all the main (most severe) defects in the low quality part and normal assessment in the remainder of the bole.

Trees of minor species 25 + cm.

Trees 15 - 24.9 cm d.b.h.o.b. but good form (form code 1, 2).

3 Trees 15 - 24.9 cm d.b.h.o.b. and poor form (form code 3, 4). Record only the form code and dendrometry for these trees, i.e. no quality assessment.

4 Standing or fallen dead or logs. Record only defects specified for logs (see later).

5 Other species. These trees only have d.b.h.o.b. and dendrometry recorded. Basal area and stocking will be calculated and volumes, but not products.

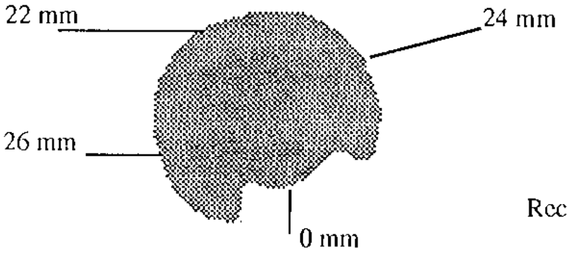
**Species** - use the standard species code (Appendix III).

**Diameter at Breast Height over bark (d.b.h.o.b.)**
Record this to one decimal place e.g. 62.3 cm.

*Hollow trees* - Measure (or estimate) the diameter of the tree as if it were still round. Record the severity of the hollow as a percentage of the *original* sectional area. This will give the best estimate of the gross bole volume, while allowing calculation of the amount of solid wood remaining.

**BT (Bark Thickness)**

Record two bark thicknesses in millimetres. These should be measured at opposite points on the stem. On trees with drysides or similar, record the average of bark thicknesses from four measurements relative to percentage dry and affect on d.b.h.



Record as 23, 13

***Form/D***

Trees requiring additional dendrometry in upper stem or crown, e.g. for forks or abnormal taper. Record D on second and subsequent lines for 15-25 cm d.b.h. trees requiring form code on first line.

| | |
|---|---|
| Form 0 | Trees 25 cm+ with no additional dendrometry. |
| Form 1-4 | Record for all small trees (15.0 - 24.9 cm d.b.h.o.b.). |
| Form 1 | Bole is straight or has sweeps less than 2%. |
| Form 2 | 90 % of the bole is straight (sweeps less than 2 %) e.g. the bole has one sharp kink but is otherwise straight. |

| | |
|---|---|
| Form 3 | 60 - 90 % of the bole is straight (sweeps less than 2 %). |
| Form 4 | less than 60 % of the bole is straight (sweeps less than 2%). |

***Dendrometry***

(Dendrometer readings at crown break or at intermediate points such as forks.)

**B/L (Base Line)**

The *horizontal* distance to the centre of the tree or the plumb point below the centre of the crown break or other measurement point (whole metres).

**Bands**

Live trees - record the number of relascope bands;
*Spiegel relascope or Wide band relascope*, record WNN, where W = number of wide bands, NN = number of narrow bands with one decimal place.
The maximum for the Spiegel relascope is 139, i.e. 1 wide band, 3.9 narrow bands.
The maximum for the Wide band relascope is 939.
*Telerelascope*
Record the number of bands (tachymeter units) to two decimal places, e.g. 247= 2.47 bands.
Fallen trees - record the top diameter in millimetres on fallen trees (Condition 4-6), in columns 19-22.

**Height** - record in *metres*

**Quality assessment**

Assess the qualities up to crown break (Appendix I). Branchwood is not to be assessed on these plots.

**Quality**

Code for the wood quality. See Appendices IV and V for the codes and definitions to use. Note the minima for each quality. Qualities below these minima are not recorded.

**Quantity**

The average quantity or amount of the characteristic in the section of bole affected.
Most qualities are described by a percentage of the tree size. Note that these are cumulative e.g. an assessment of 10% termites and 30% rot means 40 % total defect, not 10% of the 30%.

**Quadrant**

Record the quadrants affected for all wood qualities
    1 - within the quadrant or on the circumference
    2 - also central
    3 - central only (record for any quadrant).
    4 - four quadrants (record for any quadrant).
The quadrants should remain consistent throughout the bole to maintain the relativity of the defects in different sections.

***Height 1***

The height (metres) from ground to the bottom of the section of bole affected by the quality.

