AN EVALUATION OF LANDSAT MSS DATA FOR ECOLOGICAL LAND CLASSIFICATION AND MAPPING IN THE NORTHERN CAPE

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PAPER 2

A COMPUTER PROCESSED INVESTIGATION OF LANDSAT MULTISPECTRAL DATA TO DETERMINE THE REGIONAL MAPPING CAPABILITIES IN THE SEMI-ARID REGIONS OF SOUTH AFRICA

1. INTRODUCTION

A major vegetation survey of the Northern Cape necessitated the production, in the final stages, of 1:250 000 scale maps of the study area. Various practical problems occurred with the accurate positioning of classified vegetation unit boundaries, owing to poor and outdated aerial photographs as well as the general inaccessibility and vast size of the area. To overcome these difficulties, visual interpretation techniques of Landsat false colour composites at a similar scale were incorporated, with considerable success.

Paper I of this report discusses the visual interpretation possibilities of the reconstructed image of the scene viewed by Landsat sensors. In the visual interpretation of the multispectral data, a purely qualitative descriptive and subjective approach was adopted. Many researchers disagree with the procedure, owing to its subjectivity/variability per researcher, non-repeatability and inconisistency, and because the method disregards the data's most important attribute - its numerical characteristics (Nelson & Hoffer 1979). This fact, coupled with problem areas noted during the visual interpretation investigation lead to the investigation of automated, machine-processing methods.

With the computer classification approach the "analysis is concerned with the actual measurements in conjunction with probablistic or simple numerical algorithms, which are used to discriminate amongst selected phenomena" (Hancock & Fish 1984). The analysis is standardized, repeatable, automatic and objective and classifications are consistent as they are based on mathematical precepts (Nelson & Hoffer 1979). Turner (1988), however, pointed out that the digital numbers (DN) are unitless, scaleless and not true quantitative measurements.

The classification scheme or method utilizes the statistical classification of parameters which are surrogates for vegetation-landscape (terrain) attributes. These methods contrast with the classical ground- and aerial photograph-based methods of vegetation classification and mapping. It would be as well to evaluate their accuracy, cost, timeliness, usefulness, applicability and logic in vegetation map production in semi-arid regions of South Africa. Vegetation map production from computer classifications of Landsat Multispectral Scanner System (MSS) digital data is surrogate mapping, where "the primary attribute of interest cannot be directly measured but a secondary attribute can be measured and related to the primary one" (Robinove 1981). The primary attribute can be confirmed through inference, using the existence of the secondary attribute. (This statement has been verified in Paper I and will be discussed more fully in Paper IV.)

Manipulation of the data allows for computer processing techniques, where the decision-making capabilities of the computer are used for identification, extraction and classification of the information inherent in the numerical data. The Landsat image consists of data, whereas any classification done on the image is information (Cooper 1986). Landsat by itself is just a phenomenon, but when the digital data is referenced through field data and supportive information maps, then meaning is given to the classification information.

Cognisance must be taken of the comment by Schreier *et al.* (1982) that very few computer classifications of Landsat data have become operational despite the fact that theoretically such methods make better use of the data and are more quantitative. The classes generated by the computer and those generated by the investigator are often not coincidental. Mason & Langheim (1957) stated, "Classes are part of an intellectual organization system generated by the observer to explain what is being classified."

Four questions were posed with regard to the use of computer-aided classification techniques: (i) Since computers are better able to handle the sheer volume of data, would this increase in sampling give rise to more concrete ground cover units? (ii) As all data points are analysed and classified, is extrapolation potential better? (iii) Can computer classifications establish better vegetation-landscape boundaries in problem (mosaic) areas? (iv) Can computer classifications reduce the input required in obtaining adequate ground reference data?

The basic aim was to find out if this method would lead to more accurate, less time-consuming and less costly vegetation maps than can be produced using visual interpretation techniques or "hardcopy" prints. Futhermore, it was hoped that this method would lead to improved extrapolation and interpolation capabilities. The purpose of the computer classification of the MSS digital data was the production of a classified map of the vegetation-landscape units in the study area. The end product would be compared to the map produced using visual interpretation of the same MSS digital data in false colour composite hardcopy form (qualitative interpretation), as documented in Paper 1.

The vegetal field survey methods utilized and the subsequent classification results will not be described here again. This paper presents and describes the methods and results of computer techniques applied to the same data set, compares the end products and discusses the advantages and disadvantages of these methods.

2. STUDY AREA

The MSS data set was the same as that used for the visual interpretation project. It was considered advisable to re-analyse this same surface area, the Kuruman-Taung area in the Northern Cape, with biotic and abiotic attributes already classified. A single-date Landsat scene had to be chosen for the study, owing to restrictions of computer time and financial restraints. A single Landsat 3 scene, ID: 22550-07345, WRS 185-79 was chosen (Plate 1 in Paper 1). The satellite observation occurred on 15 January 1982 at approximately 09h35. This area had been chosen intially for visual interpretation because of its complexity in terms of vegetation units, soil types, geological formations and terrain morphology (Figs. 9 to 14 in Paper 1). The environmental parameters are described in some detail in Paper 1.

Standardization of study area and investigator is necessary for comparative reasons. In addition, simultaneous investigations are superior to consecutive ones when comparisons are being made. It was accepted that the prior use of visual interpretation techniques on Landsat imagery representing this same study area could, in some ways, influence of the use of computer classification techniques.

3. COMPUTER CLASSIFICATION OF LANDSAT MSS DATA

There are two common approaches to analysing and interpreting Landsat images (Swain & Davis 1978). Paper 1 discusses the use of the "visual" approach. This paper discusses the "digital", "computerized" or "numerically orientated" approach (Piper 1981; Turner 1987). The overall objective of any classification of Landsat MSS digital data is the reduction of an exceptionally large number of observations (pixels) to a few useful features or categories. This process is also known as "feature extraction" or "pattern recognition" (Piper 1981). With computer classifications, image restoration and enhancement pre-processing procedures to make data more easily interpreted are similar to those described in Paper 1. Information (feature) extraction procedures/processes utilize the decision-making capability of computers to identify and extract specific groups of information (Sabins 1978). At this stage the distinction between human and computer logic pathways diverges markedly - the so-called qualitative (clue-seeking) and quantitative (statistical) approaches (Hajic & Simonett 1976). Hypothetically, the computer system inputs the Landsat data, formats it, analyses it and outputs desired statistics (Nelson & Hoffer 1979).

Computer classification requires that the computer recognise classes of information within the data set (Nelson & Hoffer 1979), and that each bit of the data (pixels) be assigned to a class. Processing of the multi-band image or data set is made possible by recognizing and classifying the spectral signatures in their numerical form, where each pixel is assigned to a specific class by matching the spectral signature with the range of signatures determined for the class (Jarman 1981). The spectral reflectance for each pixel in a Landsat image is recorded at four different wavelength bands, (Sabins 1978). This is the pixel's spectral signature. These spectral signatures are analysed and similar signatures (pixels) are grouped into classes. This is the basis of all known computer classification methods. The spectral signatures are themselves used to define the classes (Newton 1983). Every point in the multispectral space becomes associated with one of the spectral classes (Landgrebe 1974).

In the final interpretation there is correlation of the data classes thus developed with the ground cover/terrain classes, and some hierarchical structure is given to the classes. The basis for classification of cover types (spectral classes) is the correlation of different categories of interest on the ground with statistically separable groups of data as defined by their spectral properties in multidimensional space (Short 1982). Identification of separable spectral groups without any real world interpretation does not result in a classification, as no hierarchical identification and categorization is possible. Thus, computer classifications of multispectral digital data (allocation of pixels) do not result in the classification of ground cover types in the strict sense, i.e. arrangement on the basis of their inter-relationships.

The advent of computer logic programming and rapid data processing capabilities have permitted the use of much more sophisticated analytical techniques (Driscoll *et al.* 1978). Prior to advanced computer technology, classifications were subjectively based on the investigator's ability to recognise similarities and perceive differences, such as that practised in visual interpretation of aerial photographs, Landsat imagery and the collection of ground reference data. In terms of the aims of the investigation, the final or output stage is the most important as the final product must be of some use to the investigator. This fact is often overlooked by investigators wishing to obtain results which are quantitative, statistical, objective and repeatable, almost at all costs. Some form of accuracy test (confirmation and verification) should be undertaken. Verification of results, qualitative and quatitative, is frequently ignored (Hajic & Simonett 1976). An attempt was made here, albeit subjective and qualitative.

The Satellite Applications Centre (SAC) at Hartebeeshoek (South Africa) provided the image-processing facilities and programmes were run by Mr T. Boyle. The SAC image processing system comprises a Perkin-Elmer 8/32 computer, linked to a comtal TV image service (Newton 1983). Appendix 1 gives details of hardware and software used in the SAC's Image Analysis System (IAS). All the technical details which were given in Paper 1 for the Landsat satellites are applicable here too.

3.1 TRAINING CLASSES

The range of signatures for a specific spectral class is obtained from a training class. The training class is a small set of data within a selected training area used to "train" a classification algorithm (Walsh 1980). This small set of data has a specific spectral response. The classifier, e.g. maximum likelihood classifier, attempts to group all similar spectral responses on a pixel by pixel basis to the training class (spectral class) defined by the training class statistics. The spectral signature of each pixel consists of grey scale values in the four spectral bands. The statistical parameters (mean, standard deviation, covariance and divergence) of each training class are stored by the computer and used to represent the multispectral characteristics of that class (Smedes *et al.* 1970).

Numerous training classes may be developed for the MSS digital data under classification, the number depending on the training class selection technique or method employed and on the inherent structure of the data set. The training classes should be sufficiently different (discrete) from one another to prevent confusion between them (Jarman 1981). Jarman (1981) further stated that : "This type of pattern recognition in digital image processing is statistical in character and includes 'statistical space' in which the 'pattern' is a vector made up of a number of measurements, in an n-dimensional space, where n represents the number of MSS bands utilized". Generally, training areas are selected from specific known target areas in the scene (Smedes *et al.* 1970) to provide examples of typical data from each class of interest (Boyle 1981a).

In this study, two training areas (not all cover types could be adequately represented by one training area) were chosen for the development of training classes and the selection of training sites with which to train the classifier. The training areas were 512 X 512 pixels in size (30 km x 40 km). The two training areas are depicted in Figs. 2 and 3. The training areas were pre-processed in the routine manner by the SAC's IAS (Image Analysis System).

Each training area was chosen on the grounds of presence of ecological regions and complexity of ground cover types which contained relatively "homogeneous" (minimally heterogeneous) units over considerable areas. The northern training area is referred to as the Kalahari Thornveld Training Area and the southern one as the Ghaap Plateau Training Area.

3.2 METHODS OF COMPUTER CLASSIFICATION

Various computer classification methods of data analysis of Landsat MSS digital data exist. Two broad categories in frequent use are referred to as "supervised" and "unsupervised" classifications. These are two methods for obtaining training signatures for use on the Landsat spectral data. Reference is made to Boyle (1981b) for a detailed discussion of these methods. These methods are both standardized and objective in their manipulation of the spectral digital data with the aid of computer processing techniques. A third method consists of a hybridization of these two methods where the input of information and level of integration of the two methods varies according to the study in question.

The three different training class selection techniques were employed in this study. An outline of each is given below.

3.2.1 SUPERVISED CLASSIFICATION

When ground reference data and other supportive information are available and are adequate or good, the supervised classification method is preferred (Swain 1983). This method was developed largely in the USA for the classification of crops, for which large amounts of ground reference data were available (Armstrong 1975), and has been found to work efficiently under these conditions. The researcher "supervises" the partitioning of the multivariate measurement space through his knowledge of the ground cover of the area under study. Within a given study area (or test area), one to several training areas are selected which, when combined, represent adequate samples of the units known to be present in the study area.

These samples, or training classes, are used to train the computer in the location and identity of classes of interest to the researcher. The computer is then commanded to group all pixels (resolution elements) in the training area(s) into one or other of the appropriate classes specified by the training classes which have been identified by the researcher. The study area is thus classified and the classification evaluated. Ellis (1978, in Nelson &

Hoffer 1979) mentioned the following guidelines:

a) The training areas and classes must be as spectrally distinct from one another as possible, otherwise classification confusion (cross-classification) will result;

b) The training areas and classes should be as spectrally homogeneous as possible;

c) Mixed spectral classes (mosaic or impure ground cover classes) should be avoided;

d) Training areas (and thus training classes) should be representative of the entire area being classified;

e) Training class size (number of pixels or hectares) should be an adequate sample of the training area/ground cover unit and is often dependent on the homogeneity and complexity of the training area and study area, respectively.

A number of training sites may be necessary for the training of a computer in the accurate recognition of a training class, depending on the variability (homogeneity) of a class (Short 1982). Thus, in the supervised classification method, the researcher geographically and spatially chooses and locates the areas within the image that he feels typify each of the desired classification categories/units of ground cover which should appear in the final product, e.g. a vegetation-landscape map (Sabins 1978). In supervised classification it is assumed that the different vegetation mapping units have unique spectral signatures (Cihlar *et al.* 1978). This assumption cannot be reliably applied for a given unit from one image to another, nor over large distances on the same image. The researcher uses his own interpretation of field data and Landsat image. The intention is that these areas (training areas, classes and sites) be spectrally unique and adequately characterize the spectral class (training area, classes and sites). In supervised classification only informational value classes will be stipulated, though some may not be statistically (spectrally) separable from each other.

The training sites are positioned where, according to the researcher's knowledge, the category (class) occurs in a more or less uniform distribution on the ground (from ground reference data and aerial photographs) (Short 1982). This usually turns out to be that area where the category is most extensive (most "pure") and is often that area where the field survey sample sites typify the vegetation association/community present. Often training sites are selected from known small areas within a large area.

There is a possibility that these known areas may not be the best areas for typifying the vegetation association/plant community identified in the field. It is unfortunate that, in much Landsat research conducted to date, the most common reason for conducting field research is purely for the selection of key training sites/key classes for supervised and unsupervised classification respectively. Landsat imagery is thus, in many cases, not being used as a tool in environmental quality research but vice versa. This may raise problems when a larger area is to be classified from the training site statistics generated, through signature extension.

The resultant classification can be displayed on a TV comtal or produced as a printout, and checked for accuracy and completeness based on knowledge of the area and its attributes. Supervised classification is historically older, is mathematically more simple and computationally more convenient than other methods.

3.2.2 UNSUPERVISED CLASSIFICATION

This method is statistically more sophisticated than the supervised method (Robinove 1981), and is used when the researcher has little prior knowledge of the area. In unsupervised classification the process is automatic, with minimal researcher involvement in the definition of the spectral classes (Nelson & Hoffer 1979). The pixels are grouped into "natural" classes according to the chosen mathematical routine (Newton 1983), e.g. separation of the multispectral data into classes on a variance criterion using Bayes' maximum likelihood rule. The researcher uses the apparent clustering tendencies of the data themselves (Swain 1983). Usually the researcher, prior to classification, decides on a logical number of spectral classes/categories that may be shown in the image though, at this stage, their identity is unknown.

The computer then classifies one to several training areas in the study area, i.e. a sample of the pixels. The final number of "homogeneous" classes/categories generated by the clustering process cannot be greater than that originally specified by the researcher. Every point in multispectral space automatically becomes associated with one of the yet unnamed classes. The list of classes should be reasonably large so that there is a logical class to which every point may be assigned (Landgrebe 1974). The researcher specifies the statistical parameters within which the computer must operate, e.g. number of standard deviations from the means in each band for each resolution cell, which will form the basis for separating or combining classes. He will also decide on the bases of statistical similarity or difference which classes/clusters (means and covariance matrices of each class) in the statistical data must be grouped together or should stand alone (Robinove 1981). Obviously the algorithm will maximize the statistical distance between classes of dissimilar pixels (Talbot & Markon 1986).

The classification is performed, taking into account these "instructions". Each pixel is assigned to a single, often unidentified class and the classification is displayed using theme colours for the various classes on the TV screen or produced in alpha-numeric printout format i.e. the map product.

Unsupervised classification uses only the researcher's estimate of the number, type and statistical range of the clusters desired, whereas supervised classification uses the researcher's knowledge of the terrain/ground cover to guide the statistical procedures used to divide the data logically into discrete clusters (Robinove 1981). Cluster analysis is used in the partitioning of the measurement space based on the apparent structure inherent in the data (Swain 1983). The resulting clusters are referred to as spectral classes which must be associated with ground cover classes with regard to information content.

As is the case with supervised classification but more critical in unsupervised classification, every pixel automatically becomes associated with one of the derived unidentified classes (Landgrebe 1974). Sufficient classes must be selected to allow for logical class distribution of each pixel without losing information value. If the classes produced are too numerous, many will not relate to specific terrain/ground cover categories, or, these categories will consist of several classes which are difficult to identify. There is no guarantee that the classes formed are meaningful in anything other than spectral homogeneity (cluster variance will be small). Jarman *et al.* (1983) stated that this method is particularly useful in a heterogeneous scene in which the likelihood of observing several adjacent pixels of the same cover type is low. Presumably Jarman *et al.* were referring to reflectance units which display relatively constant spectral heterogeneity.

Nagy *et al.* (1971), objecting to supervised classification as it is usually applied, strongly supported this method believing that reference data should be collected only after the clustering procedure has taken place. Despite this objection, supervised classification is known to work efficiently when good ground reference data is available (Armstrong 1975). Unsupervised classification is used mainly when the researcher has little prior ground cover data with which to interpret the imagery representing the area of interest.

Once the classification has been performed, the researcher uses the reference data he has at hand, or collects further data, to identify or interpret the spectral classes defined by the clustering process (Swain 1983). This is necessary if any measure of the accuracy of the method is required. The success of unsupervised classification rests on there being correlation between information value classes and the structure inherent in the clustered MSS digital data. There must, therefore, be some correlation between spectral reflectance and the parameter of interest on the earth's surface. This can be difficult to ascertain when the researcher has little knowledge of the area being researched. The value of Landsat is its availability in areas where ground reference data is lacking; the unsupervised method is the only one applicable under these conditions (Armstrong 1975). Many researchers do use this method of classification with good ground cover data but this use has been largely along the lines of comparison with results obtained from other methods, such as supervised or visual methods, aerial photograph interpretation and ground based methods.

3.2.3 HYBRID CLASSIFICATION

Optimum classification may be achieved by combining supervised and unsupervised methods (Newton 1983), or a significant improvement may result over one or other of the above mentioned automatic procedures used on their own. Mayer & Fox (1981) found the hybrid method most effective in dealing with problems of spectrally heterogeneous training areas and omission of unique spectral patterns. The two problems have direct bearing on this study.

The simplest hybrid approach involves specifying several training areas on the image which represent known ground cover classes in the field (equivalent to the supervised method) and then allowing the computer to define the spectral classes in the training areas specified by the researcher, by statistical procedures and the production of discrete clusters, (equivalent to the unsupervised method). The resultant spectral classes produced in the initial classification are interpreted for information value by correlation with ground reference data and valid classes are isolated or grouped until a satisfactory, final classification is achieved. This method uses much less computer time than the unsupervised classification method with little loss of accuracy (Robinove 1981).

A related form of hybrid classification was used by Newton (1983), in a rock differentiation study of arid to semi-arid South African environments, with considerable success. Here, separate supervised and unsupervised classes were combined for the final decision stage of the study, with a resultant increase in the information value of the classes finally accepted. This method of combining the supervised and unsupervised techniques is sometimes referred to as the controlled clustering technique (Walsh 1980), although the degree of hybridization is highly variable. This method reduces the number of non-information value classes by the selection of representative training areas covering much of the spectral variability (effective formulation of training statistics).

A third hybrid variation involves the use of the supervised method on known, homogeneous terrain types and the unsupervised method on known heterogeneous terrain types. Selection of areas/reflectance units for each method is not based on their appearance in the digital data, but their "appearance" in the field. The logic behind this is that the supervised method works well with simple situations.

Fig. 1 (from Boyle *et al.* 1988) is a flow chart of a procedure almost identical to that used by Boyle and the author in this study.

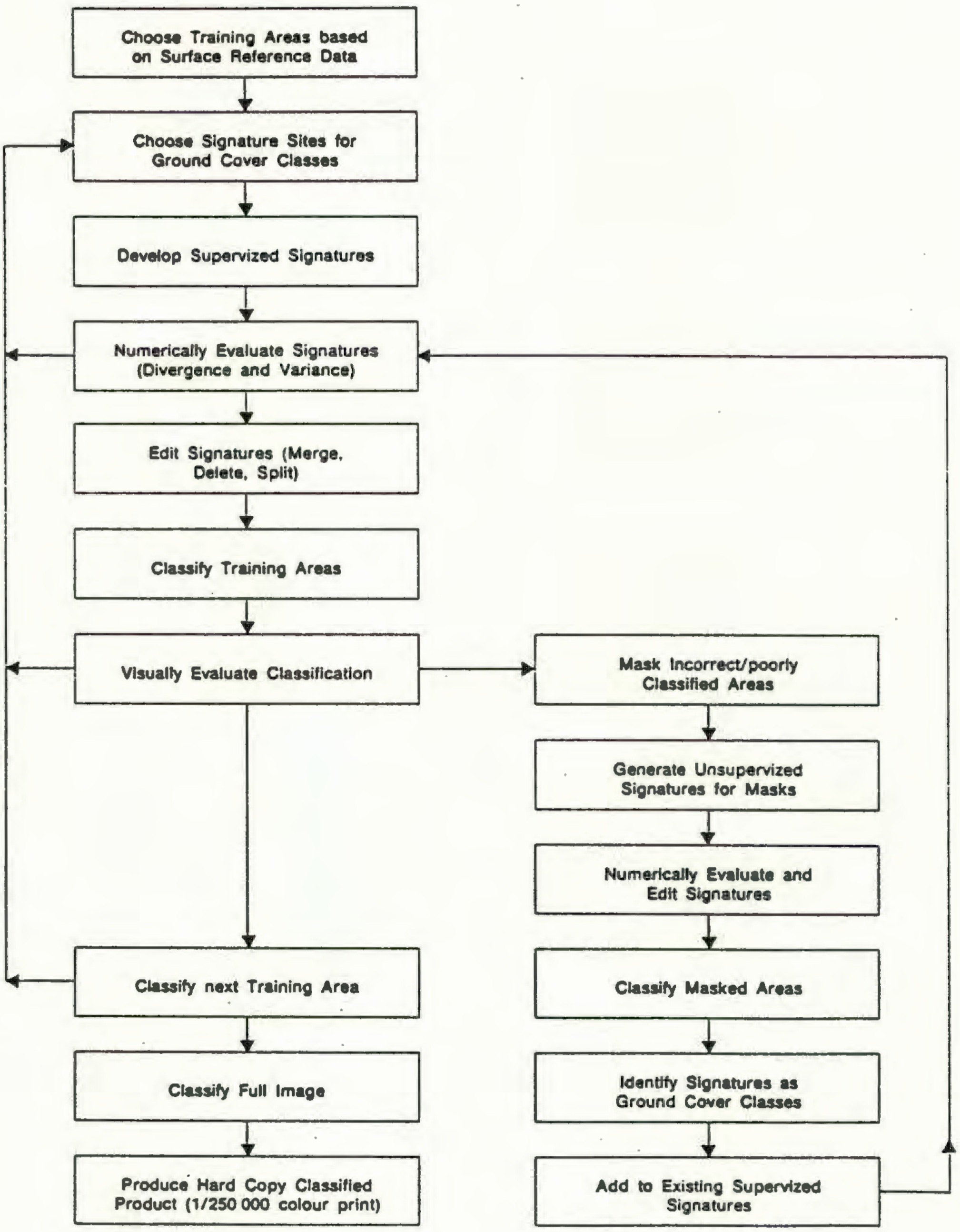


Figure 1 Flowchart of the hybrid classification method. Note that the supervised and unsupervised signatures are combined. (From Boyle *et al.* 1988).

3.3 COMPUTER CLASSIFICATION TECHNIQUES APPLIED TO THE LANDSAT MSS DATA OF THE STUDY AREA

Owing to the detail of the ground reference data, the supervised classification technique was obviously the first choice in this study. Both training areas were used in the selection of training classes for the application of the supervised classification of the multispectral data. Fig. 2 depicts the Northern Cape, the study area and the two training areas. Fig. 3 depicts the simplified terrain morphology of the study area. The two squares show the Kalahari Thornveld (north) and the Ghaap Plateau (south) Training Areas. The training classes for each training area are listed in Appendix 2. The Kalahari Thornveld Training Area was investigated first and the Ghaap Plateau Training Area subsequently. Training classes were selected on the basis of good ground reference data, aerial photography, a prepared vegetation map of the scene, various supportive resource maps and areas of relative homogeneity of the multispectral data as they appeared to the analysts on the display screen at the time of digital image processing.

The sets of training statistics or training classes for both training areas, were generated by outlining the areas (training sites) by means of a trackball or moving dot cursor. The cursor is a distinctive bright spot on the screen that may be positioned with the trackball control to designate specific pixels or outline areas within the display (Sabins 1978). The spectral signatures of the pixels incorporated by the outlined area (pixel and line numbers) were used for statistical definition of the class. Particular colours were allocated to each class. Each "colour class" was displayed individually to evaluate its distribution (small pixel clusters as well as large blocks) with respect to that of spectral/ground cover type.

The data was classified by means of class signature extension to the complete training areas and result displayed in colour on the screen. Regions having the same spectral signature in the original data are represented by the same colour in the classified map. The classifications were interpreted and assessed for accuracy of classification, good separation of spectral classes/ground cover units, misclassifications and non-classification. The supervised classification was improved to obtain maximum accuracy by reclassification and by combining similar classes. Further training classes were incorporated to improve on homogeneous separation of spectral/ground cover classes and on misclassifications and non-classifications.

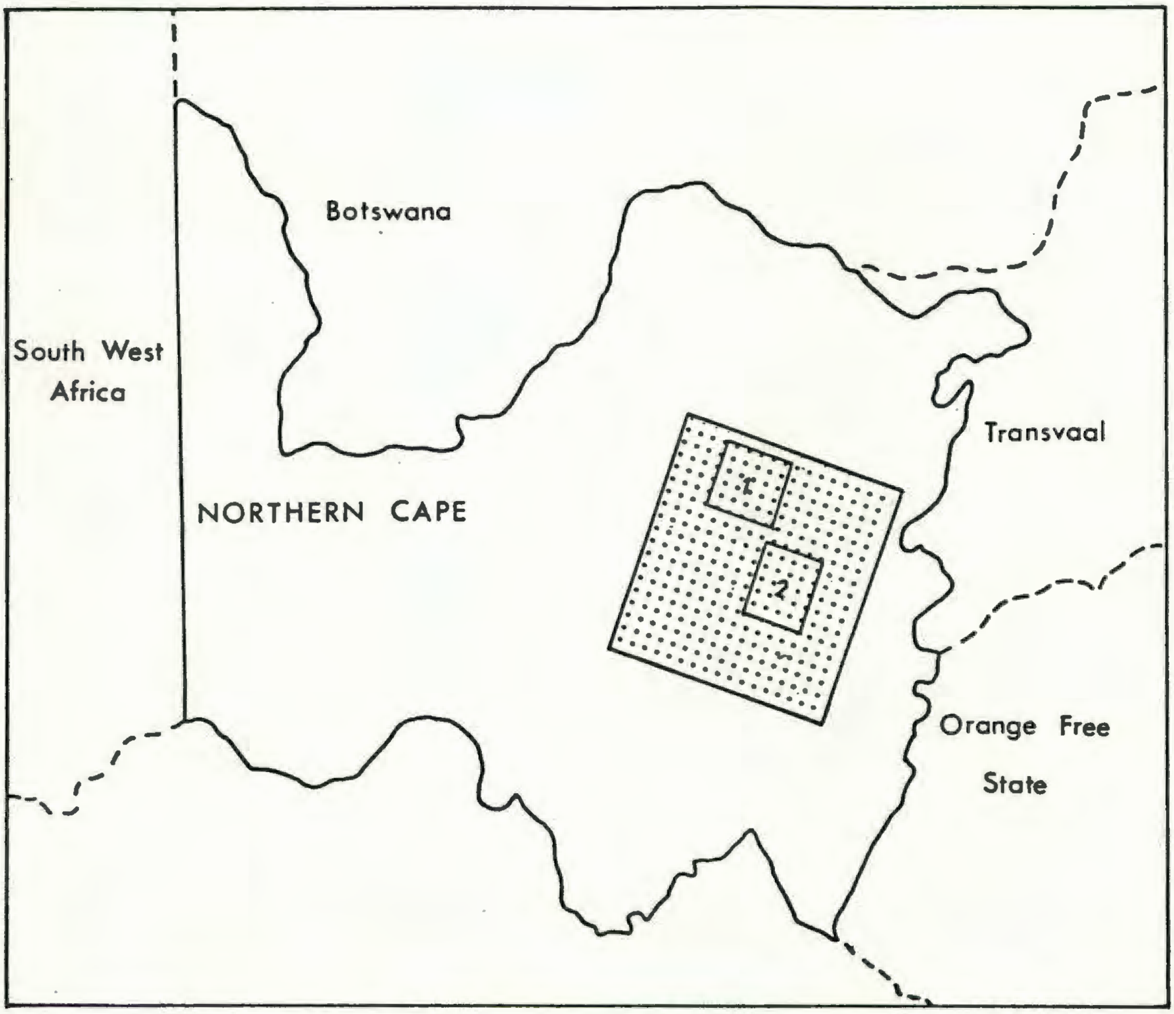


Figure 2 Map of the Northern Cape showing the position of the study area; the ground area covered by Landsat image WRS 185-79. The smaller squares within the study area, numbered 1 and 2, depict the Kalahari Thornveld and Ghaap Plateau Training Areas respectively.

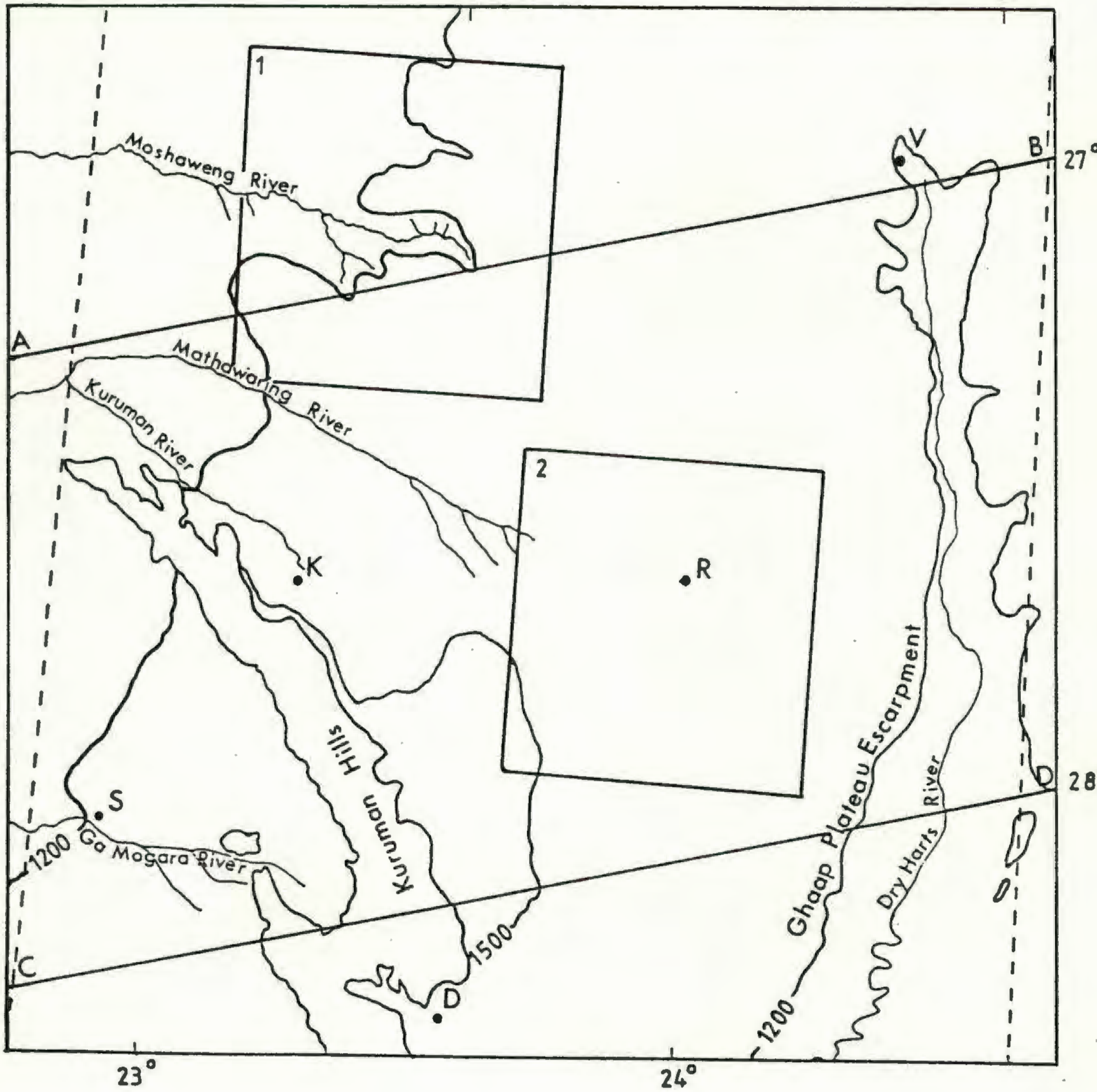


Figure 3 Map of the simplified terrain morphology of the study area. The two squares depict the positions of the Kalahari Thornveld (north) and Ghaap Plateau (south) Training Areas.

Classification accuracy was constantly related to ground reference data, the prepared vegetation map and supportive information maps. At this stage no aerial photographs were interpreted as they had been investigated in detail during the preparation the vegetation map.

Thirty-five millimetre photographic colour transparencies were used to record the various stages and the results of the classifications of the training areas. No line printer map was produced.

Owing to the problems with the supervised classification, as elucidated in section 4 below, the unsupervised classification technique was investigated. Only the Ghaap Plateau Training Area was investigated using this technique. In the pre-processing of this training area, spatial masking of part of the area was undertaken to exclude data belonging to a separate ecological region not required for the testing of automatic machine processing and classification of MSS digital data sets. After the masking operation was performed only ground cover types representing the Ghaap Plateau Ecological Region remained in the data set. The clusters/classes derived from this technique are given in Appendix 2.

Upon superimposition of the unsupervised clusters/classes on the displayed colour composite of the training area, it was found that not all spectral variability had been accounted for. Therefore several of the supervised classes/sites were added manually. All cluster sites/class sites were submitted as a single data set and classification by signature extension to the entire training area was performed. As with the supervised classifications, the unsupervised and hybrid classifications were reclassified several times. By means of class colour-coding displayed individually and in combinations on the comtal screen, the accuracy, separation, misclassifications and non-classifications were pinpointed and improved.

Again, thirty five millimetre photographic colour transparencies were used to record the various stages and results of the classification of the training area.

4. SUPERVISED CLASSIFICATION: KALAHARI THORNVELD TRAINING AREA

The Kalahari Thornveld Training Area is undulating and is dominated by red Kalahari aeolian sands. The vegetation is dominated by open to closed woodland types. The methods used in classifying the training area are discussed in Paper 1. Fig. 4 shows the terrain morphology and Fig. 5 the vegetation-landscape units. Table 1 gives detailed descriptions (ecological regions, vegetation units, plant associations, dominant species, physiognomic/structural unit descriptions, primary soils and geological parent materials and terrain morphological characteristics) of each of these "resource" classes (ground cover units) in the training area. Furthermore, the layout of Table 1 is such that the "resource" classes are given an hierarchical structure. It is evident that there is not a great amount of diversity in the training area. It is important to note which ground cover units belong to which ecological regions. Plate 1 shows the training area as it appears in the Landsat image. Plate 2 shows the pictorial display of the final computer-generated supervised classification of the Kalahari Thornveld Training Area.

Initially, seventeen discrete training classes were selected and signaturized for classification of the training area. The overall result of the signature extension classification was unacceptable, with the majority of ground cover classes classifying as two to several, mixed spectral classes; the classes were indiscrete. To improve this initial classification, a further four training classes were selected and signaturized. The training classes are listed in Appendix 2. A slight improvement resulted but the classification was far from ideal. From this result, it was concluded that a considerable amount of time, effort and finance would be required to secure a significant improvement in the classification, so no further attempt was made.

At this stage, it was decided that an in-depth comparison between and interpretation of the vegetation-landscape map units produced by conventional means and the computer-generated spectral units was called for, with an accompanying accuracy/evaluation assessment.

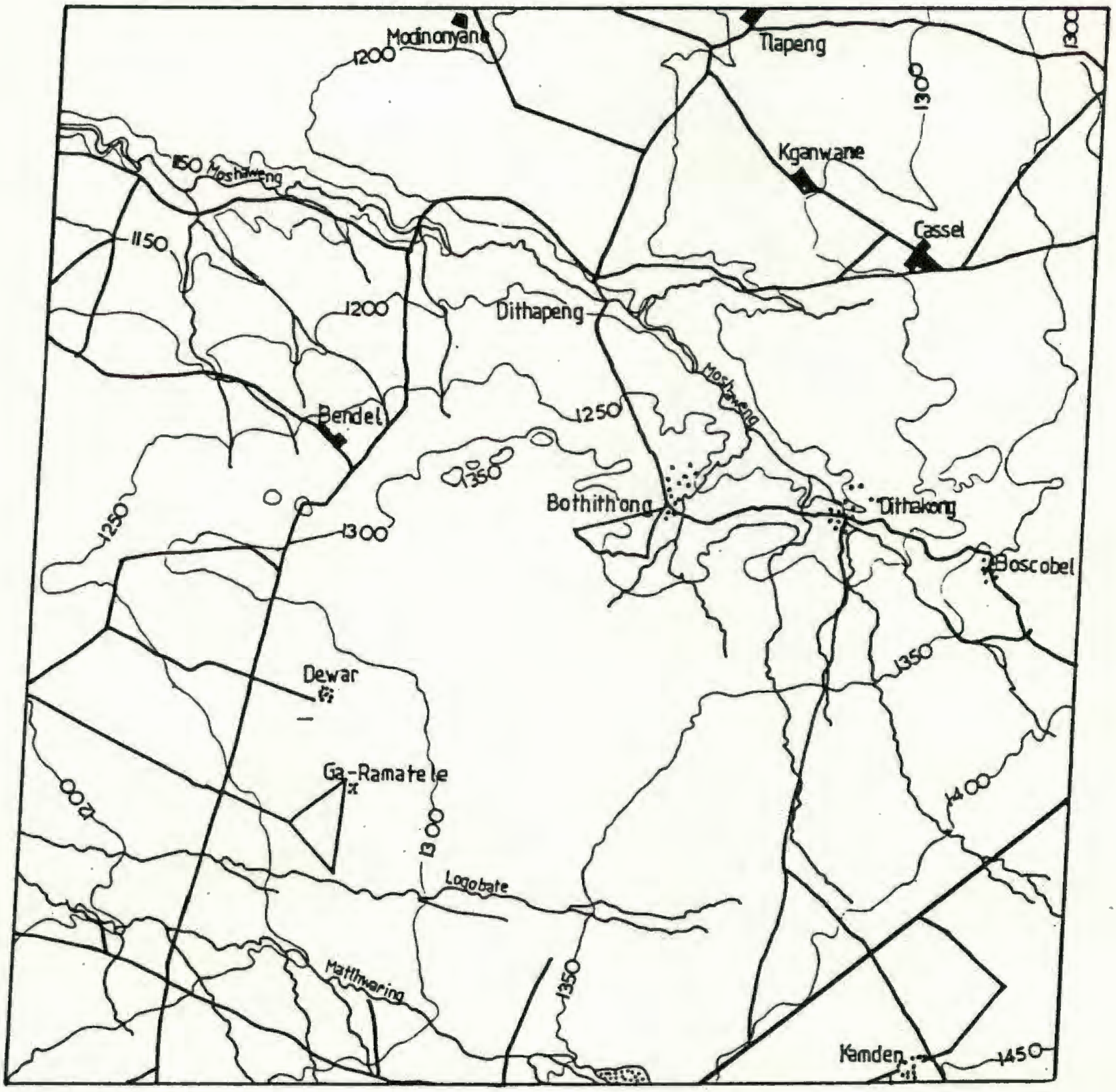


Figure 4 Map showing the detailed terrain morphology of the Kalahari Thornveld Training Area.

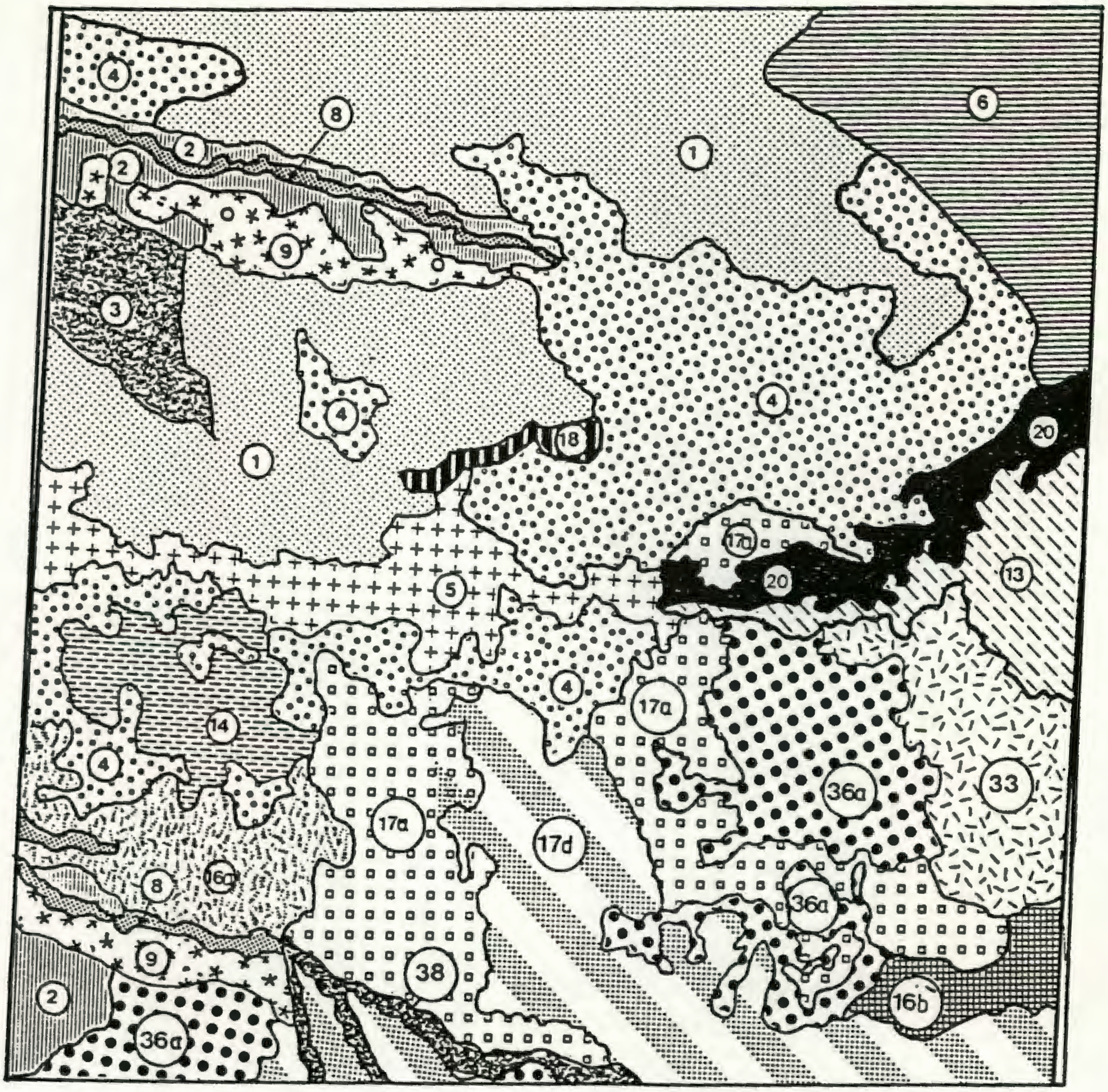


Figure 5 Map showing the vegetation-landscape units (V-L's) in the Kalahari Thornveld Training Area. The alpha-numeric codes refer to the vegetation-landscape units, which are described in Table 1.