***Height 2***

The height (metres) from ground to the top of the section of bole.
Where the quality occurs at a point (Height 1 = Height 2) or affects 20 cm or less of the bole length, record the height in Ht 1 only.
Where the heights are the same as recorded for the previous quality, (it is the same section of bole), record 'S' in column 3 of Ht 1.
Where the height to the top of the defect is the total height of the bole or fork, record T in column 3 of Ht 2.

***Total Height***

For some projects it may be necessary to record the total height of the tree crown and this should be recorded as 'Z' in the quality column and the height recorded in Ht 1.

***Forked trees***

Use the following procedure when assessing both leaders of a forked tree (Fig. 1);

| | | |
|---|---|---|
| **Line 1** | 'Tree No.' to 'BT' | record as normal |
| | 'Form' | record D |
| | 'Dendrometry' | record for the top of the section of bole below the fork-A |
| | 'Quality assessment' | record all qualities up to the fork, finishing with double heart. |
| **Line 2** | 'Tree No.' to 'BT' | leave blank |
| | 'Form' | record D |
| | 'Dendrometry' | record for the base of the first (shortest) leader -B |
| | 'Quality assessment' | leave blank. |
| **Line 3** | 'Tree No.' to 'BT' | leave blank. |
| | 'Form' | record D |
| | 'Dendrometry' | record for the top of the first leader -C |
| | 'Quality assessment' | record all the qualities for the first leader. |
| **Line 4** | | Record as for line 2 but for the second leader D. |
| **Line 5** | | Record as for line 3 but for the second leader E. |

Repeat this procedure as necessary for all leaders. It is important that the tallest leader is recorded last, i.e. the highest point in the tree appears last on the form.

### *Double dendrometry in other cases*

Extra dendrometry is required when the bole diameter decreases suddenly at a point by more than 20% (i.e. owing to branch) even if the branch itself is not to be assessed or dendrometered. (This procedure can be also used for logs above crown break.)

Procedure - as for forked trees but recording only one leader.
Record 'D' in the form column, with upper stem diameter readings as shown in Figure 2.

Figure 1.

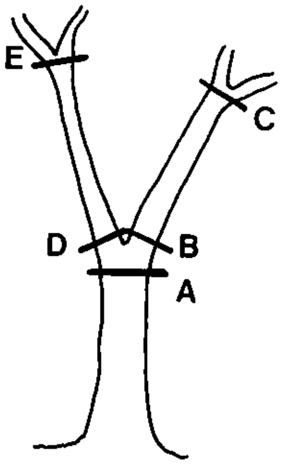


Figure 2.

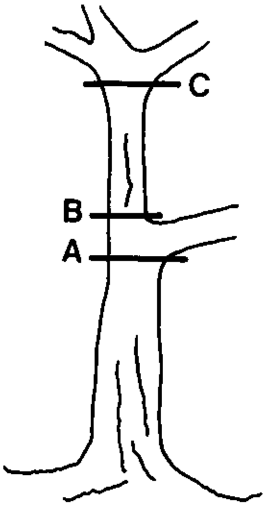
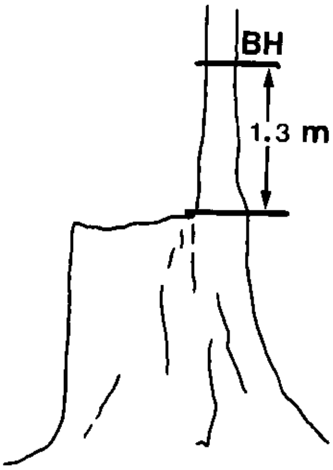


Figure 3.



### Coppice

Use the following procedures for coppice off large stumps;

**where the stump is less than 2.5 m high, do not assess the stump**

assess the coppice as a separate tree. Measure the d.b.h.o.b. at 1.3 m above the top of the join (Fig. 3). Use the relascope if necessary and convert to centimetres.

| | |
|---|---|
| coppice 15-24.9 cm at this point | should only be assessed on the subplot. |
| coppice 25+cm | should be recorded on the whole plot. |
| coppice less than 15 cm | should not be assessed. |

**where the stump is taller than 2.5 m,**

assess the stump applying normal rules.
Record the top of the stump as crown break. Assess the coppice as above.

### *Logs*

Logs should be recorded as follows;

Silvicultural class = 7, Condition = 7

Status = 4 - i.e. assess specified qualities only
d.b.h. = Centre diameter of the log
BT = Record the bark thicknesses if relevant, or 0, 0 if there is no bark.
Height = Log length

Quality assessment - record the following qualities only; burnt dryside, hollow, shatter, rot, termite and sweep or kink greater than 5%, bends greater than 10° and double heart.