TABLE 1 : DESCRIPTIONS OF THE VEGETATION - LANDSCAPE UNITS PRESENT IN THE KALAHARI THORNVELD TRAINING AREA

UNIT NO	ECOLOGICAL REGION	VEGETATION TYPE	FORMATION CLASS	SOIL-GEOLOGY	TOPOGRAPHY	DOMINANT SPECIES
1	Kalahari	Kalahari Thornveld	short, closed woodland	pink to yellow, deep, base sands	high-lying, gentle extensive slopes	*Terminalia sericea* *Acacia erioloba* *Boscia albitrunca* *Dicrostachys cinerea* *Grewia retinervis* *Rhus tenuinervis*
2	Kalahari	Kalahari Thornveld	low, open woodland	pale pink, deep, base sands	lower slopes and low, undulating "dunes"	*Acacia haematoxylon* *Acacia erioloba*
3	Kalahari	Kalahari Thornveld	low, open to intermediate woodland	pale pink to yellow, deep, base sands	low-lying, gentle, extensive slopes (undulating)	*Acacia haematoxylon* *Terminalia sericea* *Acacia erioloba*
4	Kalahari	Kalahari Thornveld	short, open to sparse woodland	deep, red, base sands - quasi-alluvium (immature)	plains and gentle, extensive slopes - partial alluvium	*Acacia erioloba* *Acacia haematoxylon* *Tarchonanthus camphoratus* *Grewia flava* *Lycium hirsutum*
5	Kalahari	Kalahari Thornveld	short, open to closed woodland	red, base sands overlying quartzite	high rounded hills	*Acacia erioloba* *Acacia mellifera* *Ziziphus mucronata* *Grewia flava* *Dicrostachys cinerea* *Terminalia sericea*
6	Kalahari	Kalahari Thornveld	short, closed woodland-thicket	red to pink, base sands	plains	*Acacia erioloba* *Tarchonanthus camphoratus* *Grewia flava* *Lycium hirsutum*

UNIT NO	ECOLOGICAL REGION	VEGETATION TYPE	FORMATION CLASS	SOIL-GEOLOGY	TOPOGRAPHY	DOMINANT SPECIES
8	Kalahari	Kalahari Thornveld	low, sparse, grassy woodlands	pink, calcereous sands and soils overlying calcrete (occ. low, calc. banks)	wide, dry riverbed	Acacia haematoxylon Acacia hebeclada Acacia erioloba Diospyros lycioides Acacia karroo Lycium hirsutum Kalahari grass species
9	Kalahari	Kalahari Thornveld	low, closed, shrubby woodland	shallow, red, base sands overlying calcrete (occ.) conglomerate, high-level gravels and calc. spurs	low-lying uneven slopes	Acacia mellifera Tarchonanthus camphoratus Acacia erioloba Acacia haematoxylon
14	Kalahari	Kalahari Thornveld Ecotonal Woodlands	short, open to intermediate woodlands (with some shrubs in understory)	red, base sands overlying calcrete (and dolomite BR)	gentle slopes and plains	Acacia erioloba Acacia mellifera Tarchonanthus camphoratus
13	Kalahari-Ghaap Plateau Watershed	Kalahari-Ghaap Plateau Watershed Ecotonal Shrublands	high, closed, woody shrublands	eutrophic red soils overlying andesite lava and occasional quartzitic hills (exposed)	plains and scattered, low hills	Tarchonanthus camphoratus Acacia erioloba Acacia karroo Grewia flava Rhus ciliata Ehretia rigida Lycium hirsutum Ziziphus mucronata
18	Kalahari-Ghaap Plateau Watershed	woody, hill shrublands	tall, closed woody shrublands interspersed with high-lying grasslands	shallow, red sands and loamy sands, overlying porphyritic granite (rarely exposed)	steep hills	Dicrostachys cinerea Tarchonanthus camphoratus Euclea undulata Rhus tenuinervis Rhus ciliata Grewia flava Ziziphus mucronata Several Kalahari graminoid species

UNIT NO	ECOLOGICAL REGION	VEGETATION TYPE	FORMATION CLASS	SOIL-GEOLOGY	TOPOGRAPHY	DOMINANT SPECIES
20	Kalahari-Ghaap Plateau Watershed	woody, hill shrublands	short to high closed, woody shrublands and shrubby woodlands	shallow, red soils with exposed andesite lava and porphyritic granite rocks and boulders	rugged hills	*Tarconanthus camphoratus* *Acacia tortilis* *Acacia robusta* *Vangueira infausta* *Acacia karroo* *Grewia flava* *Ehretia rigida* *Rhus ciliata*
17a	Kalahari	Kalahari-Kuruman Sourveld Transitional Grasslands	short, closed, mixed grasslands	shallow, red, base sands over calcrete BR	plains	*Themeda triandra* *Schmidtia pappophoroides* *Stipagrostis uniplumis* *Antephora pubescens* *Eragrosis pallens*
17d	Kuruman Sourveld	Kuruman Sourveld Grasslands	short, closed grasslands	shallow, brown base soils with chert pebbles overlying dolomite BR slabs and v. occ. calc. outcrops	undulating plains	*Themeda triandra* *Enneapogon* spp. *Stipagrostis uniplumis* *Cymbopogon plurinodis* *Elionurus argentius* *Eragrostis lehmanniana*
16a	Kalahari	Kalahari-Ghaap Plateau Mixed, woody transitional shrublands	high, open to closed shrub-	shallow, red sands overlying calcrete BR and occ., raised calcrete faults	gentle slopes and plains	*Tarchonanthus camphoratus* *Acacia erioloba* *Acacia mellifera* *Grewia flava* *Rhus ciliata* *Rhus lancea*
16b	Kuruman Sourveld	Kuruman Sourveld Shrublands	high, open to closed shrublands	shallow, brown, base soils mixed with banded ironstone chips and chert pebbles and occ. exposed dolomite BR	gentle slopes and plains	*Tarchonanthus camphoratus* *Tarchonanthus minor* *Rhus ciliata* *Rhus tridactyla* *Rhus undulata* *Grewia flava* *Lebeckia macrantha*

UNIT NO	ECOLOGICAL REGION	VEGETATION TYPE	FORMATION CLASS	SOIL-GEOLOGY	TOPOGRAPHY	DOMINANT SPECIES
33	Kuruman Sourveld	Kuruman Sourveld Shrublands	high, closed, woody shrublands	shallow, brown, base soils overlying dolomite BR slabs and calc. outcrops	Plains and occ. calc. lineaments (raised)	Tarchonanthus camphoratus Rhus lancea Rhus ciliata Acacia karroo Grewia flava Ziziphus mucronata
36a	Kuruman Sourveld	Kuruman Sourveld Grassy Shrublands	tall, sparse to open grassy shrublands to shrubby grasslands	shallow, red, base sands overlying dolomite BR slabs, interbedded with calcrete and calc. "faults"	plains	Tarchonanthus camphoratus Diospyros lycioides Acacia erioloba Acacia karroo Mixed Kalahari and Kuruman Sourveld grasses
38	Ghaap Plateau	Ghaap Plateau Woodlands (Southern Form)	short, open to closed shrubby woodlands - thickets	shallow, brown soils (frequently absent) overlying calcrete bedrock	gentle slopes (associated with vlei-marshy riverbeds)	Olea europaea ssp. africana Rhus lancea, Rhus ciliata Rhus pyroides Grewia flava Tarchonanthus camphoratus Tarchonanthus minor Euclea crispa Euclea undulata Maytenus heterophylla Ziziphus mucronata Diospyros lycioides Protasparagus laricinus

Plate 1 Photograph of portion of false colour composite Landsat image WRS 185-79 (bands 4, 5 and 7; summer) representing the Kalahari Thornveld Training Area. Originally at a scale of 1: 250 000.

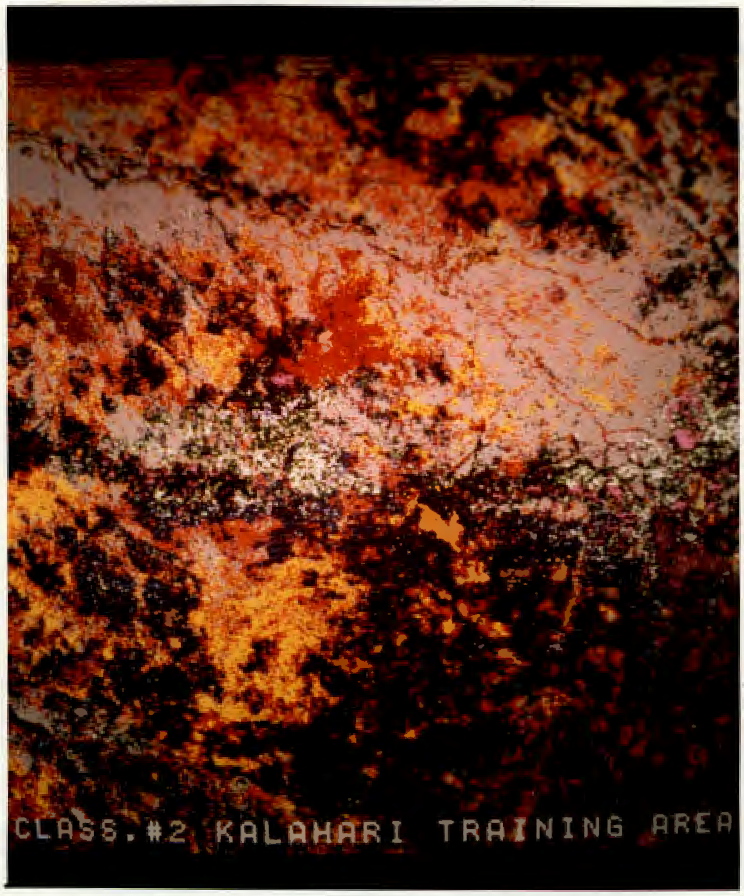


Plate 2 Final computer-generated classification of the Kalahari Thornveld Training Area, using the supervised approach. The colour-codes are interpreted and discussed in section 4.1.

4.1 COMPARISON AND INTERPRETATION

1. The bright red, central area on the computer classified image is a previous season burn which is particularly sensitive to the infra-red and near infra-red portion of the electromagnetic spectrum. This sensitivity is due to the production of new, fast-growing leaves and shoots, especially on *Acacia erioloba* and *Terminalia sericea* in Vegetation-Landscape unit no. 1 (V-L 1). V-L 2 and V-L 9, both in the north-west (NW) and south-west (SW) (colour-coded grey in the computer-generated supervised classification), have been combined, though in the SW they are reasonably distinct. V-L 2 and V-L 9 are interrelated and in the field a gradient between the two units exists (topography, structure and soil type). V-L 2 has a slope angle of 25% and that of V-L 9 is 8%, both sloping towards the dry Moshaweng River in the north and the dry Matlhawaring River in the south. V-L 2 contains pale, pink calcareous sands and V-L 9 red, base sands with areas of pink calcareous sand and the occasional calcrete outcrop. The floristic and structural similarities in the vegetation are evident from Table no 1. It is thus not surprising that V-L 2 and V-L 9 are confused in the computer classification.

2. Of a more serious nature is the confusion and addition of V-L 4 (central, eastern extensive area) to V-L's 2 and 9, though they all still belong to the Kalahari Thornveld Ecological Region. Vegetally, V-L 4 (colour-coded grey) consists of a short, sparse to open, *Acacia erioloba* woodland, individual trees scattered 50 m to 200 m apart in a random but relatively uniform manner (Plate 3). The other shrub and tree species listed are co-dominant, growing largely under the canopy of this species. The sands are more red than those of both V-L's 2 and 9. V-L 4 is an expansive, flat, drainage basin, which in geological time, is not difficult to imagine as the catchment area surrounding higher ground which gave rise to water flowing westwards along the Moshaweng River towards the now dry, deep Kuruman River. There is no doubt that all three V-L's have been shaped by water but today there is not enough similarity to result in any broad grouping. In both V-L's 2 and 4 the grass layer is of considerable importance and in terms of vegetation alone V-L's 4 and 9 contrast dramatically. V-L 9 consists of a low, closed, shrubby woodland, dominated by *Tarchonanthus camphoratus* and *Acacia mellifera* ssp. *detinens*, 1,5 m to 2,0 m. Where the spiny *Acacia mellifera* canopies meet, this formation class is almost impenetrable. Vegetally, there is more similarity between V-L's 2 and 4, but even this confusion is difficult to

Plate 3 Short, sparse to open woodland (V-L 4) on deep, red, base sands. Height 4 - 6 m. Common species: *Acacia erioloba, Stipagrostis uniplumis, Schmidtia pappophoroides, Eragrostis lehmanniana, Aristida* spp.

Plate 4 Short, closed, mixed grasslands (V-L 17a) on shallow, red, base sands overlying calcrete bedrock. V-L 17a is a Kalahari-Kuruman Sourveld transitional grassland, owing to the pedology. Height 0,7 - 1 m. Common species: *Themeda triandra, Schmidtia pappophoroides, Stipagrostis uniplumis, Antephora pubescens, Eragrostis* spp.

understand. With the knowledge of the composition of the ground cover class, an apparently good spectral class is known to be not as accurate as it appears to be.

The remaining areas represented by V-L 4 are colour-coded yellow in the computer classification. The east-west ranging V-L 4 (just below V-L 5) in the centre of the training area, has been confused with V-L 14 (colour-coded blue), a short, open *A. erioloba* woodland, which makes the latter V-L almost structurally identical. However, it occurs on red base sands overlying calcrete and dolomite bedrock (thus transitional to the ecological regions lying further to the south) and is floristically dissimilar enough to stand on its own. This confusion is not altogether unrealistic. Small clusters of pixels colour-coded pink (signature of V-L 1) and grey (signature of V-L's 2 and 9) are also to be found in the area of V-L 4 of this region. V-L's 2 and 9, in the extreme SW corner, remain relatively distinct from each other, though part of V-L 9 here is colour-coded blue and is thus confused with V-L 14.

3. It should be noted that V-L 17a (Plate 4), comprising short, closed (mixed) grasslands (grasslands whose elements are transitional between Kalahari Thornveld and Kuruman Sourveld Ecological Regions), colour-coded yellow, classifies as a reasonably compact spectral class, but is considerably confused with areas of V-L 4 (sparse to open Kalahari woodlands). V-L 17a occurs on red, base sands as well, but which overlie calcrete bedrock. Physiognomically the two are obviously dissimilar except for the intervening grassy areas between *Acacia erioloba* trees, which are structurally the same and floristically very similar. In this case, the combination of the common factors of red base Kalahari sands and importance of grass layers has resulted in sufficiently similar reflectance values for the two dissimilar ground cover units to have the same statistical clustering. With regard to the other V-L's/spectral classes discussed so far, all low-lying or lower slope areas, with Kalahari sands (especially if calcareous in any way), classify out in confusions of various degrees of colour-codes yellow, blue and grey. All Kalahari woodlands associated with dry riverbeds or catchment areas (albeit of geological time-scale) appear as the same spectral class, colour-coded grey. Note that the small area of V-L 4 just to the west of the bright red colour-coded revegetating burn, colour-coded yellow, though floristically belonging to V-L 1, has an artificial structure

and physiognomy almost identical to V-L 4. This is due to the indiscriminate removal of firewood by the inhabitants of a village close by - short, closed woodland artificially changed into a short, sparse to open woodland. It was thus inadvertantly mapped as V-L 4 from aerial photographs and subsequently positively identified during the further collection of ground reference data and interpretation of ground cover classes after computer-generated classifications were produced. This area was left as a patch of V-L 4 to indicate to the reader evidence of the importance of red, base Kalahari sands and the grass layer in the development of the signaturized spectral class recognized as colour-coding yellow (V-L 4 south of the "divide" and V-L 17a).

4. V-L 1 is an area supporting short, closed woodlands on pink to yellow deep, base sands dominated by 4 m to 6 m *Acacia erioloba* and *Terminalia sericea* or mixed *A. erioloba/T. sericea* vegetation types (Plate 5). This V-L is not extensively homogeneous but consists a mosaic of repetitive community types continually grading into one another. Topographically this V-L occurs on high-lying areas, which are more extensive to the north of the training area, with extensive gradual slopes falling off to north and south towards dry riverbeds such as the Moshaweng River. In terms of spectral class signaturization, it is clear from the computer-generated classification that several spectral clusters are required for the area supporting V-L 1. The classified image shows a mosaic of a number of colour-codes, namely pink, yellow, dark blue and grey. The spectral clustering reflects the mosaicism of the V-L unit, mainly in terms of the variations of soil types and projected canopy cover and colour of patches of vegetation ranging between and including two pure vegetation communities, *A. erioloba* woodland and *T. sericea* woodland. To separate out all these variations on a final map product at a scale of 1:250 000, is impossible. Furthermore, there is evidence that the management system/veld condition variability in these areas has played some part in the results of the spectral clustering and confusion on signaturization at the pixel by pixel level. If one accepts this overall, heterogeneous, spectral class group combination, i.e. combination of colour-codes, then the V-L is acceptable as a group of spectral classes. The spectral classes/clusters colour-coded yellow and pink relate to areas on the ground which are dominated by *A. erioloba*, while the dark blue colour-code relates to areas dominated by *T. sericea*. In terms of the computer-generated classification, there is no

Plate 5 Short, closed woodland (V-L 1) on pale pink to yellow, leached sands. Height 5 - 7 m. Common species: *Terminalia sericea* with occasional *Acacia erioloba*, *Boscia albitrunca*, *Grewia retinervis*, *Rhus tenuinervis*. Grasses are poor; *Perostis patens*, *Eragrostis pallens*, *Stipagrostis uniplumis*, *Aristida meridionalis*, *A. congesta* ssp. *congesta*.

Plate 6 Low to tall, open to intermediate woodland (V-L 3) on pale pink sands. Height 3 - 5 m. Common species: *Acacia haematoxylon* with occasional to uncommon *A. erioloba* and *Terminalia sericea* (higher ground), *Eragrostis pallens*, *Antephora* spp., *Aristida* spp. This V-L grades into V-L 2, where the tree species are low.

clear distinction between V-L 6 and V-L 1 and, in parts, V-L 6 and V-L 4. V-L 6 is a short, closed woodland reaching near-thicket proportions in places (Plate 2 in Paper 1), on deep, red to pink, base sands. Structurally, V-L 6 and 1 are very similar, only differing in the importance (density) of the tall shrub stratum in V-L 6. The sands are generally lighter in V-L 1. V-L 1 has *Terminalia sericea* (3 m to 7 m) while V-L 6 has *Tarchonanthus camphoratus*, in similar proportions and in terms of reflectance value both give rise to high reflectance values from the silvery-grey foliage. The confusion between V-L 4 and V-L 6, colour-coded grey, is mostly due to the latter having a high percentage of cleared areas for dry-land agricultural crop production. The grey colour-code would be directly related to the lands either being ploughed so exposing the soil layer, or old lands covered mainly by pioneer stage annual grasses and shrub-like forbs, which result in reflectance values similar to the dominant grass layer and light calcareous sands of V-L 4 (sparse to open *A. erioloba* woodlands).

5. V-L 3, a low, closed *Acacia haematoxylon* woodland (Plate 6), with *Terminalea sericea* and *A. erioloba* as co-dominants, on light pink to yellow, deep, base sands contains characteristics of V-L 1 and V-L 2. This spectral class was signaturized colour-code plum and the spectral cluster for a fair proportion of V-L 3's ground cover area is uniquely classified. Confusion with spectral clusters coded red and grey are for the same reasons as given above. Pixels colour-coded red represent ground cover areas within the *A. haematoxylon*-dominated vegetation where *A. erioloba* is relatively common and *A. haematoxylon* forms an understorey approximately 1,5 m to 2,5 m in height. The grey colour-code represents the northernmost areas of V-L 3 which become transitional to V-L 2, where the *A. haematoxylon* vegetation becomes a more open formation class, the grass layer is of greater importance and the slope towards the dry riverbed becomes increasingly pronounced.

6. V-L 8, the wide, dry, sandy Moshaweng and Matlhawaring linear riverbeds (east-west orientated), are relatively distinct in the computer-generated classification, owing mainly to their linearity and also because they are emphasized by being positioned within the predominantly grey colour-coded V-L's 2 and 9. Colour-codes for the ground cover areas of these two rivers are pink, dark blue and grey. Neither dry riverbed is uniquely, colour-coded and understandably so. The rivers are not perennial and thus

the vegetation does not consist of a uniform gallery forest or thicket. Patches of trees and large shrubs occur sporadically in groups where the seasonal water collects and where the banks are abrupt. The riverbed is incised into the surrounding topography. In places the slopes down towards the riverbed are gentle to almost level (V-L 2) and reddish-pink Kalahari sands have been blown and washed down into the riverbed. The vegetation consists of a low, very sparse *A. haematoxylon* woodland, or pure Kalahari grassland (the extensive, grey colour-coded patches between the linear reds and purples). In places, narrow, incised channels meander across the dry riverbed and are usually lined with *Ziziphus mucronata*, *A. karroo*, *Diospyros lycioides* ssp. *lycioides* trees and large, clumped individuals of *Lycium hirsutum* (2 m to 3 m). Rare outcroppings of granite boulders, 0,45 ha in size, also occur. Where the riverbed is exceptionally wide, it supports an open *A. erioloba* woodland (5 m to 8 m). In areas, especially along the north bank, very steep to steep rounded "ridges" of calcrete, 5 m to 30 m above the riverbed, occur. This broken topography of white calcrete is highly reflective and supports an open, dwarf, shrubby woodland of *Rhigozum obovatum*, *R. trichotimum*, *A. mellifera* and *Boscia albitrunca*. The riverbeds are generally, wide (especially the Moshaweng River in the North), grassy and have scattered large clumps of *A. hebeclada* (1,5 m high, but often 15 m in diameter), with very occasional, low, solitary *A. haematoxylon* trees. The two riverine systems are varied and support several communities generally not mappable at a scale of 1:250 000. The Matlhawaring River is the more densely vegetated of the two systems. The red colour-coding probably relates to the signatures of pixels representing ground cover areas where the vegetation is sensitive to the near-infra-red and infra- red portions of the electromagnetic spectrum, owing to active growth or the fresh greenness of grasslands and *A. karroo* - *Ziziphus mucronata* thickets, especially in damp sites and associated banks along the riverbed. The purple colour-code relates to exposed, highly reflective white calcrete outcrops and steep ridges along the "banks" (similar reflectance values to *T. sericea* and *T. camphoratus* vegetation types, e.g. parts of V-L 1, and V-L's 36a and 33).

7. The elevated topography (hills and ridges) of V-L's 5, 13, 18 and 20, though of several geological formations (quartzites, andesites and porphyritic granites) are reasonably distinct in the computer-generated classification as a colour-coded band of intermingled green and white,

purple with some dark blue in the west (V-L 5) and some grey in the east (V-L 13). This "band" runs east-west across the centre of the training area. This ridge of elevated topography is known by local farmers as the "divide" as it forms a natural boundary with the Kalahari Thornveld Ecological Region to the north and Kuruman Sourveld and Ghaap Plateau Ecological Regions to the south. This ridge also forms a natural watershed, with low rainfall (325 mm p.a.) in the Kalahari to the north and higher rainfall (412 mm p.a.) to the south. The western half of the "divide" shown in the training area (most of V-L 5) has areas where Kalahari sands have blown against and over the ridge so that the parent rock is occasionally covered by a mantle of aeolian sand (predominantly purple colour-coded in the computer-generated classification). The further west one travels along the "divide" the more frequent and deeper this windblown sand becomes; hence the presence of a sandy substrate of progressive depth in V-L's 4, 14, 17a and 16a, on the southern side of the "divide". V-L's 5 and 20 are similar over large sections of their ground distribution in the computer-generated classification and are colour-coded a speckled mixture of green and white. This is surprising as V-L 5, where not covered by deep, reddish Kalahari sands, consists of a substrate of a thin mantle of red, base Kalahari sands overlying quartzite bedrock (sometimes exposed as outcroppings on the steep northern side of the ridge), while V-L 20 consists of a substrate of red, shallow, loamy soils between exposed andesite lava rocks and stones and occasional outcrops of porphyritic granite rocks and boulders. Structurally and floristically, the vegetation of V-L 5 consists of a short, open to closed woodland; typical tree and larger shrub species are *A. erioloba*, *A. mellifera*, *Ziziphus mucronata*, *Grewia flava*, *Dichrostachys cinerea* and *Terminalia sericea*, (the latter often in intermediate to closed woodland clumps). Structurally and floristically the vegetation of V-L 20 consists of a short to high, closed, woody shrubland; typical large shrub and tree species are *Tarchonanthus camphoratus*, *A. tortilis* ssp. *heterocantha*, *A. robusta*, *A. karroo*, *Grewia flava*, *Ehretia rigida* and *Rhus ciliata*.

These two vegetation units are decidedly different except in terms of elevation and, to a degree, exposed "hard" geology. V-L 13 is a plain, widening considerably to the east, but is frequently broken by scattered hills and ridges. In areas the topography is considerably depressed, giving the effect of a shallow valley between V-L 20 in the north and V-L's 36a and 33 in the south. The plains and "valleys" are often stony with exposed andesitic lava rocks bedded in eutrophic, red soils; the hills and ridges are mainly covered by large andesitic rocks. The southern border of V-L 13 sometimes consists of low quartzite hills and ridges. While there is an obvious relationship between V-L 13 and V-L 20, especially in the low, rocky hills and ridges, V-L 13 is a mosaic of vegetal, soil, geological and topographical units which would be more accurately portrayed at a larger scale of investigation. In the computer-generated classification V-L 13 is colour-coded grey, purple and intermingled white and green. The similarity between V-L 13 and V-L 20 has been alluded to above; both areas are closed woody shrublands with several, common, dominant species (canopy colour grey-green). Andesitic lava hills and ridges and stony plains with moderate percentages of exposed geology occur in both. This results in the intermingled white and green colour-code of V-L 20 also occurring in the central areas of V-L 13. The purple colour-code relates to ground cover terrain of V-L 33, also structurally a high, closed woody shrubland. The soils of V-L 33 are very different but are mostly hidden by the vegetation. Several of the dominant species are common to both V-L 13 and V-L 33, though the structure and colour of canopy foliage is probably more accountable for the confusion in the classification than any other parameter; *Tarchonanthus camphoratus* with its grey-white foliage, is the dominant species in V-L's 13 and 33, and co-dominant tree species in both V-L's (especially *Acacia's*) give rise to a scattering of dark green foliage in the dominant grey-white canopy layer.

The grey colour-code of the computer-generated classification relates to ground cover terrain in V-L 13 which supports rounded, smooth quartzitic hills, often covered with red, eutrophic soils. In the interpretation of V-L's 1, 2, 4 and 9, it was noted the grey colour-code dominated the computer-generated classification of sparse to open woodlands, where the grass layer is of major importance. This is true of the quartzitic hills of V-L 13, where the grass layer is again of importance with only a scattering of shrub and tree species such as *Vangueria infausta*, *Acacia robusta* and *Pavetta zeyheri* on rocky outcrops, while on the gently sloping, southern side where the soil is deeper, *Acacia erioloba* and *Terminalea sericea* form a sparse woodland. The grey colour-coding of these communities is due to the grassiness of the vegetative cover and possibly, the red eutrophic soils. Certainly the exposed quartzitic rock will add little to the reflectance of this terrain owing to the minimal area (small, occasional outcrops) and the cover of those shrubby species mentioned above.

8. V-L 18, abutting the southern boundary of the burn, is hardly noticeable in the computer-generated classification. It is colour-coded a mosaic of intermingled green and white, dark blue and grey. V-L 18, which consists of tall, closed, woody shrublands, interspersed within high-lying grasslands (Plate 7 in Paper 1), is a rounded, east-west orientated ridge of porphyritic granite, mainly covered with a shallow layer of red, base Kalahari sands. The drop to the north (and the Kalahari Thornveld Ecological Region) is often precipitous and here the granite is exposed; to the south the topography consists of gentle, extensive, sand-covered slopes not dissimilar to those quarzitic hills of V-L 13. The vegetation of the exposed porphyritic granite hills consists of woody shrublands, dominant species being *Euclea undulata*, *Rhus tenuinervis*, *Grewia flava*, *Dichrostachys cinerea* and stunted *Acacia erioloba* and *Ziziphus mucronata*. Grasslands consist of typical Kalahari species, viz. *Anthephora pubescens*, *Schmidtia pappophoroides*, *Eragrostis lehmanniana*, *Stipagrostis uniplumis*, *Aristida congesta* ssp. *congesta*, *A. meridionalis* and *Eragrostis pallens*, with very widely scattered *Acacia erioloba*. It is difficult to establish precisely where V-L 18 becomes V-L 4 to the south because the two grade into each other as the Kalahari sand overburden increases in depth.

It is evident from the discussion of V-L's 5, 13, 18 and 20 (belonging to the single landscape unit "elevated hills and ridges") that the units are more based on elevated landscape attributes than vegetal ones. This is borne out by the computer-generated classification which shows some consolidation in the general east-west orientated spectral classes. The classes show strong mosaicism in the colour-coding, which relates to the complexity of the ground cover classes, especially the vegetal-soil attributes, where each landscape unit (V-L's 5, 13, 18 and 20) consists of a number of major plant communities often decidedly different from each other in structure and floristics and which cannot easily be mapped at a reconnaissance scale of 1:250 000. There is no doubt that the elevated hills and ridges of the linear "divide" can stand on their own as a landscape unit constituting a linear feature running east-west and forming a natural boundary between the Kalahari Thornveld Ecological Region to the north and Kuruman Sourveld and Ghaap Plateau Ecological Regions to the south. This landscape unit can be divided further into a number of subunits based on geology (where this geology is exposed) and partly on vegetal attributes. This unit can be subdivided further on a third level based purely on vegetal structure and floristics (colour and % Projected Canopy Cover (PCC)) related to complexities in the soil-geology complex, the presence and depth of Kalahari sands, the aspect and slope (too detailed and patchy to be shown at a scale of 1:250 000). The computer-generated classification, based on the reflectance values originating from each picture element (pixel) of 0,45 ha, reflects all three of these levels of complexity; no single attribute dominates the classification throughout the landscape unit, and key attributes change with (a) level of classification and (b) scale of investigation.

V-L 14, a short, open woodland on red, base Kalahari sands, 1 m to 2 m deep, overlying calcrete and dolomite bedrock, supports widely scattered dominant species such as *Acacia erioloba*, *A. mellifera* ssp. *detinens* and *Tarchonanthus camphoratus* in an important grass layer. V-L 14 occurs on gently south-sloping featureless plains. In the computer-generated classification, this ground cover class is largely colour-coded blue and is thus confused with parts of V-L 4 (in centre west of training area, just below V-L 5, and northern areas of V-L 36a). Without a doubt, as with many of the V-L's just south of the "divide", this V-L is ecotonal or transitional to the Ghaap Plateau or Kuruman Sourveld Ecological Regions (calcareous soils, calcrete, chert and dolomitic soils and bedrock areas), and hence some dark blue colour-coding of the V-L group 17d, 16a, 16b and 36a. The presence of the Kalahari sand overburden, however, results in a strong Kalahari element. Confusion with the spectral class V-L 4 is due to the Kalahari sands and similarity in structural attributes; trees and large shrubs are generally more widely scattered (grass layer is of greater importance) and the Kalahari sands are deeper. The difference between V-L 36a (tall, sparse to open grassy shrublands to shrubby grasslands) and V-L 14 is greater - mainly in terms of the vegetation. The soil/geology complex is very similar but the Kalahari sands are very shallow at 300 mm or less. The thin covering of Kalahari sand results in the dominant (PCC) grass layer being a mixture of Kalahari and Kuruman Sourveld species. The most important and dominant shrub species is *Tarchonanthus camphoratus*. V-L 14 and V-L 36a are physiognomically quite different but the similarities in the presence of a strong grass layer and Kalahari sands at the the surface result in reflectance values being sufficiently similar for the two spectral classes to be confused, especially in the north of V-L 36a where the similarities are at their greatest.

10. V-L 17a (western distribution) is a short, closed, mixed Kuruman Sourveld grassland on shallow, red, base sands, overlying pure, crumbly, calcrete bedrock (an even stronger Kalahari grass element than shown in Plate 4). This ground cover unit is largely colour-coded yellow in the computer-generated classification. The southern areas are not as clear; the considerable amount of dark blue with the yellow makes the classification of this area confusing. The dark blue colour-code is that of a second grassland type, viz. V-L 17d, a pure Kuruman Sourveld grassland. That the computer-generated classification has distinguished between these two grasslands to such a degree is remarkable. This southern area is not as pure as the rest of V-L 17a; it is more transitional to V-L 17d with respect to the grass species and has a wide scattering of trees and large shrubs of the species typical of V-L 16a, but not in the same density. The influence of the Matlhawaring river in this area is obvious. The computer-generated classification reflects the real-world situation accurately. In terms of clarity, V-L 17a (eastern distribution) is not as successfully classified as V-L 17a (western distribution). Much of its area is colour-coded red instead of yellow. On the ground, V-L 17a (eastern distribution) is largely juxtaposed with patches of V-L 36a and it is probable that this has affected its identification, resulting in the classification of these areas as V-L 1. That V-L 17a (eastern distribution) has been successfully separated from V-L 36a in the classification is pleasing, but that much of its ground cover should be confused with V-L 1 is disturbing. This indicates a confusion between grasslands and sparse woodlands. Both plant communities belong to the same vegetation type, based on a complex of environmental parameters and not just vegetative structure and/or floristics. If this were based on structure and/or floristics (foliage colour) alone, the two grasslands V-L's 17a and 17d would surely have been confused in the classification.

11. In terms of the computer-generated classification, V-L's 16a, 16b, 17d and 36a can be discussed together, for all these ground cover units are classified as the same spectral class, colour-coded dark blue and are not clearly separable. V-L's 16b, 17d and 36a all belong to the Kuruman Sourveld Ecological Region while 16a belongs to the Kalahari Thornveld Ecological Region. In terms of vegetation types, there is a gradient in

vegetation-cover density and number of strata, from V-L's 17d (Kuruman Sourveld Grassland) to 36a (Kuruman Sourveld grassy shrublands and shrubby grasslands with a Kalahari element in the grass layer) to 16b (Kuruman Sourveld Shrublands) and finally through to 16a (Kalahari Thornveld-Ghaap Plateau mixed transitional woody shrublands). All have a shallow soil layer overlying calcrete, dolomite, chert and banded ironstone chips, usually more than one, and most commonly calcrete and dolomite. These bedrock types are often exposed, especially calcrete. *Tarchonanthus camphoratus* is the dominant shrub, except in V-L 17d (Plate 7). All are extensive plains and/or gentle slopes. V-L's 16b and 36a contain occasional linear, raised, calcrete "faults", which usually support tall, closed, woody shrublands (infrequently of thicket proportions). These linear "faults" are obvious in the computer classification from their linear distribution and proportions, and from the colour-code red and yellow (particularly evident against a background of dark blue). In terms of the distribution of these ground cover units, it is difficult to separate V-L's 17d and 36a owing to the frequently small unit size of patches of grassland; very sparse, shrubby grasslands; sparse to open grassy shrublands and open shrublands. In the field V-L's 17d, 36a, 16a and 16b are easily separable. It must be concluded that the soil/geology complex, especially the calcrete and dolomite, has an overriding influence on the spectral reflectance of ground cover classes. One cannot rule out the effect which the dominant shrub *T. camphoratus* (with its striking grey-white foliage colour) has in any confusion which appears between V-L's 16a, 16b, 36a and 33, nor the effect of the important grass layer in V-L's 17d and 36a. Once again one obtains the impression that no single environmental parameter has overriding influence on the reflectance values, but rather that a combination effect is at work, and the parameters of two V-L's may result in reflectance values similar to those obtained from different parameters of the other two V-L's. Moreover, the gradient of reflectance values obtained for several similar or widely differing ground cover units may be well within the acceptable range of reflectance values assignable to a single spectral class (statistical values of a single spectral cluster). In this case, no amount of searching for parameters common to all the ground cover classes will result in an acceptable explanation for their combination in the computer-generated classification.

12. V-L 33 (Kuruman Sourveld shrublands) consists of high, closed, woody shrublands on shallow, brown, base soils overlying dolomite bedrock slabs

Plate 7 Short, closed grasslands (V-L 17d) on shallow, brown, base soils mixed with chert pebbles and overlying dolomite bedrock. Height 0,85 m. Common species: *Themeda triandra, Enneapogon* spp., *Cymbopogon plurinodis, Elionurus argenteus, Digitaria eriantha, Eragrostis* spp.

Plate 8 High, closed, woody shrublands (V-L 33) on shallow, brown, base soils overlying dolomite bedrock. Height 2 - 4 m. Common species: *Tarchonanthus camphoratus, Acacia karroo, Rhus ciliata, R. lancea, Ziziphus mucronata, Grewia flava, Diospyros lycioides* and typical mixed Kuruman Sourveld - Ghaap Plateau grasses.

(Plate 8). Topographically, this ground cover unit consists of plains interspersed with the same raised, linear, calcrete "faults" as in V-L's 16a and 36a. Again *Tarchonanthus camphoratus* is dominant, with co-dominants in the shrub and tree layer being *Rhus lancea*, *R. ciliata*, *Acacia karroo*, *Ziziphus mucronata* ssp. *mucronata*, *Grewia flava* and *Diospyros austro-africana*. This ground cover unit is colour-coded purple and dark blue in the computer-generated classification. The raised, linear "faults" support thickets of *A. karroo*, *Diospyros lycioides*, *Boscia albitrunca*, *Euclea undulata*, *R. lancea* and occasional *Olea europaea* ssp. *africana*, *G. flava* and *Maytenus heterophylla*. It is obvious that there is some confusion in the classification between V-L's 16b and 33; hence the dark blue colour-coding. The purple colour-coding portrays the uniqueness of, or difference between V-L's 16b and 33.

V-L 38 (Plate 9), a short, open to closed, shrubby woodland (to occasional thicket formations), belongs to the vegetation type "Ghaap Plateau Woodland (southern form)" of the Ghaap Plateau Ecological Region and as such, is the only example in the training area belonging to this extensive ecological region better represented further to the south-east. This V-L follows the Matlhawaring River, which here, is little more than a narrow seasonal, Cyperaceae-covered drainage line/marsh with V-L 38 extending from its banks to a kilometer or so either side of it. The soils are dark brown, base soils, very shallowly overlying a soft, crumbly calcrete-type bedrock. Frequently the soils are almost wholly absent, presumably having suffered sheet erosion as this V-L forms the essence of the rainfall catchment area of these important linear, marshy vleis (flowing episodically as "rivers" after good rains). This V-L supports such diverse species as *Olea europaea* ssp. *africana*, *Rhus lancea*, *R. undulata*, *R. pyroides*, *R. tridactyla*, *R. ciliata*, *Tarchonanthus camphoratus*, *T. minor*, *Ziziphus mucronata* ssp. *mucronata*, *Diospyros lycioides*, *Euclea crispa* ssp.*ovata*, *E. undulata*, *Maytenus heterophylla*, *Grewia flava*, *Protasparagus laricinus* and many others of lesser importance. Dwarf shrubs such as *Pentzia calcarea*, *P. incana* and *Walafrida saxatilis*, *Aptosimum* spp. are also of importance, while grasses such as *Themeda triandra*, *Sporobolus fimbriatus*, *Eragrostis lehmanniana*, *Cymbopogon plurinodis*, *Chrysopogon montanus*, *Eragrostis truncata*, *Enneapogon desvauxii* and *E. scoparius* also occur noticeably in this V-L. In terms of the computer-generated classification this V-L is not uniquely colour-coded, and is confused with V-L 33 and the V-L group 17d,

Plate 9 Short, open to closed, shrubby woodlands - thickets (V-L 38) on shallow, brown soils overlying calcrete bedrock. Height 3 - 6 m. Common species: *Olea europaea, Rhus pyroides, R. ciliata, R. lancea, Ziziphus mucronata, Grewia flava, Tarchonanthus camphoratus, T. minor, Euclea crispa* ssp. *ovata, E. undulata, Maytenus heterophylla* and others - a species-rich vegetation type. Grasses are *Themeda triandra, Cymbopogon plurinodis,* several important *Eragrostis* spp., *Chrysopogon montanus, Panicum* spp., *Digitaria* spp., *Fingerhuthia africana, Sporobolus fimbriatus, Enneapogon* spp. In areas V-L 38 forms an attractive *Olea* parkland vegetation type, especially alongside vleis and streams.

36a, 16a and 16b (dark blue) probably in terms of vegetation structure and soil-geology complex. The linear vlei/marsh is confused with V-L's 4 and 17a (yellow and red), probably because of the alluvial soils and dominance of riverbed "grasslands" (Cyperaceae and alluvial graminoids). The restricted area of this vegetation type in the training area, plus the lack of other examples of ground cover classes belonging to this important ecological region most likely prohibited its unique classification. There is no real suprise in the fact that this V-L was largely classified with V-L's 16b and 33 as the two ecological regions, Kuruman Sourveld and Ghaap Plateau, are strongly related to each other in terms of spatial and geographical position, soil/geological formations as well as vegetation structural and floristic parameters.

4.2 COMMENTS

It is obvious from the above discussion of the computer-generated classification that no single V-L is uniquely classified. In general, the computer classification lacks cohesion. There is a basic overall pattern, but the true heterogeneity of the landscape is, in all probability, reflected. This is noticeable in the fact that many of the colour-codes, while representative of specific vegetation-landscape units, are present in varying amounts in any one "homogeneous" spectral class/ground cover unit in the classification. This is evidence that the Landsat MSS digital data represents the total ground-surface environment and not just vegetal cover. It is interesting to note, however, that heterogeneity due to poor vegetation management cannot be detected in the computer classification unless tha change is of a high level.

In the arid and semi-arid regions of South Africa, with a projected canopy cover (PCC) of the vegetation generally below 50% (and often below 25%), 50% to 75% of the MSS data represents other environmental parameters, especially the soil surface. In the Kalahari, it is assumed that the higher the level of reflectance from the sand, the lower the grass cover. Low grass cover indicates a degree of change. Low-lying, compacted, calcareous sands, however, naturally support low grass cover and naturally reflect at higher levels. This type of interpretation is difficult from computer classifications, even with a good ground knowledge of the area.

The spectral data captured by the sensors on Landsat represent surrogate data in the form of outgoing (reflected) radiation from terrain features and the atmosphere. A correlation between these environmental parameters (one to several, as the case may be) and the Landsat spectral data must be shown. Unlike manual studies, this sequence of interpretation is difficult with the collage-like, computer-generated product. The requirement of adequate ancillary ground reference data and aerial photography (preferably in combination) is emphasized. Even this correlation is not adequate for the production of vegetation maps and classification schemes. There must also be a strong correlation between field measured parameters and vegetation units, i.e. vegetation units and environmental parameters such as soil, geology, topography and climate. This correlation is generally accepted as factual. In the arid to semi-arid regions there is good correlation; the environmental parameter which has the greatest control over the vegetation's abilty to develop in a given area, is dependent on the scale of investigation, e.g. biomes and climate; ecological regions and soil-geology complex; major plant communities on a combination of soils and topography.

The resolution of the Landsat sensors is 57 m X 79 m (pixel or picture element dimensions). For each resolution cell of ground cover a single reflectance value is recorded which is a mean value of that ground cover area of about 0,45 ha, regardless of its homogeneity/heterogeneity. Any given 0,45 ha area of ground cover consists of a mosaic of soil- geology patches, grass patches, trees and large shrubs, shadows, etc. either singly or as stratified combinations. The final reflectance value per pixel is dependent upon the structure of the ground cover and, most important, whether this intrinsic pattern falls within the pixel element size or not. (This aspect is discussed in detail in section 7.) If the intrinsic patterns are small, of several types and highly repetitive, then the mean reflectance values of the pixels representative of the ground cover unit/class will be very similar, making for an accurate computer-generated classification, e.g. V-L 17a and the area of V-L 1 completely destroyed by fire (and, therefore extremely homogeneous in its lack of structure). Unfortunately what vegetation ecologists refer to as homogeneous portions of vegetation (those hierarchical classification units referred to as vegetation types in vegetation maps of various scales and spatial geographical areas) are for the large part not homogeneous, but are what has previously been referred to here as portions of vegetation of minimal heterogeneity. Vegetation ecologists tend to reduce the intrinsic pattern of the ground cover by placing a boundary around an area of vegetation and referring to that portion of ground cover by means of a binomial name. This gives the reader a false impression of homogeneity which is seldom borne out in nature. Acceptable limits to which this may apply are dependent on the scale of investigation, survey and map product and the natural diversity and complexity of the soil-geological types, topography, climate, etc., and thus the vegetation.

In the Northern Cape boundaries between vegetation units at a reconnaissance scale of investigation (1:250 000 mapping scale and 1:50 000 field survey scale) are relatively abrupt, while within each vegetation unit a gradient from the centre to the edge usually exists. Thus vegetation units, while considerably uniform over large areas (as is usually the case in arid and semi-arid regions) are not without internal variation. This internal variation may take on several forms within the linear, "homogeneity to heterogeneity" scale. Theoretically the most difficult concept to assess with Landsat MSS data is that of the environmental continuum or gradient. The concept of mosaicism has been introduced previously and will be highlighted in the discussion of the Ghaap Plateau Training Area (section 5 of this paper).

In the Kalahari Thornveld Ecological Region, continual and gradual internal variation from the centre to the edge of vegetation-landscape units is typical. The continuum is primarily indicated by changes in species composition and cover abundance. The degree to which this internal variation affects the reflectance recorded by the Landsat sensors is not known, though there certainly must be some effect. The colour-coded classification does not display within-class variance, nor the existence of gradients (Jupp & Mayo 1982). Mosaicism can be allowed for in the signaturization of training sites, but the concept of environmental continuum is much more difficult to cater for. Possibly a transect of several signature sites across a vegetation-landscape unit should become a more common practice; a training site is usually a quadrat placed in the centre of the "homgeneous" spectral unit. Worcester & Dalsted (1980), using Landsat MSS data, successfully tested the continuum concept in relation to arid and semi-arid soils. Under these conditions, the soil background accounts for most of the spectral reflectance. This concurs with the findings of Ezra *et al.* (1984) and

Horvath *et al.* (1984). The vegetation is sensitive to soil change, supporting the applicability of the continuum concept in the Kalahari Thornveld Training Area.

The internal variation affects the computer-generated classification at two levels: at the "within pixel" level and the "between pixel" level (section 7 of this paper). The latter occurs when the intrinsic patterns in the vegetation unit are larger than the resolution cell dimensions (0,45 ha) resulting in only a portion of that pattern falling within any given resolution cell. This situation results in computer classifications lacking unity or cohesion and so contrasting with thematic maps produced using conventional methods and/or false colour composite (FCC) imagery.

In several areas, the finer detail of the distribution of V-L's can be improved by reference to the computer-generated classification. This is not to say that slight changes in boundary positions are made simply because small patches in the computer classification are added or subtracted from one unit and added or subtracted to adjacent units. Where a discrepancy occurs, these areas must be checked by referring to recorded ground reference data (where available at that larger scale) or reassessed in the field. This type of "change" is also obvious on the false colour composite image; when drawing a boundary between two units, it is doubtful whether many small areas should be included or excluded from a unit. The hardcopy image and the computer-generated classification are frequently correct in their designation, either through direct interpretation of hue/texture/pattern relationships (hardcopy image) or by colour-coding (computer-generated classification). Often these small-area discrepancies (usually 10 km^2 or less) are well within the geographic boundaries of other V-L's, e.g. patches of woodland within a sparse, high shrubland and pans, and their mapping is impossible at the reconnaissance level.

Frequently the hue/texture/pattern and colour-coding has resulted from the dominance of only one of the environmental parameters, e.g. soil colour and not vegetation structure and/or floristics (canopy cover and colour), making it similar to another resulting from, say, vegetation structure and soil type together. In this case the similarity, e.g. yellow colour-coding, is false. If the yellow colour-coding relates to pans supporting sparse to open *Acacia* woodland on pink aeolian sands in its major distribution, it does not necessarily follow that all the small yellow colour-coded fragments scattered throughout the computer-generated classification belong to the same V-L, although this may be true for a good percentage of them. This does not change the fact that, in most cases, where there is a change in colour-coding, albeit small fragments, these fragments are different from each other in one to several environmental parameters. The investigator must decide on whether the change warrants an alteration of the V-L map product, always bearing in mind the scale of survey, classification and final map product, the aims and objectives of the investigation and especially the identity of the users for which it is meant. Where the fragmentation occurs close to the boundary, the researcher must make a decision on possible inclusion and thus, an extension of the boundary, provided the fragments meet the classification requirements of the unit in question.

It was concluded that the existing V-L map of the Kalahari Thornveld Training Area could be improved slightly in several areas. This was a direct consequence of the computer-generated classification which acted as a necessary reminder of the true heterogeneity of the natural landscape and that the field surveys only sample a small portion of what the Landsat sensors record in full.