Forked logs can be treated as separate logs.

Record all logs which satisfy the following criteria.

1 All major species.
2 Mid diameter under bark 150 mm-250 mm and length 1.8 m - record only on the 10 m subplot.
3 Mid diameter under bark 250 mm+, length 1.0 m - record on the full plot.
4 Solid wood greater than 20% of sectional area in one piece.

NB: a log is in or out of the plot or subplot if its centre point is in/out.

**Leaning trees - measurement of upper stem diameter**

0° - 15°

Measure the base-line from the plumb point below the crown break - preferably at right angles to the lean. Record the height and diameter without further correction. The error introduced will be less than 4%.

15° +

Measure the base-line and height and diameter as before. Use slope tables or the Pythagoras formula to calculate the actual bole length. Record this in the bole height column. All assessment should then relate to this value i.e. length along the bole, not height above ground. Record the Relascope bands as observed - they do not require correction.

CLM 129

# DEPARTMENT OF CONSERVATION AND LAND MANAGEMENT W.A.

.INVENTORY BRANCH

## WOOD QUALITY ASSESSMENT

DATE .................................... ASSESSOR ...................................

BLOCK .................................... TIE POINT ...................................

SHEET No. .......... of ...................................

TIE ...................................

...................................

................................... BRG ..........

| Cell No. | Plot Number | Ass't Type | Block No. | Plot Size | | | Date | | F D | D B K | Reg | | L M | G L S | Status | Species Codes | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Radius (m) | Length (m) | Width (m) | Mth | Yr | | | 1° | 2° | | | Species | | | | |
| | | | | | | | | | | | | | | | Class | Recorded Code | 0 | 9 | 8 |
| | | | | | | | | | | | | | | | Percentage | Absolute Code | | | |

| Tree No. | Silvic | Condition | Status | Species | DBHOB (cm) | BT (mm) | BT (mm) | Form | Dendrometry | | | | Quality | Quantity | Quadrant | | | | Height 1 (m) | Height 2 (m) | Quality | Quantity | Quadrant | | | | Height 1 (m) | Height 2 (m) | Quality | Quantity | Quadrant | | | | Height 1 (m) | Height 2 (m) | Quality | Quantity | Quadrant | | | | Height 1 (m) | Height 2 (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | B/L (m) | Bands | | Height (m) | | | 1 | 2 | 3 | 4 | | | | | 1 | 2 | 3 | 4 | | | | | 1 | 2 | 3 | 4 | | | | | 1 | 2 | 3 | 4 | | |
| | | | | | | | | | | W | N | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 2 3 | 4 | 5 | 6 | 7 8 | 9 10 11 12 | 13 14 | 15 16 | 17 | 18 19 | 20 | 21 22 | 23 24 25 | 26 27 | 28 29 | 30 | 31 | 32 | 33 | 34 35 36 | 37 38 39 | 40 41 | 42 43 | 44 | 45 | 46 | 47 | 48 49 50 | 51 52 53 | 54 55 | 56 57 | 58 | 59 | 60 | 61 | 62 63 64 | 65 66 67 | 68 69 | 70 71 | 72 | 73 | 74 | 75 | 76 77 78 | 79 80 81 |

# Appendix III

## Species Codes

**Major Species**

| | | |
|---|---|---|
| 1 | *Eucalyptus marginata* | jarrah |
| 5 | *Eucalyptus calophylla* | marri |
| 4 | *Eucalyptus patens* | blackbutt |
| 13 | *Eucalyptus rudis* | flooded gum |
| 3 | *Eucalyptus wandoo* | wandoo |
| 9 | *Eucalyptus accedens* | powderbark |
| 10 | *Eucalyptus laeliae* | buttergum |

The following will be regarded as major species when encountered although the areas in which they occur will generally not be covered by the jarrah inventory.

| | | |
|---|---|---|
| 2 | *Eucalyptus diversicolor* | karri |
| 6 | *Eucalyptus guilfoylei* | yellow tingle |
| 7 | *Eucalyptus jacksonii* | red tingle |
| 8 | *Eucalyptus gomphocephala* | tuart |