5. SUPERVISED, UNSUPERVISED AND HYBRID CLASSIFICATIONS: GHAAP PLATEAU TRAINING AREA

The Ghaap Plateau Training Area consists of a number of soil types and is dominated by calcretes and dolomites. The topography is flat (Fig. 6), but is intersected by numerous lineaments. The prepared Vegetation-Landscape map of the Ghaap Plateau Training Area (Fig. 7), shows the spatial and geographical distribution of ground cover units/classes based on field surveys, aerial photographs, supportive information maps and visual interpretation of a false colour composite Landsat hardcopy 1:250 000 image. Table 2 gives detailed descriptions (ecological regions, vegetation units, plant associations, dominant species, physiognomic/structural unit descriptions, primary soils and geological parent materials and terrain morphological characteristics) of each of these "resource classes" (ground cover units/classes) present in the training area. The "resource classes" are given an hierarchical structure. Plate 10 shows the Ghaap Plateau

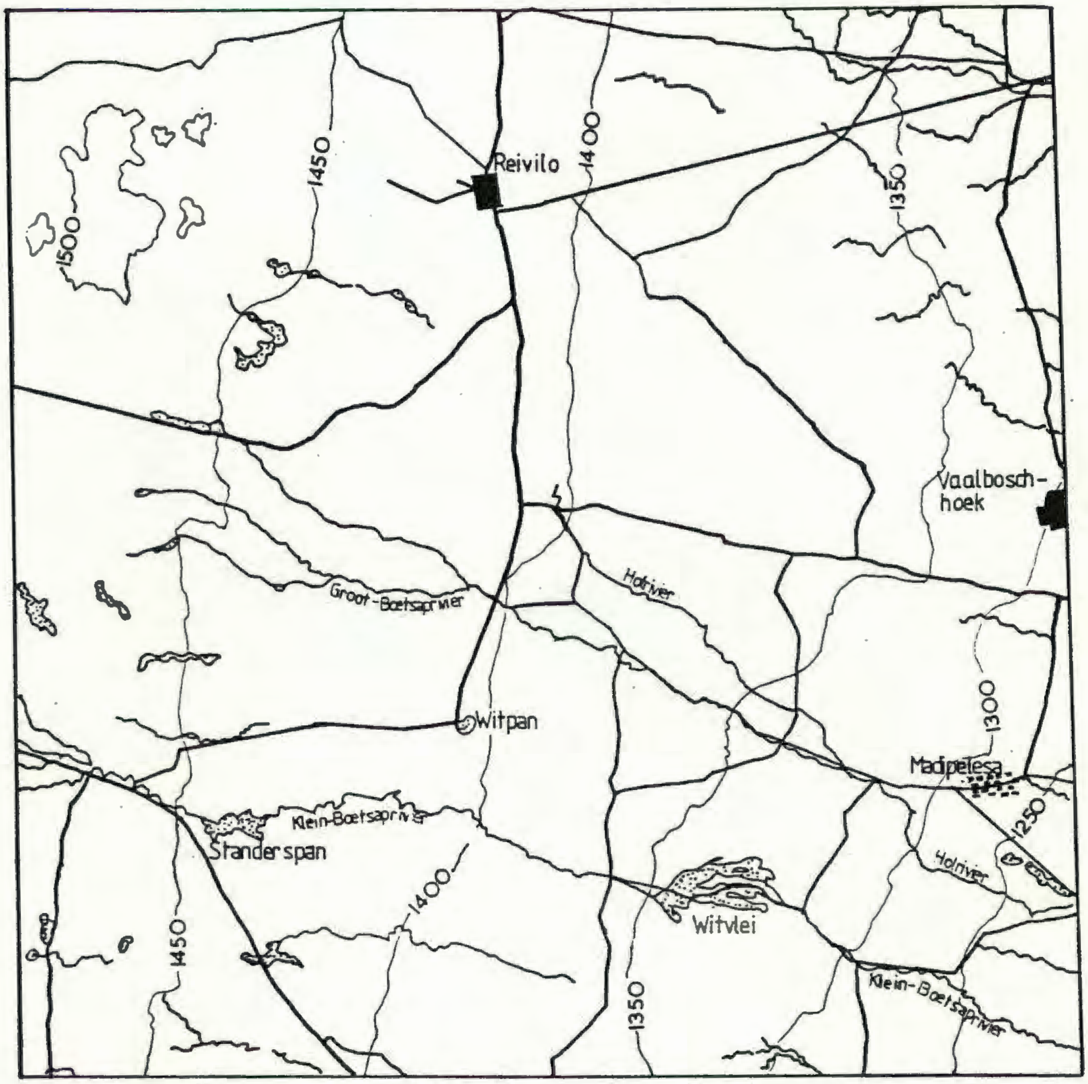


Figure 6 Map showing the detailed terrain morphology of the Ghaap Plateau Training Area.

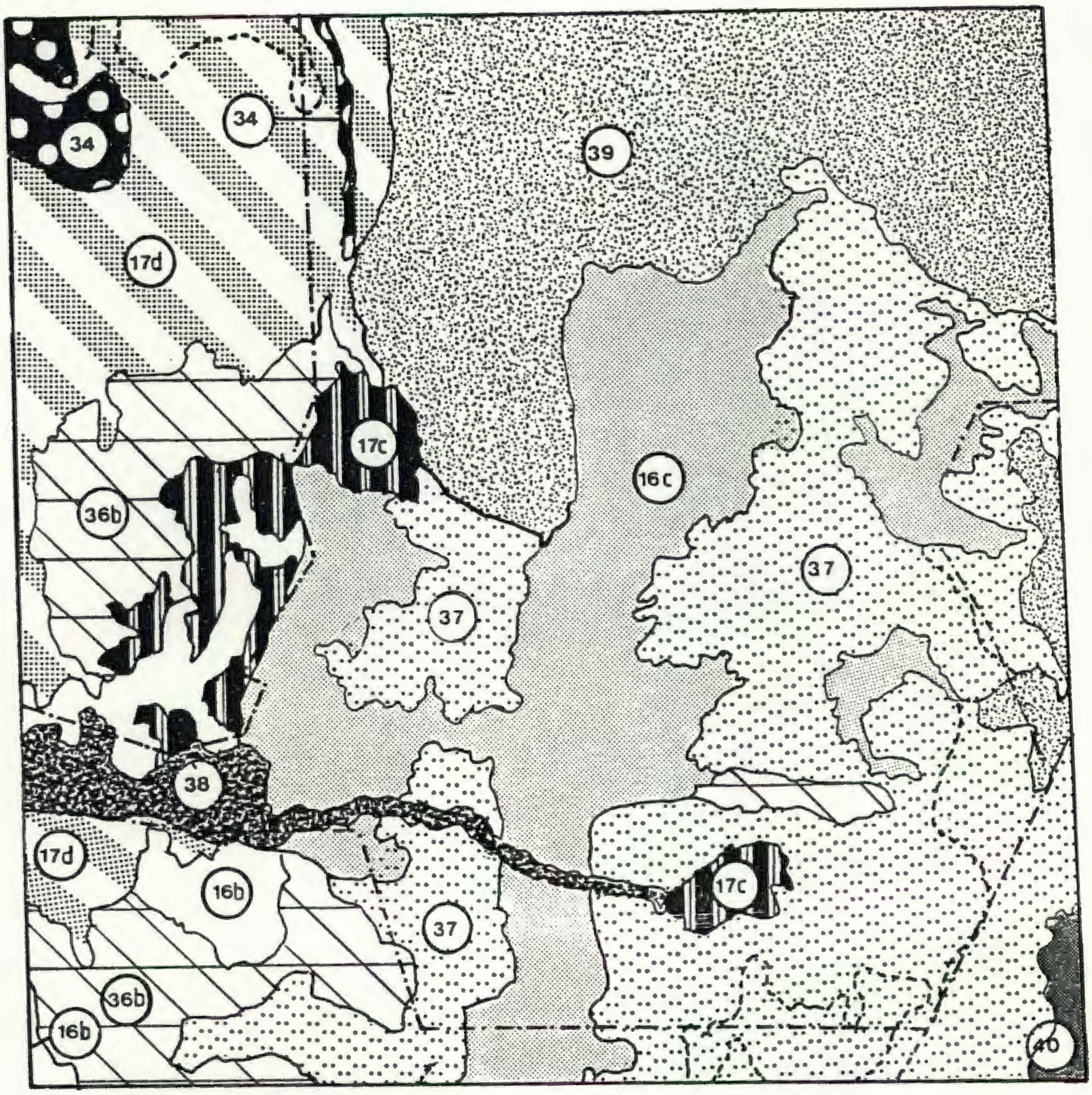


Figure 7 Map showing the vegetation-landscape units (V-L's) in the Ghaap Plateau Training Area. The alpha-numeric codes refer to the vegetation-landscape units, which are described in Table 2. The dotted line shows the area omitted during classification.

TABLE 2 : DESCRIPTIONS OF THE VEGETATION - LANDSCAPE UNITS PRESENT IN THE GHAAP PLATEAU TRAINING AREA

UNIT NO	ECOLOGICAL REGION	VEGETATION TYPE	FORMATION CLASS	SOIL-GEOLOGY	TOPOGRAPHY	DOMINANT SPECIES
*16b	Kuruman Sourveld	Kuruman Sourveld Shrublands	high, open to closed shrublands	shallow, brown, base soils mixed with banded ironstone chips and chert pebbles and occ. exposed dolomite BR	gentle slopes and plains	*Tarchonanthus camphoratus* *Tarchonanthus minor* *Rhus ciliata* *Rhus tridactyla* *Rhus undulata* *Grewia flava* *Lebeckia macrantha*
16c	Ghaap Plateau	Ghaap Plateau Shrublands (Southern Form)	tall, closed shrublands	shallow, red, base soils overlying calcrete bedrock	plains, pockmarked by small pans and intersected by several vlei-marshy streams	*Tarchonanthus camphoratus* *Rhus ciliata* *Rhus pyroides* *Olea europaea* ssp. *africana* *Grewia flava* *Rhus lancea* *Ziziphus mucronata* *Diospyros lycioides*
17c	Harts River Valley	Harts River Floodplain Grasslands (Ghaap Plateau Extension)	low, closed grasslands	alluvial soils (dark brown) soils; exposed dolomite BR ; patches of exposed calcrete	occ. seasonally waterlogged wetlands (low floodplain)	*Cynodon* spp., *Themeda triandra*, *Agrostis* spp., *Panicum* spp., Aquatic grass spp., *Typha capensis* *Phragmites australis*
*17d	Kuruman Sourveld	Kuruman Sourveld Grasslands	short, closed grasslands	shallow, brown, base soils with chert pebbles overlying dolomite BR slabs and v. occ. calc. outcrops	undulating plains	*Themeda triandra* *Antephora pubescens* *Stipagrostis uniplumis* *Cymbopogon plurinodis* *Elionurus argenteus* *Eragrostis pallens*

UNIT NO	ECOLOGICAL REGION	VEGETATION TYPE	FORMATION CLASS	SOIL-GEOLOGY	TOPOGRAPHY	DOMINANT SPECIES
34	Kuruman Sourveld	Kuruman Sourveld Shrublands	high, closed shrublands	shallow, brown base soils overlying banded ironstone BR (chert pebbles ; interbedded dolomite ; occ. calc. lineaments)	plains and occ. calc. lineaments (raised)	Tarchonanthus camphoratus Grewia flava Rhus ciliata Ziziphus mucronata Diospyros austro-africana Euclea undulata
*36b	Kuruman Sourveld	Kuruman Sourveld Grassy Shrublands	tall, sparse to open grassy shrublands to shrubby grasslands	shallow, brown soils with chert and banded ironstone chips and pebbles, on dolomite BR slabs	uneven plains	Tarchonanthus camphoratus Rhus ciliata Lebeckia macrantha Diospyros austro-africana Euclea crispa Protasparagus laricinus Many sour grass species
37	Ghaap Plateau	Ghaap Plateau "Bushlands" (Southern Form)	short, closed, woody shrublands and shrubby woodlands to almost thickets	shallow, red-brown to dark-brown, base soils overlying, often exposed, calcrete and dolomite BR	rocky plains	Tarchonanthus camphoratus Olea europaea ssp. africana Rhus undulata, Rhus tridactyla Rhus pyroides, Tarchonanthus minor, Acacia mellifera Acacia karroo, Euclea crispa
38	Ghaap Plateau	Ghaap Plateau Woodlands (Southern Form)	short, open to closed, shrubby woodlands - thickets	shallow, brown soils (frequently absent) overlying calcrete bedrock	gentle slopes (associated with vlei-marshy riverbeds)	Olea europaea ssp. africana Rhus lancea, Rhus ciliata Acacia karroo, Lycium hirsutum Rhus pyroides, Grewia flava Tarchonanthus camphoratus Tarchonanthus minor, Euclea crispa, Euclea undulata Maytenus heterophylla Ziziphus mucronata, Diospyros lycioides, Protasparagus laricinus

UNIT NO	ECOLOGICAL REGION	VEGETATION TYPE	FORMATION CLASS	SOIL-GEOLOGY	TOPOGRAPHY	DOMINANT SPECIES
39	Ghaap Plateau	Ghaap Plateau Woody Shrublands (Northern Form)	a mosaic of classes - high, open shrublands (dominant); short, closed grasslands; short, closed woodlands on raised lineaments	brown soils on dolomite BR intersected by raised calcrete lineaments	plains and occ. calc. lineaments (raised)	Tarchonanthus camphoratus Rhus lancea Rhus ciliata Euclea crispa Acacia karroo Diospyros lycioides Ziziphus mucronata
*40	Ghaap Plateau	Ghaap Plateau Escarpment Bushlands Thickets	short bushlands and thickets	shallow, brown soils with exposed dolomite rocks and rugged boulders (bedrock) and occ. exposed calcrete tufas	steep to precipitous slopes and kloofs, cut by deep drainage lines	Rhus undulata Rhus tridactyla Rhus lancea Rhigozum obovatum Olea europaea ssp. africana Cadaba aphylla Euclea crispa Maytenus heterophylla Celtis africana Ficus cordata Nuxia gracilis Acacia tortilis Acacia karroo Tarchonanthus camphoratus Tarchonanthus minor

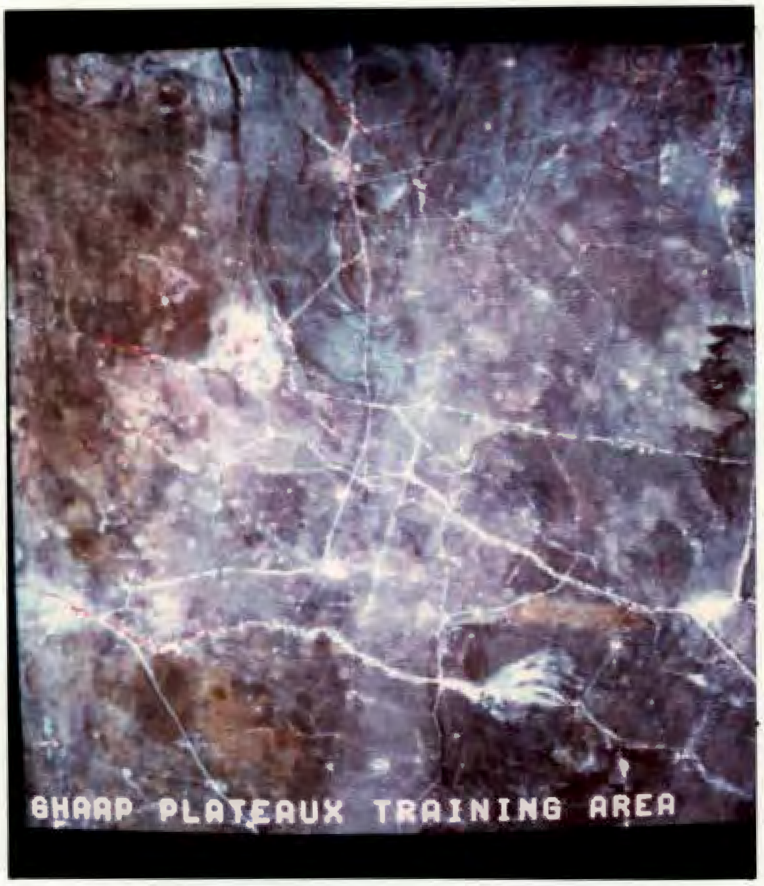


Plate 10 Photograph of portion of false colour composite Landsat image WRS 185-79 (bands 4, 5 and 7; summer), representing the Ghaap Plateau Training Area. Originally at a scale of 1 : 250 000.

Training Area as it appears in the Landsat image. Plate 11 pictorially displays the final computer-generated hybrid classification product.

As a result of experience gained in the supervised classification of the Kalahari Thornveld Training Area, especially in terms of the intrinsic heterogeneity of natural systems, a positive spatial mask was placed over that area of the Ghaap Plateau Training Area which would be utilized in the computer-generated classification. Not the whole of the Ghaap Plateau Training Area was used for classification purposes, as is evident from Plate 11 and Fig. 7. An attempt was made to restrict the training area, as far as possible, to a single landscape ecological region - the Ghaap Plateau. The positive mask included V-L's 16c, 37, 38 and 39; small ground cover areas of V-L's 17d, 17c and 36b and even smaller areas of 16b and 34 were included but ignored in the ensuing classification. V-L's 16c, 37, 38 and 39 all belong to the Ghaap Plateau Ecological Region.

The reflectance range of most of the "new" training area is quite narrow. On the FCC image (Plate 10) this is visible as dark areas of blues, blue-green and near-blacks (mainly shrublands with an important grassy intershrub component). The other important ecological region of the training area, Kuruman Sourveld, seen on the image as various intensities of brown (mainly grasslands and open, grassy shrublands) is largely excluded from the "new" training area. This action was solely for the purpose of allowing the computer-generated classification maximum chance of success in an area consisting of highly related vegetation-landscape units. In the light of the results obtained with the Kalahari Thornveld Training Area , it was felt that the number of spectral classes used in statistical training needed to be reduced and be as homogeneous as possible in terms of environmental parameters.

In the classification of the Ghaap Plateau Training Area, supervised, unsupervised and hybrid methods of computer classification were used. V-L's which showed strong reflectance value homogeneity and which corresponded with single ground cover units were signaturized manually. Where a ground cover unit consisted of a mosaic of subunits (and showed corresponding mosaicism in terms of reflectance levels on the image and in the MSS digital data sets) the area was signaturized using the unsupervised method (V-L's 16c and 39). In the final stages before classification, the supervised and unsupervised spectral classes/clusters were combined in a manner which has now become known as one of the hybrid methods of classification.

It was hoped that the computer-generated classification would reach reasonably high levels of accuracy. The accuracy of the classification generated by the computer can only be judged if the researcher has very good ground reference data. The number and identity of the manually and computer-generated spectral classes/clusters are given in Appendix 2. It should be noted that not all the spectral classes/clusters were generated at the first classification. The data was classified several times. Using the results or inaccuracies of each previous classification, further manual and unsupervised signaturization of specific ground cover areas/spectral classes was undertaken in an attempt to improve the subsequent classification. One cannot, however, continue with classification runs unless appreciable improvements occur. The prepared vegetation map and the image were used in making this decision.

5.1 COMPARISON AND EVALUATION

Two signature extension classifications are worthy of discussion. They are referred to here as classification no. 1 and classification no. 2, though they are not the first and second classifications attempted. Classification no. 2 (Plate 11) will be discussed fully, but some reference will be made to classification no. 1. The initial impact of the final computer-generated classification is its simplicity in terms of orange and blue, criss-crossed with white, linear strips. The Ghaap Plateau computer classification is much simpler than that of the Kalahari Thornveld Training Area. This fact relates to the following features of the training area:

a) ground cover is predominantly covered by shallow, brown-red soils overlying calcrete and dolomite parent material,

b) topography is simple; plains and/or gentle slopes are traversed by occasional, sightly raised lineaments and shallow, longitudinal, riverine-like vleis/marshes,

c) vegetation units consist predominantly of even-height, open to closed shrublands, generally extensive in distribution and dominated by *Tarchonanthus camphoratus*

d) vegetational-landscape units belong predominantly to the extensive Ghaap Plateau Ecological Region (in numbers and ground cover area).

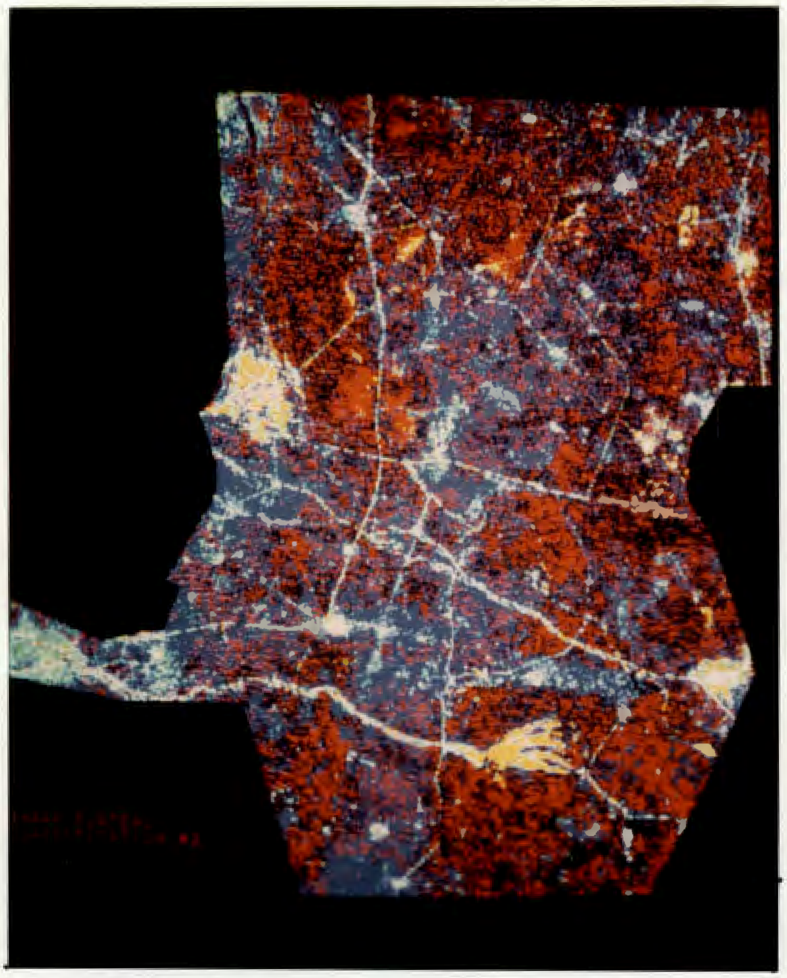


Plate 11 Final computer-generated classification of the Ghaap Plateau Training Area, using the hybrid (supervised - unsupervised combined) approach. The colour-codes are interpreted and discussed in Section 5.1.

In the Ghaap Plateau Training Area, roads, pans, the typical linear "vlei-marshy" seasonal streams and raised calcrete "faults" or lineaments form ideal landmarks with which to assess accurately the success of the computer-generated classification as they can be accurately located on the ground and on the classified image. The Kalahari Thornveld Training Area contained very few sharp, narrow, linear features or small pans for accurate identification and reference.

As a generalization, there is a gradient of colour-codes in the computer classification which correlates well with the colour of the canopy layer of the vegetation. Colour-codes dark blue, orange, pink and blue, form the major group with white, yellow and light blue the second group, relative to V-L's 37, 39, 16c, and 17c, 38, 17d, roads, faults and pans, respectively. These relationships and their spatial and geographical distributions need to be assessed more closely.

1. The narrow, linear, white and sometimes light blue colour-coded lines traversing the computer-generated classification are calcrete farm and district roads, as well as slightly raised, linear calcrete "faults" or lineaments. Many of the roads have been produced simply by scraping the calcrete lineaments shallowly. The calcrete of the linear "faults" is often soft and crumbly, and hardens to a smooth surface with vehicular use, especially after rains. Many of the small, approximately circular, white and light blue or white surrounded by light blue colour-coded patches pock-marking the computer-generated classification are small, shallow, calcareous-surfaced, saucer-shaped pans. These pans frequently hold water for one to several weeks following adequate rains. The flat, almost non-vegetated, fine-grained, calcareous soil, pan centres show on the classification as a white colour-code, while the surrounding light blue relates to that ground terrain, covered by various grass and dwarf to low shrub species, sloping gently towards the pan centre. Several of the white colour-code patches also relate to calcrete quarries and overgrazed, exposed, calcrete farm homestead surroundings and large, domestic stock watering points. The small villages of Reivilo in the north (colour-coded as an obvious white rectangular block) with its adjacent golf course (colour-coded as a light blue patch) and Madipelesa in the ESE (colour-coded white surrounded by yellow) are clearly evident. A few of the more dependably

seasonal, extensive "vlei-marshy" streams cut deeply into the calcrete and dolomite bedrock and also show clearly in the computer-generated classification as a white colour-code, e.g. Holrivier, Groot-Boetsaprivier and Klein-Boetsaprivier. This relates more to the exposed calcrete banks and surrounding slopes than to the central "riverbed" grasses and sedges, which are minimal at this scale.

2. V-L 17c is a low, closed grassland on fine-grained alluvium. It belongs to the Vaal-Harts River Valley Ecological Region, the Harts River Floodplain grasslands vegetation type (Plate 8 in Paper 1). This may seem contradictory, since in this case, V-L 17c is found on the Ghaap Plateau and at some distance from the Harts River which is situated below the Ghaap Plateau Escarpment and is 30 km to 60 km further to the east. The extensive Ghaap Plateau catchment areas are structurally and floristically similar to the Harts River Floodplain grasslands. All the linear vlei-marshy streams traversing the Ghaap Plateau and the small circular pans (not shown at the reconnaissance level) fall within this vegetation unit. The catchment areas of V-L 17c consist of several plant communities; their distributions are frequently dependent on moisture levels and depth and/or type of soil, with the gradient radiating from the centre of the catchment area, outwards (very similar to the vegetation structure and floristic distribution of pans). Typical species, from the central areas outwards are various species of Cyperaceae, *Cynodon* spp., *Agrostis* spp., *Chloris virgata, Typha capensis*, *Phragmites australis*, *Panicum* spp., *Eragrostis lehmanniana*, *E. truncata, Themeda triandra* and widely scattered *Rhus lancea*.

In the computer-generated classification, the two catchment areas demarcated 17c and the vlei-marshy streams and pans are clearly colour-coded with white and yellow as are streams and the major portion of the catchment areas, representing reflectance from the highly reflectant alluvial-calcareous soils of the catchment areas and from the vegetation (mainly *Cynodon* spp., *Agrostis* spp., Cyperaceae spp., *Themeda triandra* and several other less common aquatic to semi-aquatic grass species). The dark, peaty soils of the vlei-marshy streams would not add any significant reflectance data owing to the vegetation having a very high PCC. As mentioned above, the roads, "saucer" pans, quarries, farm homestead surroundings, towns/villages and linear "faults" also have this colour-coding plus light blue in the classification, owing to the high reflectance of the often very-exposed calcrete bedrock, even though the linear "faults" are covered by a closed woodland to thicket formation in some areas. The colour-coding of yellow (predominantly) and some white found on the outer zones of V-L 17c relates to *Themeda triandra* grasslands with widely scattered *Rhus lancea*, *Acacia karroo* and very occasional *Diospyros lycioides* and *Tarchonanthus camphoratus*, where there is transition both in vegetation, slope angle and soil type (towards shallow, red-brown, base soils overlying calcrete bedrock).

3. V-L 38 is also largely colour-coded white, predominantly surrounded by light blue. V-L 38, belonging to the Ghaap Plateau Ecological Region, Ghaap Plateau Woodlands (southern form) vegetation type, is a short, open to closed shrubby woodland - much of it a true parkland structural formation (Plate 9). This formation class very occasionally reaches thicket proportions. V-L 38 is situated on each side of the Klein-Boetsaprivier which is not a river *per se* but one of the typical, though more extensive in this case, seasonal vlei-marshy streams common to the Ghaap Plateau. V-L 38 is related to this stream only in terms of the calcrete deposited during geological times and the increased presence of seepage moisture available from the stream to support the high density of trees and shrubs. The stream bed itself, representing a small ground cover area, consists mainly of Cyperaceae and aquatic grass species, with occasional thickets of *Typha capensis* and *Phragmites australis*, and is strongly related to V-L 17c, other streams and some of the larger pans. As with the pans, streams and linear faults, the stream bed central to V-L 38 has not been demarcated on the vegetation-landscape map owing to the small area. The streambed does, in actual fact, form a small part of the white colour-code of V-L 38, especially the grassy, gentle slopes of the calcrete banks. V-L 38 occurs on very shallow brown (humic) soils overlying calcrete bedrock; the soils are frequently absent. The typical species is *Olea europaea* ssp. *africana* with its grey canopy colour (dominant in cover-abundance and 4 m to 6 m high); many species of trees and large shrubs grow in association with its canopy through the seed-distribution by birds, viz. *Rhus lancea*, *R. ciliata*, *R. pyroides*, *Acacia karroo*, *Grewia flava*, *Maytenus heterophylla*, *Ziziphus mucronata*, *Diospyros lycioides*, *Euclea crispa*, *E. undulata*, *Protasparagus laricinus*, a few *Tarchonanthus camphoratus* and *T. minor* and many others to a lesser extent. Between the groups of *Olea europaea* ssp. *africana* are hundreds of depressions or small (75 m² to 125 m²) "saucer pans". These are shallow depressions in the calcrete, covered with grasses, especially

Themeda triandra, which are probably responsible for giving V-L 38 a predominantly light blue to white colour-coding in the computer-generated classification. Open grassland between the grey canopy colour of the Oleas probably accounts for 60% PCC, and up to 90% where the Oleas are occasionally scattered, especially on the western edge of V-L 38 included in the training area classified by the computer.

4. V-L 34 has only a limited distribution in the training area, appearing as a linear extension running north-south, in the upper north-west corner. V-L 34 consists of Kuruman Sourveld Shrublands - high, closed shrublands on shallow, brown, base soils overlying banded ironstone bedrock, chert pebbles with interbedded dolomite and occasional calcrete lineaments. In that part of the training area used for computer classification, the linear "finger" is a banded ironstone marker with some exposed dolomite and chert. Here the high, closed shrubland consists of such species as *Diospyros austro-africana*, *Ziziphus mucronata*, *Euclea undulata*, *Tarchonanthus camphoratus*, *Grewia flava* and *Rhus ciliata*. V-L 34 was not used as a training site for signaturization and this may explain its similarity in colour-coding to V-L's 37 and 39, viz. orange and dark blue.

5. V-L 17d, in the upper north-west corner of the training area, is colour-coded similarly to V-L 38 - white and light blue. V-L 17d is a short, closed grassland (Plate 7), belonging to the Kuruman Sourveld Ecological Region. This grassland occurs on shallow, brown, base soils mixed with chert pebbles, overlying dolomite bedrock slabs. Very occasional exposed calcrete outcrops also occur. Topographically, the area is an extensive, undulating plain. Typical species are *Themeda triandra*, *Anthephora pubescens*, *Stipagrostis uniplumis*, *Cymbopogon plurinodis*, *Elionurus argenteus* with occasional *Eragrostis pallens* and very widely scattered solitary, woody species such as *Diospyros austro-africana*, *D. lycioides*, *Acacia karroo*, *Rhus lancea*, *R. ciliata* and *Tarchonanthus camphoratus* patches. It would seem that the similarity in colour-coding is due to similarities in frequency of the exposed soil-geology complex of V-L 17d with the scattered *Olea europaea* ssp. *africana* of V-L 38 and the grass layer of V-L 17d with the grass and exposed calcrete of V-L 38. Although the ground cover (physiognomy) of the two V-L's is quite different in the field, the reflectance values for these two V-L's are similar enough to result in almost identical computer classification (in all classifications produced). There is

also some similarity between V-L's 17d and 17c, probably because of the importance of the grass layer in both, though surprisingly, these two grassland types remain reasonably distinct. As in the Kalahari Thornveld Training Area, the identification and classification of ground cover by means of reflectance data is artificial and need not necessarily relate to, and most often does not, vegetal attributes in different cover classes. No real vegetal (or possibly any other) hierarchical relationships can be deduced directly with any confidence. For example, based upon reflectance data alone (i.e. no ground reference data), one would be led to believe that V-L's 17d and 38 are closely related in terms of vegetation. In actual fact, V-L's 17c and 17d are related (structure and floristics). In terms of topography and moisture levels, V-L's 17c and 38 are related, but in terms of soil/geology complex V-L's 17d and 38 are closer to each other but still separable. In fact, in terms of vegetation <u>and</u> soil/geology complex, V-L's 17d and 39 are more closely related than any of the combinations mentioned above, though the computer classification reflects their belonging to two very different groupings (white-light blue and dark blue-orange).

Reflectance data values relate to several environmental parameters interacting in complex ways; the well-exposed soil/geology colour is a major factor to be considered, either as a reflectance factor on its own or, more often, as a major ingredient of the reflectance "mixture". It is also obvious from the computer classification that the region of V-L 17d (southern distribution) surrounding the tip of the linear extension of V-L 34 (southern end of the banded-ironstone marker) is colour-coded as belonging to V-L 16c: tall, closed shrublands. On further investigation of this region in the field, it was found that the soil/geology complex is transitional between V-L's 17d and 16c, having more calcrete bedrock outcrops exposed to the surface and scattered *Tarchonanthus camphoratus* and *Rhus ciliata* in higher density than in 17d and could be classified as an open, grassy shrubland. In this case, the computer-generated classification is probably more accurate than the vegetation-landscape map.

6. V-L 36b, with a much more extensive distribution along the western edge of the training area which was omitted from the "new" training area, was not used as a training site for signaturization and hence does not appear unique in the computer-generated classification. No interest was shown in V-L 36b, a vegetation type belonging to the Kuruman Sourveld Ecological region, and

thus it is lumped with V-L's 16c and 17d in the computer classification. The tall, sparse to open, grassy shrublands to shrubby grasslands of V-L 36b bear some resemblance to V-L 17d in vegetal structure and soil/geology complex, as well as topography. V-L 36b resembles V-L 16c in terms of spectral reflectance values (see false colour composite image, Plate 10 and bispectral plot, Fig. 9), presumably owing to the presence of *Tarchonanthus camphoratus* in both V-L's and the high reflectance of calcrete in V-L 16c and the grass layer in V-L 36b. This is an example of the dangers of inadequate signaturization of all spectral classes in the training area, whether belonging to a single spectral cover class (as in this case) or whether one omits only one of several spectral classes belonging to a single cover class (usually the prevailing situation). In such a case, the computer lumps that spectral class with the closest mean reflectance to it, regardless of uniqueness. The same applied to the several very small areas of V-L 16b found in the "new" Ghaap Plateau Training area.

In the computer classification of V-L's 16c, 37 and 39, rather different results were obtained in the various attempts at classification (in terms of differentiation and extensiveness). These will be discussed below. Classification no. 2 more accurately separates and depicts the spatial and geographical distribution of V-L's 17c, 17d, 34, 16b, 36b and 38 and the lower degree of uniformity of V-L 16c. Classification no. 1 gives better separation of V-L's 37 and 39.

7. V-L 16c is a tall, closed shrubland on shallow, red, base soils overlying calcrete bedrock. Topographically, this Ghaap Plateau shrubland occurs on extensive plains and covers a large portion of the training area. In the computer-generated classification, this V-L is colour-coded blue and pink, and is more extensive in classification no. 1 (where it occurs in V-L's 39 and 37 too) than in classification no. 2. Classification no. 1 also shows some orange colour-coding (V-L 39) and even smaller amounts of dark blue colour-coding (V-L 37), in V-L 16c. The orange and dark blue colour-coding is more extensive in classification no. 2, embracing V-L's 39 and 37 better, but the distinction between these two cover classes is unclear. Classification no. 2 also uniquely separates V-L 17c from V-L's 38 and 17d, more clearly separates V-L's 36b and 16b from surrounding cover types, while linear "faults", calcrete roads, pans, vlei-marshy streams and villages/towns have very sharp and good, contrasting boundaries.

Classification no. 2 is therefore preferred for all cover types, but classification no. 1 should be referred to for distinction between V-L's 37 and 39 (orange and dark blue colour-codes respectively) and the true distribution of V-L 16c.

The computer classification inaccurately depicts the distribution of V-L 16c just north and south of Reivilo as a blue colour-code instead of orange (V-L 39) in both classifications. The distribution of V-L 16c is very good in classification no. 1; it contains far too much of the orange colour-code (V-L 39) in classification 2. Occasional light blue patches and sometimes white relate to the cover of grass in odd grassy, very sparse shrublands and "saucer" pans (exposed calcrete and grass stratum only). Occasional orange patches presumably relate to the odd closed, woody or dense shrub patch distributions.

8. V-L 37, the most extensive cover type in the training area, varies in structural density and formation class from tall, closed, mixed, woody shrublands to short, closed, mixed, shrubby woodlands, both sometimes reaching almost thicket proportions. This cover type consists of several obvious spectral classes, relating to the variations in structure and physiognomy, each requiring separate training site selection and signaturization to build up a range of reflectance values capable of including (allowing for) all areas/spectral classes within the data set representing the ground cover of V-L 37. V-L 37 occurs on shallow, red to brown, base soils overlying often-exposed calcrete and dolomite (major area) bedrock. Variations in structure and physiognomy and therefore species cover/abundance (the same species generally occur throughout the cover type but vary in frequency and density) relate to the variations in subsurface geology and ruggedness of the topography (rocky plains) and exposed geological formations, especially dolomite outcroppings. Typical species are *Tarchonanthus camphoratus*, *Olea europaea* ssp. *africana*, *Rhus undulata*, *R. tridactyla*, *R. pyroides*, *Tarchonanthus minor*, *Acacia mellifera* and *A. karroo*.

V-L 37 belongs to the Ghaap Plateau Ecological Region, the Ghaap Plateau "Bushlands" (southern form) vegetation type. The term "bushlands" has been used owing to the presence of mixed, woody shrublands and mixed, shrubby woodlands, all approximately the same height and density in the same vegetation type. At a larger scale of investigation this vegetation type would probably be subdivided as follows:

a) On rugged exposed dolomite bedrock - mixed, shrubby *Olea* woodlands

b) On flat calcrete-dolomite plains - mixed, woody *Tarchonanthus* shrublands.

These two sub-types represent the two extremes. In the computer classification, this V-L was colour-coded dark blue. In classification no. 1, this V-L is relatively poorly classified in terms of cover-type distribution, though well-distinguished from V-L 39 (orange). In classification no. 2, the reverse was true (well-classified in terms of spatial and geographical cover-type distribution, but integrated and confused with V-L 39). Comparison with the vegetation-landscape map (Fig. 7) shows this clearly. In both classifications, V-L 37 north and south of Witpan (western distribution) is poorly defined, showing a lack of cohesion in its distribution. This is probably a true reflection of the situation in the field, as V-L 16c and V-L 37 in this area show a strong mosaicism and are difficult to separate from each other at this scale of investigation. The computer classification does so with some success, showing that V-L 37 dominates the mosaic and should thus be classified as such at this scale. By doing so, one gives a false impression that V-L 16c is not present at all. In fact, throughout the distribution of V-L 37 along the boundary with V-L 16c, a more accurate definite and "real world" V-L map may be produced from the computer-generated classification though the amount of detail portrayed is much greater than usually portrayed at a scale of 1:250 000. This is often true of Landsat-based (visual and computer-generated) thematic maps.

The eastern, patchy distributions of V-L 16c, lying within V-L 37, though isolated in the computer-generated classification, are not as clearly defined as in the V-L map. This may be explained partly by inadequate and unrepresentative training site signaturization and partly by the fact that the vegetation is not an ideal "fit" with that occurring on the major portion of V-L 16c.

9. V-L 39, Ghaap Plateau woody shrublands (northern form) vegetation type, consists of a true, large scale, mosaic of formation classes:

a) short, closed shrubby grasslands

b) high, open (occasioanlly intermediate) shrublands (the dominant formation class)

c) short, closed, shrubby woodlands on raised lineaments/faults and ridges.

These formation classes occur on:

a) shallow, brown soils on dolomite bedrock slabs

b) shallow, brown soils on calcretes and interbedded dolomites

c) raised calcrete (occasionally exposed dolomite at the edges) lineaments or "faults", often covered by dark, brown, rich soils (sometimes up to 1 m deep) and broken, rugged dolomite bedrock (exposed) on the ridges.

Topographically V-L 39 consists of plains intersected by occasional, raised "faults". A few vlei-marshy streams also occur, most only of short length, but some feed into larger streams which run off the Ghaap Plateau escarpment in the east to join the Harts River. Pans are rare in this V-L. Typical species are:

a) the shrubby grasslands: *Themeda triandra, Cymbopogon plurinodis, Eragrostis nindensis, Tragus racemosus, Eragrostis tricophora, E. lehmanniana, Sporobilis fimbriatus, Digitaria eriantha, Enneapogon desvauxii, Pogonathria squarrosa* and many others, while woody shrubs such as *Rhus ciliata, Diospyros lycioides, Rhus lancea* and *Tarchonanthus camphoratus* are very widely scattered, occurring solitarily or in small mono-specific clumps.

b) the high, open (occasionally intermediate) shrublands: *Tarchonanthus camphoratus, Rhus lancea, R. ciliata, Acacia karroo, Ziziphus mucronata, Euclea crispa* ssp. *ovata* and several others; typical grasses are *Themeda triandra, Cymbopogon plurinodis, Heteropogon contortus, Panicum* spp., *Sporobolus fimbriatus, Enneapogon scoparius, Digitaria eriantha* and *Fingerhuthia africana* to name but a few. Frequent patches of grassland with scattered *Rhus lancea* also occur.

c) the raised, calcrete lineaments or "faults" supporting short, closed shrubby woodlands: *Acacia karroo, Diospyros lycioides, Olea europaea* ssp. *africana, Maytenus heterophylla, Grewia flava* and various *Protasparagus* spp. (Plate 12).

d) the broken, "step" ridges of exposed dolomite supporting a short, closed, mixed, woody shrubland: *Olea europaea* ssp. *africana, Rhus undulata, R. ciliata, R. lancea, Tarchonanthus minor, T. camphoratus, Acacia mellifera, Boscia albitrunca, Euclea undulata, E. crispa, Rhigozum obovatum* and many more.

Plate 12 Short, closed shrubby woolands (V-L 39) on raised calcrete lineaments shallowly covered with dark brown humic soils. Height 3 - 7 m. Common species: *Tarchonanthus camphoratus* (mainly outer slopes), *Acacia karroo, A. tortilis, Rhus pyroides, R. lancea, Diospyros lycioides, Boscia albitrunca, Euclea undulata.*

In general, the major portion of this V-L consists of a high, open shrubland on shallow, brown soils overlying flat dolomite bedrock slabs (sometimes exposed). As with V-L 37, these structural/physiognomic, topographic and soil/geological types in V-L 39 resulted in several spectral classes. Some of these spectral classes were manually selected as training sites for signaturization, but a few were created by using the unsupervised method. In the computer-generated classification, V-L 39, colour-coded orange with some dark blue, is rather well classified spatially and geographically but occasional areas were confused with V-L 37 (dark blue colour-coding). These areas are, for the most part, areas of ground cover where the dolomite bedrock is exposed and rugged, such as the dolomitic "step" ridges and where the vegetation is dense (high PCC of species with dark foliage colour). It is obvious that, in taking great care with the signaturization of all spectral classes belonging to this V-L mosaic, increased success was obtained in the computer classification.

5.2 COMMENTS

There is no doubt that upon signature extension, the Ghaap Plateau Training Area computer-generated classification was more successful than that of the Kalahari Thornveld Training Area. This increased success may be attributed to:

a) the classified area mainly constituting a single ecological region and thus all environmental parameters falling within a specific range of variability

b) the use of three computer classification methods of data analysis, viz. supervised, unsupervised and hybrid.

This resulted in most of the spectral variability being accounted for not only in structurally simpler units but also in complex mosaic cover classes. Not only were most of the pixels assigned to a specific spectral class/ground cover type, but the assigment was also more meaningful. Carr *et al.*(1983), also working in an arid to semi-arid region, obtained much better results in isolating mining activity upon signature extension. Retraining of the classifier was not found necessary. Possibly their simpler objective of discriminating mining activity from natural terrain resulted in improved signature extension capabilities of the computer. By way of contrast, frequent retraining of the classifier was necessary in this study.

There is possibly better correlation of various ground cover types with statistically separable groups of data, as defined by their spectral properties in multi-dimensional space. Bearing in mind the importance of reflectance from the soil/geology complex in the MSS digital data, there is obviously a lesser problem with the correct identification and separation of several ground cover units in the Ghaap Plateau Ecological Region than in the Kalahari Thornveld Ecological Region. Other environmental differences between units notwithstanding, the various Kalahari Thornveld vegetation-landscape units relate most often to the geological bedrock below the aeolian Kalahari sands, albeit only just below the sand surface. Where the Kalahari sands are very deep, different units occur on different types of sands (red base sands or pink calcareous sands or deep "white" leached, nutrient-poor sands, etc.) The problem arises from the fact that the Landsat sensors, by and large, sense and record reflectance from the surface layer of soil and do not record changes in the soil/geology occurring at subsurface levels. For the most part, vegetation (structure and canopy-density colour) does not dominate the reflectance values recorded per reflectance cell (Paper 1), thus an equivalent change in soil-geology complex is more effective than that in vegetation type. There is little or no difference in the degree of change in the vegetation (structure, floristics, etc.) between units in both training areas. The degree of change in the soil/geology complex is more important to the success of the computer classification than an equivalent degree of change in the vegetation cover and spatial pattern. While exposed soil/geology in the Ghaap Plateau Ecological Region may be of help in the separation of units in the classification, it is assumed that the higher the level of reflectance from the soils, calcretes and dolomites, the greater the imbalance in the shrub to grass ratio: an indicator of the degree of change. With the added advantage of using more than one classification method and as a result of the presence of many more observable (reflecting) environement-based contrasts, the classification of the Ghaap Plateau Training Area was more successful than that of the Kalahari Thornveld Training area.

In general, several V-L's are classified clearly and accurately, especially V-L's 17c, 38, 16c as well as vlei-marshy streams, linear "faults", pans, roads and towns/villages. V-L's 17d, 34, 36b and 39 are adequately classified. Only V-L 37 gave problems in the classification. Although the computer classification still lacks good cohesion, it is far more successful than the classification of the Kalahari Thornveld Training Area for reasons elucidated above. It is of interest to note that the several attempts at classification gave mixed results: improvement in certain V-L's with increased spectral variability signaturization may result in a deterioration of a V-L classification elsewhere; areas within a V-L are removed and colour-coded differently in answer to the new spectral range which has been given to the classifier, e.g. V-L's 37 and 39 in classification 2.

Again the "between pixel" and "within pixel" problem (Section 7) is present in the Ghaap Plateau Training Area computer classification and is especially noticeable in V-L's where mosaicism is pronounced, such as V-L's 16, 37 and 39. This results in many of the colour-codes being present in varying amounts in any one "homogeneous" spectral class/ground cover unit even though the colour-codes may possibly be dominated by a single colour-code per V-L.

The successful separation of different grassland types from each other in the computer classification is both surprising and pleasing. This occurred with V-L's 17d and 17c; neither were these V-L's confused with the very open, grassy patches of V-L 39. These results, with examples in both training areas, allude to the potential success of using Landsat imagery in the classification and mapping of various types of grasslands in the Grassland Biome. On a number of occasions, the boundaries of vegetation-landscape units appearing in the vegetation-landscape map could be, and were, improved by reference to this computer-generated classification "map", e.g. V-L's 17d, 16c and 37.

Once again, as with the computer classification of the Kalahari Thornveld Training area, it is obvious that the Landsat sensors are sensing the total environment and no one environmental parameter. To some extent this is due to the 50% or less PCC of vegetation formations in the arid to semi-arid regions of South Africa.

Lo *et al.* (1986) felt that computer-generated land cover classifications require significant improvement in both accuracy and specificity in order to be operational. They suggested that investigation of multi-temporal analysis procedures of Landsat MSS data may provide some solution. It must be concluded that within the bounds of this study, the automatic machine processing pattern recognition techniques applied to Landsat MSS data were at best an imperfect way of utlizing the data. The purpose of the study was the mapping of environmentally complex natural landscapes, containing a great degree of spectral variability, at the reconnaissance scale. Simple factors such as the time, amount, intensity and distribution of rainfall could play havoc with meaningful signature extension. Considerable effort is required before useful spectral signatures for extension over heterogeneous natural environments are obtained.

Maps produced with the help of satellite imagery depicting the vegetation of a given region are at best vegetation-landscape map products. Owing to the fact that the total landscape is recorded, Landsat imagery is of help in the interpretation of the presence of a vegetation unit in terms of topography, moisture levels, soil types and geological formations. Vegetation is the product of its environment. Correlation of the vegetation with other environmental parameters can be deduced with considerable accuracy from the study of surrogate Landsat MSS digital data set.

6. BISPECTRAL PLOTS

6.1 INTRODUCTION

One important consideration in the selection of training sites for signaturization (training the classifier) is that the training site should, in total, include a sample of all spectral classes within the training area. For the purpose of extrapolation from the training area to the study area, the training area should be spectrally representative. From image WRS 185-79 (Plate 1 in Paper 1) it was evident that this would be an impossible task even with the use of several training areas strategically positioned on the image. The image represents over 100 ground cover/vegetation landscape units and sub-units, each with at least three to eight spectral classes. The software utilized by the SAC, Hartebeeshoek allows for a maximum of only 32 classes per classification. At the very least, the image/MSS digital data set would require several sectional divisions to be classified separately. Owing to the variability of the V-L units throughout the image, nearly the whole image would have to be manually classified (supervised method) so defeating the whole object of the exercise.