**Minor species**

| | | |
|---|---|---|
| 11 | *Eucalyptus megacarpa* | bullich |
| 25 | *Agonis flexuosa* | peppermint |
| 26 | *Agonis juniperina* | warren river cedar |
| 27 | *Allocasuarina fraseriana* | sheoak |
| 28 | *Allocasuarina decussata* | karri oak |
| 32 | *Banksia seminuda* | river banksia |
| 33 | *Banksia littoralis* | swamp banksia |
| 34 | *Banksia ilicifolia* | hollyleaf banksia |

**Other species**

| | | |
|---|---|---|
| 14 | *Eucalyptus haematoxylon* | mountain marri |
| 15 | *Eucalyptus ficifolia* | red-flowering gum |
| 18 | *Eucalyptus brevistylis* | Rate's tingle |
| 29 | *Nuytsia floribunda* | christmas tree |
| 30 | *Banksia grandis* | bull banksia |
| 31 | *Banksia attenuata* | slender banksia |
| 36 | *Melaleuca rhaphiophylla* | paperbark |
| 37 | *Melaleuca preissiana* | swamp paperbark |
| 38 | *Melaleuca cuticularis* | saltwater paperbark |

# Appendix IV

## Definitions of Wood Quality Categories

**Clearwood 'CW'**

No visible defect or irregularity (other than twist or sweep) and no indication of internal defects.

**Sweep 'S'**

Continuous curvature over the specified length, i.e. unlike a bend, sweep cannot be cut out.

*Multiple 'SM'*

Changes in direction of sweep. Record as the average when all the sweeps are of similar magnitude, otherwise record separately.

Measured as the amount of deviation from a straight edge as a percentage of the specified length.

Those quadrants the section sweeps out of at the top end - which are missing wood, should be recorded as those carrying the defect.

Minimum : 1%. e.g. maximum permissible for poles is 1% and for chipwood is 5%.

**Bend 'A'**

Angles or sharp changes in direction at a point on an otherwise straight bole. Can be obviated by cutting. Minor or gradual bending should be specified as sweep. Also record angles at ground level (lean) exceeding 10°.

Measured in degrees of change of direction.

Those quadrants the section bends out of at the top end, which are missing wood, should be recorded as those carrying the defect. Minimum : 3° (1 in 20 or 5%). e.g. Maximum permissible in chipwood is approximately 20° (1 in 3 or 36%). (Note many products convert slight bends to sweep specifications per unit length.)

*Multiple 'AM'*

Additional bend(s) within 900 mm (i.e. no straight section exceeding 900 mm length).

**Kink 'K'**

Sharp deviation and tight sweep back to vertical. Usually resulting from reshooting after tip death.

*Multiple 'KM'* As for multiple bends.

Measured as percentage deviation from start of kink to point where bole straightens out again. Those quadrants the section sweeps out of at the top end, which are missing wood, should be recorded as those carrying the defect.

Minimum : 1% e.g. maximum for poles is 2%.

**Wind (Twist) 'W'**

Deviation in grain angle from straight along the bole axis. Measured in degrees deviation from bole axis.Minimum : 2° (1 in 33). e.g. Maximum permissible in poles is 3° (or 1 in 20).

**Dryside (Dead) 'D'**

Exposed dead wood resulting from injury, and generally bordered by callus tissue. Includes fresh injury scars since these have the same implications for utilization.

| | |
|---|---|
| *Clean 'D'* | No associated degrading characteristics. |
| *Burnt 'DB'* | The dryside has been burnt producing charcoal. |
| *Pins 'DP'* | Pinhole borers (*Atractocerus kreuslerae*) have entered the exposed wood soon after the damage. |
| *Pins,Burnt 'DM'* | Dryside has both charcoal and pins. |

Measured as the average percentage of circumference taken up by dryside to outsides of callus. If the dryside is rather deep, so that it would exceed 10% of sectional area or more then it should be classed as a hollow. Minimum : 10 cm including the collar of callus tissue, unless pins occur also. e.g. maximum allowable in poles is 10%.

*Many 'DW'* Many (4+) small (<10%) dryside clean, record as a rating (Appendix V).

**Overgrowth 'O'**

Distinguished from drysides as having overgrown the faults so that the associated defects are no longer visible. Owing to the time since injury, particularly with deep callus tissue, there is usually considerable internal degrade - wood separation, gum and rot. Measured as the average percentage circumference occupied by the callus tissue.

*Multiple 'OM'*

Multiple small overgrowths on a section of the bole. Recorded as a rating (Appendix V).