Two very different training areas were chosen manually and a classification attempted; classifying the whole study area would, in all likelihood, be improbable. The problems encountered in attempting to computer-classify just two training areas have been outlined. "Eyeballing" the hardcopy false colour composite image showed that the V-L's identified using conventional methods could be seen with ease. Why were there problems with the computer classification?

To help with the evaluation and/or to resolve classification problems and increase classification accuracy, a statistical test of the separability of all pairs of spectral cluster classes appearing in the classification may be performed. This is obtained by plotting the spectral class centres in a two-dimensional diagram known as a bispectral plot. The bispectral plot or cluster diagram method of analysis, with the simultaneous ground cover interpretation of the identity of the spectral classes if the unsupervised technique is used, gives the researcher a good idea which classes are discrete and should remain on their own and which classes could either be split or lumped together. Talbot & Markon (1986) had considerable success in interpreting their data using this method. The bispectral plot can also reveal important information about the relationships between cluster classes and ground cover units in terms of their reflectance values. A good example would be the grouping of all plant associations which develop on calcareous soils (given that there is low PCC in this vegetation unit and a good correlation between plant associations and substrate, and substrate and reflectance value of Landsat spectral class). This grouping of clusters (spectral classes relate to terrain classes) results in what is referred to as resource classes, i.e. the broad grouping of related landscape units or subunits.

Where an hierarchical classification system accompanies the prepared vegetation-landscape map (supervised technique), it is of interest and importance in the evaluation and understanding of the classified Landsat data, to compare the groupings or relationships between the spectral clusters of the bispectral plot with the inter- relationships of the ground cover units in the field. This gives an idea of the artificiality or otherwise of the resulting computer classification and helps to give an idea of the environmental parameters giving rise to the recorded reflectance.

The bispectral plot method (sometimes referred to as spatial stratification, Todd *et al.* 1980) is useful in the unsupervised classification technique to resolve classification problems where spectral clusters representing various unrelated ground cover units group together, or where pixels shown to belong primarily to one cluster (from signaturization of a specific training class/training site) are interspersed in one or more primarily unrelated clusters (Todd *et al.* 1980). An algorithm can be used to "change" pixel classification within designated regions, so that incorrectly located pixels may be added to the "correct" spectral class.

A bispectral plot of the mean values of the signatures generated per class/cluster (average reflectance of the visible bands 4 and 5 against the average reflectance of the invisible bands 6 and 7) during the supervised and unsupervised classifications was undertaken for both training areas. During the original training site signaturization, a specific spectral class is submitted as a data set to the clustering algorithm. Upon classification, this information, representing a specific range of reflectance, is used to produce a spectral cluster. The bispectral plots, Figs. 8 and 9, present these spectral clusters as numbers positioned according to their mean reflectance centres, and have been identified by the number of the vegetation-landscape unit from which they were originally signaturized. These clusters have been circled into groups according to their reflectance affinity with each other. It should be noted that where several centres are identified with the same number, these centres represent clusters which all belong to the same vegetation landscape-subunit (where a single ground cover type showed several spectral cover classes, each of which required separate signaturization to incorporate the range of spectral reflectance present in that ground cover type). The superscript numbers relate to the spectral classes present, and signaturized, in a given V-L. The circled groupings depict clusters which show similarity in spectral reflectance range (through the averages of their means).

The bispectral plot of the (spectral) signaturized class centres supplied visual information on the actual measurement of separability of the reflectance-based V-L's, or parts thereof. It was hoped that this would supply useful information about why the spectral classes of certain V-L's or parts thereof were being confused with each other (misclassified as belonging to another unit). It should be noted that, in general, bispectral plots are used as part of the methodology in obtaining a "better" classification. After obtaining class statistics and the separability of all pairs of classes, those that have a low separability and appear as border classes or have a small number of samples, are deleted from the classification. By so doing, the final outcome will be a representative and separable set of spatially stratified classes for use in the final classification. This series of steps was employed in this study. Where the spectral classes of vegetation-landscape units, or parts thereof, remain close to each other in terms of spectral reflectance, even after further attempts at statistical separation, then those V-L's cannot be identified as separate, unique entities. The resultant classification errors may be attributed directly to the Landsat system itself, provided the mapping objectives are attainable in the first place and provided the researcher's analysis of the ground reference data is correct.

Reference to Tables 3 and 4, description of ground cover classes (simplified from the hierarchical classification scheme derived for the vegetation-landscape map), helps in the improvement of classification of the digital data (spectral classes) by showing which ground cover classes are being confused with each other in the computer classification.

6.2 KALAHARI THORNVELD TRAINING AREA

Fig. 8 is the bispectral plot showing the derivation of the spectral clusters appearing in the classification. Table 3 is the bispectral plot matrix with the identification of the "resource" classes which were signaturized manually. Owing to the variability within V-L's and the large scale nature of the computer classification, several V-L's were divided into subunits for the purpose of analysis. These subunits are indicated by means of a superscript with the V-L alpha-numeric code.

6.2.1 GROUP A

Group A consists of two closely related cluster centres, representing V-L's 5^1 and 33. They have very low reflectance values in both the visible (4 and 5) and the invisible (6 and 7) bands. V-L 5^1, appearing as the darkest portion of the "divide", consists of short, open grassy woodland on shallow red, base sands overlying quartzite bedrock (infrequently exposed). Typical scattered tree species in the highly-reflectant grassland are *Acacia erioloba, Dicrostachys cinerea,* and *Terminalea sericea.* On occasional

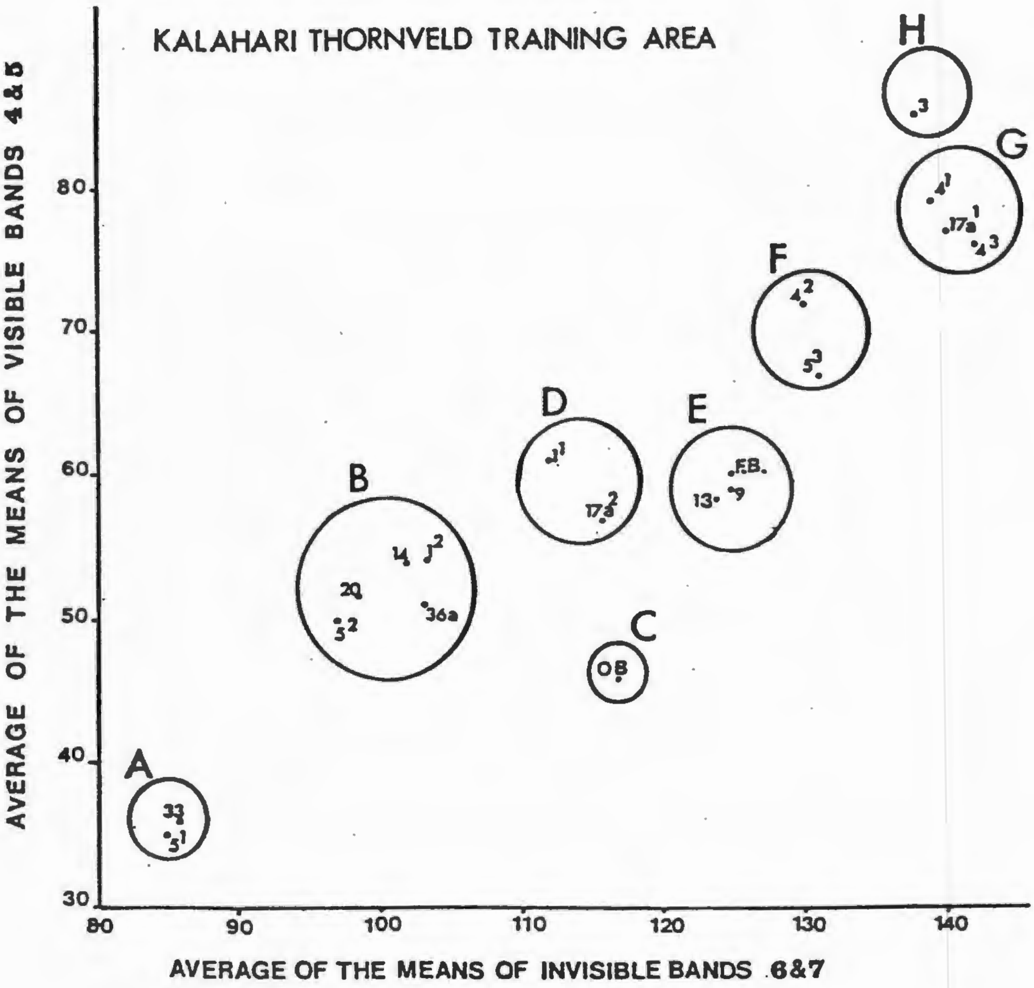


Figure 8 Derivation of spectral cluster groupings, using the bispectral plot clustering technique, resulting from the supervised, unsupervised and hybrid methods of classification of Landsat MSS digital data.

TABLE 3 : CLUSTER CLASS AND VEGETATION - LANDSCAPE UNIT DESCRIPTIONS FOR COMPUTER - ASSISTED, LANDSAT - DERIVED CLASSIFICATION OF THE KALAHARI THORNVELD TRAINING AREA

AVERAGE OF MEANS - VISIBLE (BANDS 4 AND 5)	AVERAGE OF MEANS - INVISIBLE (BANDS 6 AND 7)	VEGETATION-LANDSCAPE UNIT/SPECTRAL CLUSTER CODE	DESCRIPTION OF GROUND COVER OF VEGETATION-LANDSCAPE UNIT OR SUBUNIT/SPECTRAL CLUSTER	CLUSTER CLASS GROUP	GENERALIZATION OF SPECTRAL CLUSTER
35	85	5^1/K44(1)	high, rounded hills; short, open, grassy woodland (Acacia erioloba, Dicrostachys cinerea, Terminalia sericea) on shallow, red, base sands overlying quartzitic BR sometimes exposed	A	open woodland on sand - quartzite (hills)
36	86	33 / K39	high, closed, woody shrublands (Tarchonanthus camphoratus, Rhus spp., Acacia karroo, Ziziphus mucronata) on shallow, brown, base soils overlying dolomite BR slabs and calcrete outcrops	A	closed woody shrubland on brown soils
50	97	5^2/K44(2)	N-facing slopes; short, intermediate woodland (A. erioloba, A. mellifera, Z. mucronata, Grewia flava, patches of T. sericea) on red, base sands deeply overlying quartzitic BR (see 5^1) - never exposed	B^1	intermed. woodland on sand-quartzite (steep slopes)
51	98	20/K101	high, closed, woody shrublands (T. camphoratus, A. karroo, A. tortilis) on shallow, red-brown soils on andesite lava and porphyritic granite (often exposed) - rugged hills	B^1	closed, woody shrubland on red-brown soils, lava + granite hills
51	103	36A/K40(2)	tall, sparse to open, grassy shrublands (shrubby grasslands) (T. camphoratus and mixed Kalahari-Kuruman Sourveld grasses) on shallow, red, base sands overlying dolomite BR slabs	B^3	sparse shrubland on sand - dol.

AVERAGE OF MEANS - VISIBLE (BANDS 4 AND 5)	AVERAGE OF MEANS - INVISIBLE (BANDS 6 AND 7)	VEGETATION-LANDSCAPE UNIT/SPECTRAL CLUSTER CODE	DESCRIPTION OF GROUND COVER OF VEGETATION-LANDSCAPE UNIT OR SUBUNIT/SPECTRAL CLUSTER	CLUSTER CLASS GROUP	GENERALIZATION OF SPECTRAL CLUSTER
54	102	14 / K42	open to intermediate, shrubby woodland (woody shrubland) (T. camphoratus, A. mellifera, A. erioloba) on shallow, red, base sands overlying calcrete BR (some dolomite exposed)	B^2	intermed. shrubby woodland on sand - calc.
54	103	1^2/K52A	short, intermediate to closed, shrubby woodland (A. erioloba, T. camphoratus, G. flava) on deep, pink, base sands overlying calcrete	B^2	intermed. shrubby woodland on sand
57	116	$17a^2$/K40(1)	short, closed, mixed Kalahari-Kuruman Sourveld Grasslands (Themeda triandra, Stipagrotis uniplumis, Schmidtia pappophoroides) and very sparse, large shrubs and trees (solitary) on shallow, red, base sands overlying calcrete BR	D	grassland on sand - calc.
61	112	1^1/K52	closed, mixed woodland (T. sericea, A. erioloba, B. albitrunca) on deep, pinkish-yellow, leached Kalahari sands (high ground)	D	closed T. sericea woodland on deep, leached sand
58	124	13/K102	high, closed, woody shrubland (T. camphoratus, R. ciliata, Acacia spp., Z. mucronata) on shallow, red, loamy sands and andesite rocks and pebbles	E	closed, woody shrubland on sand - lava
59	125	9 / K46	low, closed Acacia woodland-thickets (A. mellifera, T. camphoratus, scattered A. erioloba and G. flava) on pink, calcareous Kalahari sands overlying calcrete BR	E	low, closed A. mellifera woodland on sand - calc.

AVERAGE OF MEANS - VISIBLE (BANDS 4 AND 5)	AVERAGE OF MEANS - INVISIBLE (BANDS 6 AND 7)	VEGETATION-LANDSCAPE UNIT/SPECTRAL CLUSTER CODE	DESCRIPTION OF GROUND COVER OF VEGETATION-LANDSCAPE UNIT OR SUBUNIT/SPECTRAL CLUSTER	CLUSTER CLASS GROUP	GENERALIZATION OF SPECTRAL CLUSTER
60	125	Fresh burn / K52(0)	fresh burn on V-L 9 (mainly A. mellifera and T. camphoratus on calcareous Kalahari sands)	E	shrubby woodland on calc. - sand ; burn
67	131	5^3/K44(3)	patches of sparse - open, grassy woodland (A. erioloba, T. sericea, D. cinerea) on deep, red, base sands (overlying quartzitic BR)	F	sparse woodland on sand-quartzite
72	130	4^2/K54	sparse to open woodland (A. erioloba, T. camphoratus, G. flava) on pink, calcareous sands	F	sparse woodland on calcareous sand
77	140	$17a^1$/K43	short, closed, mixed Kalahari-Kuruman Sourveld Grasslands (T. triandra, S. uniplumis, S. pappophoroides) with very sparse, scattered, solitary A. erioloba	G	grassland on sand
76	142	4^3/K54(1)	short, open to closed, mixed woodland (A. erioloba, A. mellifera, G. flava); open grassy A. erioloba woodland with occ. patches of A. mellifera invasion on pink, calcareous Kalahari sands	G	short, open woodland on calcareous sand
79	139	4^1/K49A	sparse - open, grassy woodland (A. erioloba, B.albitrunca, T. sericea) on deep, red Kalahari sands	G	sparse woodland on sand

AVERAGE OF MEANS - VISIBLE (BANDS 4 AND 5)	AVERAGE OF MEANS - INVISIBLE (BANDS 6 AND 7)	VEGETATION-LANDSCAPE UNIT/SPECTRAL CLUSTER CODE	DESCRIPTION OF GROUND COVER OF VEGETATION-LANDSCAPE UNIT OR SUBUNIT/SPECTRAL CLUSTER	CLUSTER CLASS GROUP	GENERALIZATION OF SPECTRAL CLUSTER
46	117	Old Burn / K52(00)	An old burn on V-L 1 (refer to 1^1 above)	C	closed *T. sericea* woodland on deep, leached sand; burn
85	138	3 / K50A	open *A. haematoxylon* woodland with scattered *A. erioloba* (occ. patches of *T. sericea* woodland-thicket) - on deep pink Kalahari sands	H	open *A. haematoxylon* woodland on sand

outcrops of rock a closed, woody shrubland is present (1%). Neither the vegetation nor the soil/geology complex justify such low reflectance values. It has been noticed during visual interpretation exercises on this and several other Landsat FCC images, that elevated topography terrain types, in general, result in low reflectance pixel values, probably due to shadows and sun angle and azimuth. Exposed geology usually occurs and must also account for a good percentage of the reflectance value. In this case, the quartzitic rocks and boulders are seldom exposed above the thin layer of Kalahari sand but there is some primary parent material in the form of "grit", in the surface layer.

The cluster centre represents pixels belonging to V-L 33, which consists of high, closed, woody shrublands on shallow, brown soils overlying dolomite bedrock slabs and calcrete outcroppings (Plate 8). Species diversity is relatively high; dominant-codominant tree and large shrub species are *Tarchonanthus camphoratus*, several *Rhus* spp., *Acacia karroo* and *Ziziphus mucronata*. A few lineaments (linear, calcrete "faults") also transect V-L 33. Low reflectance levels are mainly from the dark green foliage of the above species, as well as the dark soils and dolomitic bedrock. In contrast to the openly-vegetated, high, rounded hills of V-L 5^1, V-L 33 consists of well-vegetated plains.

It is obvious that these two ground cover types differ markedly from one another. It is quite remarkable that there should be assignment of pixels from both these areas to cluster centres so strongly associated with each other. This can be seen clearly in the computer classification, as these pixels are colour-coded purple. Some pixels from ground cover types designated V-L 20 (10%) and V-L 1 (< 0,5%) are also assigned to these cluster centres. These misclassifications would seem to be due to the reflectance-based Landsat system itself, i.e. the mean value of the reflectance range of each of the two ground cover classes (recorded on the bispectral plot as cluster centres 5^1 and 33 in group A) is so close that pixels representing each class are classified as belonging to the same group. The "mixed pixel" problem may be of relevance here.

6.2.2 GROUP B

Group B, a reasonably tight grouping, consists of five cluster centres representing V-L's 5^2, 20, 14, 1^2 and 36a. This group can be divided further into three subgroups.

1. Subgroup 5^2 and 20: Both these ground cover types are on elevated sites, situated on "the divide". V-L 5^2 consists of a short, intermediate woodland on deep, red, base sands, overlying quartzitic bedrock. The quartzite is never exposed to the surface. V-L 5^2 is a true Kalahari Thornveld type on elevated, north-facing, sandy slopes. Typical species, besides the usual Kalahari Thornveld grass species are *Acacia erioloba*, *A. mellifera* ssp. *detinens*, *Ziziphus mucronata*, *Grewia flava* and occasional patches of *Terminalea sericea*.

V-L 20 consists of a high, closed, woody shrubland on shallow, red-brown soils, on and between andesite lava and porphyritic rocks and boulders. These low hills are rugged and fairly steep, and the geology is exposed throughout their length. Typical species covering these hills are *Tarchonanthus camphoratus*, *Acacia karroo*, *A. robusta* ssp. *robusta*, *A. tortilis*, *Grewia flava* and *Rhus ciliata*.

As with Group A, these two cover types are quite different from each other in terms of environmental parameters (vegetation, soils, geology) but V-L's 5^2 and 20 at least both belong to the topographical type "elevated sites". It is interesting that the related subunits, V-L's 5^1, 5^2 and 5^3, like related units, V-L's 20 and 13, are spectrally separated. The "mixed pixel" problem would seem to be present here, although the strong possibility does exist that elevated sites which result in similarities of shadow effect, sun angle and azimuth, give rise to similarities in reflectance values. This environmental parameter on its own, is not enough to result in a distinct resource class. On the computer generated classification these two units are colour-coded speckled green and white. Some of the pixels in the ground cover class V-L 13 have also been assigned to this cluster, probably because of the similarity to V-L 20, in terms of geology and vegetation (species foliage colour).

2. Subgroup 14 and 1^2: Both these ground cover classes belong to the Kalahari Thornveld vegetation types, but V-L 14 is south of "the divide" and

ecotonal to the Kuruman Sourveld-Ghaap Plateau vegetation types, while V-L 1^a is a pure Kalahari Thornveld vegetation type.

V-L 14 consists of an open, shrubby woodland (occasionally an intermediate, woody shrubland) on shallow, red, base sands overlying calcrete bedrock (occasionally dolomite bedrock is exposed). Typical species are *Tarchonanthus camphoratus, Acacia mellifera* ssp. *detinens* and scattered *Acacia erioloba*. Much of this vegetation type and especially the grass layer, has been over-utilized leading to the encroachment of *A. mellifera* ssp. *detinens*.

V-L 1^a is that part of V-L 1 which consists of a short, intermediate to closed, shrubby woodland on deep, pink, base sands overlying calcrete. V-L subunit 1^a lies on much higher ground than V-L 14. The Kalahari sands are 2 m to 3 m deep whereas those of V-L 14 most often barely cover the calcrete. Typical species of V-L subunit 1^a are *Acacia erioloba*, *Grewia flava* and *Tarchonanthus camphoratus* (similar to Plate 2 in Paper2). Most species are associated with the *Acacia erioloba* canopy area. The inter-wooded areas consist of small patches where the grass layer is dominantly exposed.

Pixels associated with these two cluster centres have been colour-coded blue in the computer classification. V-L 14 has a compact distribution, while V-L 1 is extensive and pixels assigned to V-L 1^a are not distributed throughout a single area, but arise from several patches distributed throughout V-L 1. Although V-L's 14 and 1^a are environmentally different, straight reflectance levels and the resultant "mixed pixel" problems, give rise to values too similar for distinction.

3. <u>Subgroup 36a</u>: This subgroup represents the ground cover class V-L 36a. It is slightly removed from the other two subgroups of Group B and is more closely associated with sub-group 14 and 1^a. This is evident from the same blue colour-code of subgroups 36a, and 14 and 1^a in the computer classification. That there should be any confusion between V-L 36a and V-L's 14 and 1^a is difficult to accept or understand. V-L 36a consists of tall, sparse to open, grassy shrublands (shrubby grasslands) on shallow, red, base sands overlying dolomite bedrock (sometimes exposed). A few wooded lineaments traverse this V-L. Typical species in the shrub layer are

Tarchonanthus camphoratus, Diospyros lycioides and *Acacia karroo*, but they are generally solitary and well-spaced. This V-L, part of the Kuruman Sourveld Ecological Region, is environmentally quite different to 14 and 1^2. The grasses are a mix of Kuruman Sourveld and Kalahari species and are a major constituent of this V-L.

V-L 36a is also environmentally dissimilar to V-L's 5^2 and 20. In group B, V-L's 5^2, 14 and 1^2 are related, while V-L's 20 and 36a are not related to each other, nor are they related to V-L's 5^2, 14 and 1^2. However, by means of the bispectral plot cluster centre grouping it is evident that, with regard to the reflectance from V-L 36a, a relationship in terms of foliage colour does exist, more so with V-L 14 and 1^2 (Kalahari Thornveld Types). Neither of the latter has a grass layer of dominance such as occurs in V-L 36a. *Tarchonanthus camphoratus* (grey-white) occurs in all three classes, but is mostly hidden in V-L 1^2 by the dominant *Acacia erioloba*. In V-L 14, *Tarchonanthus camphoratus* is much more abundant than it is in V-L 36a and is the only cover class in which the reflectance from the grey-white foliage would have a marked effect on the reflectance reading. V-L 36a is predominantly a browny-green colour from the grass layer, V-L 14 a grey-white with dark green and V-L 1^2 an olive green, grey and browny green mixture. Obviously, the Kalahari sands would give rise to a high reflectance where exposed, which would be a considerable amount in the semi-arid regions. V-L 36a has a higher PCC than both V-L's 14 and 1^2 and would reflect quite highly as a result of the grass layer and red, base sands, with occasional patches of low reflectance as a result of some exposed dolomite bedrock slabs. Group B can be explained only in terms of the "within mixed pixel" problem, as all three cover classes are reasonably uniform in distribution of vegetation pattern. It should also be recorded that many of the pixels representing V-L's 16a, 16b and 4 (just south of the central region of V-L 5) have also been assigned to the multicluster group 14, 1^2 and 36a, but none of these spectral classes was originally used for signaturization.

6.2.3 GROUP D

Group D consists of two cluster centres, representing ground cover types 1^1 and $17a^2$ which are not tightly associated with each other. V-L 1^1 consists of a closed, mixed woodland on deep, pink to yellow, leached Kalahari sands (*Terminalea sericea, Acacia erioloba, Boscia albitrunca* and several other species of less importance, such as *Grewia flava, Ehretia rigida* and

Tarchonanthus camphoratus). V-L 1^1 is a major spectral class of V-L 1. Topographically 1^1 lies on high ground intersected by the Moshaweng River.