**Hollow (Burnt) 'HB'**

Hollowed sections of the bole resulting from fire and/or mechanical damage (and subsequent growth), generally in the butt section of the bole and burnt, producing charcoal. (Hollowbutts.)

*Pins Burnt 'HM'* Burnt hollows which also have pin hole borer associated.

**Hollow (Unburnt) 'H'**
Holes or cavities resulting from mechanical damage, breaking away or rotting of branches, generally in the upper section of the bole, and unburnt.
*Pins 'HP'* Unburnt hollows which also have pinhole borer. Measured as the average percentage of the cross-sectional area missing. Minimum : 5% (smaller areas may be classified as dryside). e.g. Maximum permissible for sawlogs would be 50% if remaining area were sound. (However, hollow butts would generally be minimized with high stumps.)
**Rot 'R'**
Any form of wood decay (or the resulting voids in the rotting material) either as pipe, pocket rot associated with limbs, drysides, insect holes. or more dispersed rot and stain type fungal decay. (Presence of fruiting brackets on the stem is positive evidence of active decay.) Measured as the average percentage of the sectional area affected.
Minimum : 5%. e.g. Maximum for peelers is 11.5% (up to a maximum diameter of 150 mm if central).
*Termites 'RT'* Where it is considered rot and termite activity are present together in similar proportions and distribution. Measurement and minimum as above.
**Termites 'T'**
Soil based tunnels and galleries of termites associated with dead or decayed wood. Measured as an average percentage of sectional area. Tunnels in bark are not significant. Minimum : 5%.
**Branch**
*Sound 'B'* Green branches or dead branches or stubs which are still solid with no visible decay.
*Multiple 'BM'* Multiple small sound branches with less than 60 cm between each. Recorded as a rating (Appendix V ).
*Unsound 'BU'* Branches or stubs which have started to decay or with a decayed socket, and are no longer solid wood tightly contained. Measured as the percentage of bole circumference taken up by the branch collar diameter. (If diameter is less than 20 cm record the central point of attachment, and record the bole heights for larger limbs.) minimum : 5% or 5 cm branch, 10 cm collar. e.g. Maximum permissible sound branch for poles or mining timber is 20%. Maximum unsound for poles is 5%.
*Many Unsound 'BW'* Many (4+) small (<10%) unsound branches or stubs with less than 60 cm between each. Record as a rating
(Appendix V).
**Epicormic 'E'**
Branches with minimal knot, mainly confined to the sapwood.
Measurement and minimum as above.
*Multiple Epicormics 'EM'* Multiple small epicormics along the bole. Recorded as a rating (Appendix V ).
**Double Heart 'Q'**
Sections of the bole where the bole heart and branch heart occur together. Measured in degrees as the angle between the two hearts. This can be used in data processing where necessary to calculate distances between the two hearts in relation to the bole diameter. When recorded below breast height, this indicates that the tree forks below BH and will be cut with a high stump. Since the fork is below BH, the two trees are recorded separately. Both should include an assessment of double heart. Maximum : 70°-80° (Greater angles closer to 90° would have minimal length of double heart) e.g. Maximum separation of centres in mining timber, at crown, is 33% of diameter.
**Insect Borers 'IL'**
Evidence of activity of any larger insect larval borers in the bole such as holes (greater than 1 mm diameter), gum bleeding, frass or overgrown gum holes.
Recorded as a rating (Appendix V ).
*Pinhole 'IP'* Evidence of Pinhole Borer from damage not recorded on the bole.
**Checks /Splits 'CH'**
Longitudinal splitting of the surface of the bole or log. Measured in centimetres of depth. Minimum : 2 cm. e.g. Maximum allowable in peelers is 5 cm.
**Shatter 'SH'**
Shattering of the wood resulting in fibre separation splintering or breakage.
Measured as the average percentage of sectional area affected.
**Gum Pockets 'G'**
Cavities below swellings (associated with damage),causing kino production.
Measured as the average percentage of the circumference. Minimum : 10 cm diameter.
*Multiple 'GM'* Multiple small gum pockets on a section of bole. Recorded as a rating (Appendix V ).
**Lump (Swelling) 'L'**
Various lumps or swellings of straight-grained wood, with no callus. May be related to small overgrown damage or fluting or growth irregularities.
Measured as the average percentage of the circumference occupied by the swelling.

Minimum : 10 cm diameter.
*Multiple 'LM'* A number of smaller swellings spread along the bole. Recorded as a rating (Appendix V).
**Circularity 'C'**
Non circularity of the bole which may result from stress producing eccentricity and tension wood, abnormal growth or buttressing or fluting but do not record for normal buttressing. e.g. Pole maximum diameter must not exceed the minimum by more than 25% over 80% of the pole. Recorded as the percentage by which the maximum diameter at a point exceeds the minimum at that point. Record 99 for irregular shaped boles. Record the quadrants which have the narrower diameters (missing wood) as having the defect or the quadrants which are irregular.
**Burl 'N'**
Growth irregularities producing outgrowth of sound wood on the bole.
Measured as a percentage of the circumference taken up by the burl diameter.
Minimum : 10 cm diameter.
*Multiple 'NM'* multiple small burls on a section of bole. Recorded as a rating (Appendix V).
**Figurative Grains 'F'**
Figurative grains for feature wood uses.
Record presence over the length of bole affected.
**Wild Grain 'X'**
Erratic multi-directional and interlocked grained wood.
Record presence over the length of bole affected.

Note: Any section of bole remaining unclassified as above will be assumed by default to be generally sound with only minimal faults below the minima specified above. Code 'CU'.

# Appendix V

## Wood quality classification

| Wood Quality | | Code | Quantity in Section Affected | Recording |
|---|---|---|---|---|
| Clearwood | | CW | | |
| | Unclassified | CU | Unclassified, minor defects only. | |
| Sweep | | S | Percentage deviation over length | XX% |
| | /Multiple Sweep | SM | Percentage deviation over length | XX% |
| Bend | | A | Angle of direction change | XX° |
| | /Multiple Bends | AM | Angle of direction change | XX° |
| Kink | | K | Percentage deviation over length | XX% |
| | /Multiple Kink | KM | Percentage deviation over length | XX% |
| Wind (or twist) | | W | Degrees from bole axis | XX° |
| Dryside/Clean | | D | Percentage of circumference | XX% |
| | /Burnt | DB | Percentage of circumference | XX% |
| | /Pins | DP | Percentage of circumference | XX% |
| | /Pins, Burnt | DM | Percentage of circumference | XX% |
| | /Many small,clean | DW | Rating 1 - 3 | X |
| Overgrowth | | O | Percentage of circumference | XX% |
| | /Multiple Overgrowth | OM | Rating 1-3 | X |
| Hollow /Burnt | | HB | Percentage of sectional area | XX% |
| | /Pins, Burnt | HM | Percentage of sectional area | XX% |
| Hollow | /Unburnt | H | Percentage of sectional area | XX% |
| | /Pins Unburnt | HP | Percentage of sectional area | XX% |
| Rot | | R | Percentage of sectional area | XX% |
| | /Termites | RT | Percentage of sectional area | XX% |
| Termites | | T | Percentage of sectional area | XX% |
| Branch | /Sound | B | Percentage of circumference | XX% |
| | /Multiple Sound | BM | Rating 1-3 | X |
| | /Unsound | BU | Percentage of circumference | XX% |
| | /Many unsound | BW | Rating 1 - 3 | X |
| Epicormic | | E | Percentage of circumference | XX% |
| | /Multiple Epicormic | EM | Rating 1-3 | X |
| Double Heart | | Q | Angle between hearts | XX° |
| Insect Borers | | IL | Severity rating 1-3 | X |
| | /Pinhole | IP | Severity rating 1-3 | X |
| Checks (Splits) | | CH | Depth | XX cm |
| Shatter | | SH | Percentage of sectional area | XX% |
| Gum Pocket | | G | Percentage of circumference | XX% |
| | /Multiple Gum Pockets | GM | Rating 1-3 | X |
| Lump | | L | Percentage of circumference | XX% |
| | /Multiple Lumps | LM | Rating 1-3 | X |
| Circularity | | C | Percentage oversize/irregular | XX% |
| Burl | | N | Percentage of circumference | XX% |
| | /Multiple Burls | NM | Rating 1-3 | X |
| Figurative grain | | F | | |
| Wild grain | | X | | |
| Total Tree Height | | Z | | |

| | | | |
|---|---|---|---|
| Ratings | 1 - few | 0 - 2 per $m^2$ | over the length affected |
| | 2 - moderate | 2 - 6 per $m^2$ | over the length affected |
| | 3 - numerous | 6 + per $m^2$ | over the length affected |

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