V-L $17a^2$ is primarily a mixed, short, closed, Kalahari-Kuruman Sourveld grassland (similar to the vegetation in Plate 4, but with some tall, widely scattered shrubs). The Kalahari element dominates but not excessively. It should be made clear at this point that the training site signaturized to account for the spectral class V-L $17a^2$ (colour-coded dark blue and red in the computer-generated classification) is situated in the eastern distribution of V-L 17a. It is becoming transitional to V-L 36a, and, being a sparse to open, grassy shrubland to shrubby grassland, is often difficult to distinguish from V-L 17a. The eastern and western distributions of V-L 17a are hierarchically separated from each other at the subunit level. V-L $17a^2$ occurs on shallow, red, base, Kalahari sands overlying calcrete bedrock. As with V-L's 14 and 4 (south of "the divide"), V-L 17a represents a rather young extension of the Kalahari sands south of "the divide", currently accelerated by over-utilization of the Kalahari vegetation to the north by white settlement. This results in wind-blown sands, which originate in the Kalahari, being deposited in the south-east by prevailing north-westerly winds. In pre-historic times this area would probably have been vegetated similarly to V-L's 36a and 33. The vegetal cover of V-L 17a is directly related to the presence of the shallow layer of Kalahari sands; the very sparse distribution of solitary species such as *Diospyros austro-africana, Acacia karroo, Tarchonanthus camphoratus* and *Diospyros lycioides* point to its previous structure.

Once again, it is difficult to understand how, in terms of reflectance from the terrain cover, a true Kalahari woodland could become confused with a grassland. The sands, though aeolian, are different in colour. The reflectance of the silvery-white *Terminalia sericea* canopy layer in V-L 1^1 may be similar to the values sensed from the grass layer in V-L $17a^2$, especially if the values of the sand and calcrete (white) are added. It is presumed that once again, the "mixed pixel" problem is in operation. Small percentages of pixels from most cover types have also been assigned to these two clusters.

6.2.4 GROUP E

Group E is colour-coded grey in the computer-generated classification. It consists of three tightly associated cluster centres representing ground cover types 13, 9 and the fresh burn, the latter which would normally consist mainly of terrain cover typical of V-L 9. The burn in the centre of the training area, just north of "the divide", is of two ages: a fresh burn (F.B) was, at the time of field surveying, about a season or two old and occurred mainly in the northern half of the burnt area; an old burn (O.B.) was several years of age and occurred mainly in the southern half of the burn. In the FCC image the two aerially contiguous burns can be distinguished by shades of red; the fresh burn is pinkish red, while the old burn is a deeper brownish red. The burn spans two vegetation landscape units, V-L 9 (mainly the fresh burn) and V-L 1 (mainly the old burn) and must not be confused with *Terminalea sericea* woodland on the FCC image, which is also red. V-L 13 consists of a high, closed, woody shrubland on shallow, red, loamy soils mixed with frequently exposed, andesite rocks and pebbles, typical of V-L 20 just to the north of it. Typical species are *Tarchonanthus camphoratus, Rhus ciliata, Acacia tortilis* ssp. *heteracantha, A. karroo*, and *Ziziphus mucronata*. The grass layer is only patchily exposed and does not dominate the vegetation.

V-L 9 is relatively extensive and occurs in association with both the Moshaweng and Matlhawaring Rivers. It consists of a low, closed woodland, sometimes forming thicket proportions, on pink, calcareous sands, shallowly overlying calcrete bedrock. The calcrete bedrock is highly exposed in places where it forms raised, rounded spurs running perpendicular to the river bed. It is often deeply eroded by dry drainage lines feeding into the rivers, especially the Moshaweng River in the north. Typical species are *Acacia mellifera* ssp. *detinens* (dominant), *Tarchonanthus camphoratus* (dominant and co-dominant), scattered dwarf *Acacia erioloba* and *Grewia flava*. *Acacia mellifera* becomes abundant where the spurs consist of exposed calcrete, while *Tarchonanthus camphoratus* is dominant where the calcrete is covered by a thin layer of Kalahari sands. In this case, thickets do not form, more species of grass occur (also increased biomass) and occasional dwarf *Acacia erioloba* and even very occasional dwarf *A. haematoxylon* are present.

The third spectral cluster centre represents the fresh burn ground cover type. This cover type is obviously temporal and consists of a fire-modified phase of mainly V-L 9 described above (though it extends southwards into V-L 1 as well). At the time of field surveying, the grass layer was well re-established and *Tarchonanthus camphoratus* had begun to coppice, while the major portion of the *Acacia mellifera* woodland on calcrete was still present. This is probably the result of partial destruction only, due to the lack of a high biomass grass layer inherent in this community, thus resulting in lower fuel levels and a "cool" burn. *Tarchonanthus camphoratus*, high in phenols, burns well under any circumstances and hence its removal here.

There is a similarity in the pixel reflectance values in V-L 9 and the fresh burn, representing a portion of V-L 9. The fire damage has not affected the reflectance levels to the extent that pixels representing this cover type are clustered either uniquely or confused with another cluster centre. This is surprising because of the general "opening up" of vegetation to reveal and allow development of a strong grass layer. It should be noted that the vegetation-landscape map should show V-L 9 to be more extensive here. In the vegetation-landscape map, the area which was burnt has not been delineated or classified as a separate unit. Some pixels in the fresh burn have been assigned to the old burn. Field data available are not sufficiently detailed to be certain whether these areas belong to V-L 9 or V-L 1 (where the old burn occurred predominantly).

It is more difficult to assess the reasons for confusion between spectral classes representing ground cover types V-L 9 and fresh burn, and that of V-L 13. Not all the pixels representing this latter V-L are involved, as some were assigned to V-L's 20 and 33. Those that are classified with V-L 9 and the fresh burn are colour-coded grey. It is interesting to note from their distribution that many of these pixels are positioned in an area with relatively large numbers of Tswana inhabitants. The vegetation has had a long history of heavy utilization by goats and donkeys and many of the *Acacia* trees have been cropped for firewood. It is probable that the "mixed pixel" problem may be involved in the confusion of V-L 9 and the fresh burn with V-L 13. It is also obvious that V-L 13 was not sufficiently signaturized to account for the spectral variability present within this unit. The problem is compounded by the fact that V-L 13 is positioned within Bophuthatswana (western regions) and also within the South African farming community (eastern regions) with large differences in vegetation utilization and management practice.

6.2.5 GROUP F

Group F represents ground cover types 5^3 and 4^2 and consists of two cluster centres, not too strongly associated with each other.

V-L 5^3 consists of a sparse to open grassy woodland on deep, red, base sands overlying quartzitic bedrock. Typical species, besides the obviously dominant Kalahari Thornveld grass species (*Stipagrostis* spp., *Schmidtia pappophoroides*, *Eragrostis* spp. etc.), *Acacia erioloba, Terminalea sericea* and occasional *Dicrostachys cinerea*, are widely scattered. V-L 5^3 aerially accounts for only a minor portion of V-L 5, and is geographically patchy. V-L 5^3 is a signaturization of the light patches present in V-L 5 - the high, rounded, sand-covered quartzitic hills forming the western region of "the divide". 5^3 occurs only on the northern, Kalahari-side of the "divide", i.e. the north-facing gentle slopes falling towards the vast Kalahari Thornveld which goes deep into Botswana.

V-L 4^2 consists of a sparse to open, grassy woodland on pink, calcareous sands (similar to the vegetation in Plate 3), positioned within the large section of V-L 4, a vast catchment area for the Moshaweng River. Presumably calcrete bedrock lies deep below these light coloured sands. Typical species, besides the dominant grass layer are *Acacia erioloba*, with some *Tarchonanthus camphoratus, Ziziphus mucronata* and *Grewia flava*; the latter species is associated with the canopy of *A. erioloba*. V-L 4^2 consists of those areas within the catchment zone which appear as a pale grey colour on the FCC image. Both V-L's 5^3 and 4^2 are colour-coded grey in the computer-generated classification and are thus confused with the Group E cluster centres.

V-L's 5^3 and 4^2 are physiognomically very similar, though structurally and floristically dissimilar (many of the grass species in V-L 4^2 are not found in V-L 5^3). Terrain morphology and soil-geology are also dissimilar. The two are in fact, very different landscape types. In terms of reflectance (colour of vegetation and sands) the two cover classes are similar, e.g. the yellow-green of the grass layer, the silver-grey of *Terminalea* and *Tarchonanthus* and the olive green of the *Acacia erioloba* (common to both), while the red and pink Kalahari sands are not all that distinct from each other. Acccordingly, the confusion between V-L's 5^3 and 4^2 can be explained by lack of distinction between several environmental parameters, especially vegetation physiognomy and sands. This results in reflectance values which are so similar that the Landsat system is unable to distinguish adequately between the two vegetation-landscape sub-units, each arising from a different vegetation-landscape unit.

Pixels positioned within sparse to open woodland types present in V-L's 6, 2 and 4 (just south of V-L 5 in the centre of the training area) have also been assigned to these two clusters. In the Kalahari Thornveld Training Area, sparse to open woodland formations are generally problem cover-types for the Landsat system to analyse and classify correctly. Exceptions to this generalization exist and will be discussed below. Pixels in V-L 6 assigned to this grouping are those representing agricultural fields which contain scattered, large *Acacia erioloba* trees not removed during clearing operations. These fields have reflectance values similar to sparse to open woodlands.

6.2.6 <u>GROUP G</u>

Group G consists of three cluster centres representing ground cover types $17a^1$, 4^3 and 4^1. These cover types represent a gradient from grasslands to open woodlands.

V-L $17a^1$ represents pixels which correlate with the western distribution of V-L 17a. It consists of short, closed, mixed Kalahari-Kuruman Sourveld Grasslands with very sparse, scattered *Acacia erioloba* (Plate 4). V-L $17a^1$ occurs on red, base sands overlying calcrete bedrock and has a slightly more dominant Kalahari element (grass species and lack of sparsely scattered Kuruman Sourveld large shrubs; red sands are definitely deeper). It is structurally transitional to V-L 4 (sparse to open woodland, Plate 3) and a gradient exists between V-L's 4 (further to the west and to the north of V-L $17a^1$), $17a^1$ and $17a^2$ (in the east). The gradient is dependent on the depth of the red Kalahari sand (depth below the surface of calcrete and/or dolomitic bedrock).

V-L 4^3 consists of the very pale spectral class within V-L 4 (the large catchment area feeding the Moshaweng River system). These pale cream areas are clearly evident in the FCC image, and appear in the vicinity of drainage lines - the beginnings of the Moshaweng River. V-L 4^3 tends to display some mosaicism, consisting of short, open woodlands (with species such as *Acacia* *erioloba*, *A. mellifera* ssp. *detinens* and *Grewia flava*) or open, grassy *Acacia erioloba* woodland, with occasional patches of *A. mellifera* thicket invasion near the drainage lines. V-L 4^3 occurs on well-washed, pink-white, calcareous soils, but calcrete bedrock is not evident. The particle size is small compared with the red Kalahari, base sands. V-L 4^1 is situated in the extreme north-western corner of the training area (V-L 4) and consists of a sparse to open, grassy woodland on deep, red, base sands. Topographically, it slopes gently southwards towards the dry riverbed of the Moshaweng River. V-L 4^1 contains such species as *Acacia erioloba, Boscia albitrunca* and *Terminalea sericea* and is floristically strongly related to V-L 1, but physiognomically/structurally is related to the sparse to open woodland types on Kalahari sands, V-L 4. In this study, as with all reconnaissance level investigations, the physiognomic/structural type, together with the landscape type, takes preference over pure floristics, which relate more strongly to the plant community/plant association level. Floristically V-L 4^1 is different and V-L's $17a^1$ and 4^3 are similar to each other. Physiognomically/structurally the combination would be V-L's $17a^1$ and 4^1 (parkland-woodland types) with V-L 4^3 separate. In terms of final classification based on all vegetation-landscape attributes, V-L $17a^1$ belongs to one V-L and V-L's 4^1 and 4^3 to another, although V-L's 4^1 and 4^3 belong to two different V-L subunits (the catchment area is a subunit on its own while all other geographical distributions of V-L 4 fall into another subunit).

Vegetal physiognomic/structural attributes (canopy type, cover and colour) correlate more closely with the reflectance-based Landsat system, but even more so when other environmental landscape attributes, such as surface soils, are combined. This is evident from the colour-coding in the computer classification, where V-L $17a^1$ is colour-coded yellow and, while V-L 4^1 is colour-coded brown-orange, many of its pixels have been assigned to the V-L $17a^1$ cluster and so appear yellow too. This shows the physiognomic/structural similarity between V-L's $17a^1$ and 4^1, but this is even more evident in the yellow and brown-orange colour-code mixture of all other geographical distributions of V-L 4 (not specifically signaturized but classified into the same V-L unit. The assignment of many of the pixels in V-L $17a^2$ to $17a^1$ (evident as a yellow colour-coding) shows the similarity of these two subunits and justifies their assignment to V-L 17. The major red colour-coding of V-L $17a^2$ emphasizes its transitionality toward V-L 36a. Many pixels, widely scattered in small groups in V-L 1, have also been assigned to the V-L 17a[1] cluster centre (yellow colour-code). Presumably this occurs where this closed, mixed woodland shows natural patches of sparse to open woodland, or where the closed woodland has been opened up, through anthropogenic disturbance, or where the mixed pixel problem is in operation.

Cluster centre 4^3 represents pixels signaturized in the large catchment area of V-L 4, colour-coded grey.

6.2.7 MONOCLUSTER GROUPINGS

Groups C and H both consist of a single cluster centre, showing the uniqueness of the cover types. Group C consists of pixels representing the burn in the upper central region of the training area. The majority of the pixels belong to what has been referred to as the old burn, although a considerable number of pixels representing the fresh burn are also assigned to this cluster centre. The old burn is colour-coded bright red in the computer classification. This ground cover type consists of a low to short, closed woodland thicket of *Terminalea sericea* on pink, leached sands. Other species present, but scattered, are *Acacia erioloba, Boscia albitrunca* and *Grewia flava* and thus the old burn typically belongs to one of the sub-types present in V-L 1. The grass layer is poorly developed. Much of the *Terminalia* invasion is probably due to heavy grazing pressure following the regrowth of the grass layer after fire (and probably burnt for this reason although this practice is not usual in the semi-arid Northern Cape). The fire probably occurred during 1977 or 1978, following the heavy rains of 1976.

Group H consists of pixels representing V-L 3, colour-coded plum in the computer classification. V-L 3 consists of a dwarf to low, open to intermediate, grassy *Acacia haematoxylon* woodland on pale pink to yellow, deep, base sands (similar to the vegetation in Plate 6). The only other tree species of note is *Acacia erioloba*, usually of scattered density only. Occasionally clumps of *Acacia erioloba* or *Terminalia sericea* occupy some areas. Topographically the area is a gently undulating slope, rising away from the Moshaweng River in the north. Many of the grasses, forbs and herbaceous shrubs are typical of the Southern Kalahari Duneveld, lying to the west and north-west of the training area. It is obvious from the computer classification that not all of the pixels in this cover type have been assigned to this cluster centre. Pixels along the northern boundary have been assigned to the sparse to open woodland groups (colour-coded grey), associated largely with slopes or valleys relating to riverine systems. In this case, it is possible that the pixels have been classified with V-L 2, on which V-L 3 borders. It should also be noted that V-L's 2 and 3 are related to each other in terms of soils, topography and vegetal attributes. A great number of the pixels of this cover type have also been assigned to pixel cluster centres representing short, closed woodlands on pink to yellow, deep, base sands (mainly V-L 1) and are colour-coded pink in the area of computer classification representing V-L 3. Presumably all of these represent at least the wooded patches dominated by *Acacia erioloba* and *Terminalea sericea*, and thus rightly belong to V-L 1, but could not be mapped at this scale. Consequently Group H, representing V-L 3, can be satisfactorily explained in terms of the environmental parameters present.

6.2.8 COMMENTS

As discussed previously in this section, any pixels from cover types 13, 9, fresh burn, 5^3, 4^2 (from the catchment area) and the northern part of 3, are also colour-coded grey in the computer classification. It is interesting to note that some agricultural fields in V-L 6, fresh burn, the unsignaturized V-L's 2, 4^2, 4^3 and small areas within V-L 1 near the river, are all sparse to open woodlands associated with riverine/catchment zones (grey colour-codes). V-L's $17a^1$, 4^1, several unsignaturized areas of V-L 4, many small, scattered areas within V-L 1 and some agricultural fields deep within V-L 6 are very sparsely treed grasslands to open woodlands on aeolian Kalahari sands (yellow colour-code). The extremely broad physiognomic/structural formation of very sparse to open woodlands has been subdivided into two broad groups by the Landsat system. These groups correlate well with soil/geology (pink, calcareous sands and red sands, respectively) and topography (valleys associated with riverine systems and high-lying, sand-covered plains respectively). Here a broad, vegetation physiognomic/structural formation has been subdivided according to topographical and soil/geological criteria. The relationship is not pure in that it is not applicable in every case. For instance, V-L 9, a low, closed woodland thicket, also occurs on the pink, calcareous sands of the valley associated with the Moshaweng riverine system and yet, despite this physiognomic/structural difference, is also colour-coded grey in the computer classification. The same applies to the grey colour-coded V-L 13, a high, closed, woody shrubland on red, loamy soils mixed with andesite rocks and pebbles. Several further examples could be given, even though they are represented by minor pixel clusters. What is of importance here is the fact that, in semi-arid regions with PCC's in the order of 30% to 50%, vegetal attributes such as physiognomy and structure, are not adequate or sufficiently dominant parameters with which to isolate similar or the same vegetation units. It is evident that all environmental parameters have potential use in the system (soil, geology, vegetation, moisture, topography) acting either singly or in complex combinations, or even primarily one parameter but with secondary influence from others. On the other hand, examples have been found where errors are directly due to the Landsat system itself, resulting mainly from the size of the resolution cell, the fundamental unit of the Landsat system). This type of error has been referred to as the "mixed pixel" problem (see section 7). From the comparison of the relevant bispectral plot (Fig. 8) and Table 3 of cluster groupings, it is evident that the generalization of the cluster groupings into broad resource classes is not possible. By comparing the ground cover, it is difficult to describe the Landsat-derived cluster groupings in any meaningful way.

6.3 GHAAP PLATEAU TRAINING AREA

Fig. 9 is the bispectral plot showing the derivation of the spectral clusters appearing in the classification. Table 4 is the bispectral plot matrix with the "resource classes" obtained using the supervised, unsupervised and hybrid methods of classification.

6.3.1 GROUP A

This group, with the lowest range of reflectance values, consists of four clusters which represent ground cover areas containing V-L's 37^3, 37^1, 39^5 and 39^4. V-L 37^3 is slightly removed from the other subunits. For the greater part, V-L 37 consists of woody shrublands; thickets on brown soils overlying calcrete and dolomite. Likewise, the greater part of V-L 39 consists of grasslands and sparse to open shrublands on brown soils overlying dolomite bedrock. Both V-L's 39^5 and 39^4 are minor subunits of V-L 39 and certainly not representative of this unit, though V-L 39^5 is of importance. V-L 39^4 is an isolated area containing a closed, shrubby woodland-thicket (*Acacia karroo, Rhus lancea, Diospyros lycioides, Maytenus heterophylla*) on dark brown soils, shallowly overlying rugged dolomite bedrock. V-L 39^5 is a

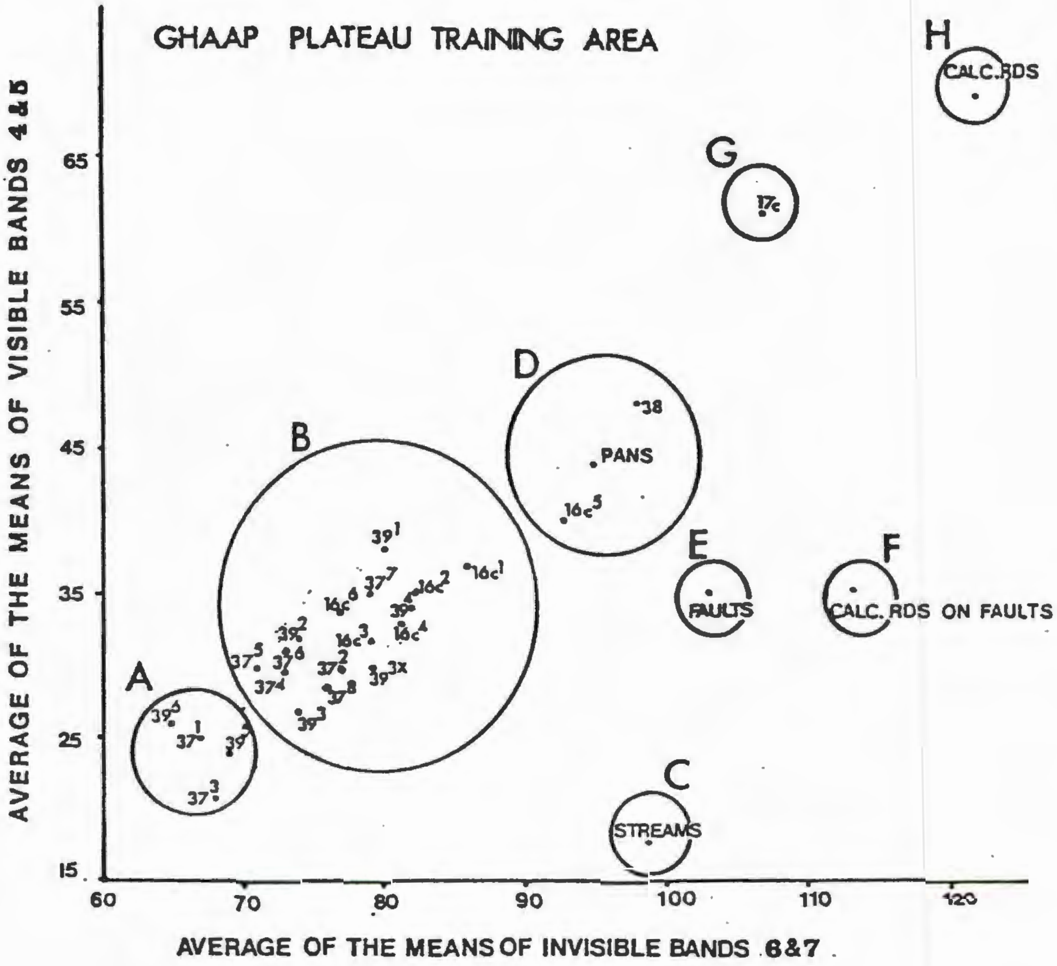


Figure 9 Derivation of spectral cluster groupings, using the bispectral plot clustering technique, resulting from the supervised, unsupervised and hybrid methods of classification of Landsat MSS digital data.

TABLE 4 : CLUSTER CLASS AND VEGETATION - LANDSCAPE UNIT DESCRIPTIONS FOR COMPUTER-ASSISTED, LANDSAT - DERIVED CLASSIFICATION OF THE GHAAP PLATEAU TRAINING AREA.

AVERAGE OF MEANS - VISIBLE (BANDS 4 AND 5)	AVERAGE OF MEANS - INVISIBLE (BANDS 6 AND 7)	VEGETATION - LANDSCAPE UNIT/SPECTRAL CLUSTER CODE	DESCRIPTION OF GROUND COVER OF VEGETATION - LANDSCAPE UNIT OR SUBUNIT/SPECTRAL CLUSTER	CLUSTER CLASS GROUP	GENERALIZATION OF SPECTRAL CLUSTER
21	68	37^3/G14B(3)	short, closed, mixed shrubby woodland (Olea, Rhus spp.,Euclea spp., T.camphoratus T. minor, Maytenus heterophylla, Rhigozum obovatum, Acacia mellifera) on rugged dolomite BR (often exposed) (Ghaap Pl. Escarp.)	A	closed shrubby woodland on dol.
24	69	39^5/G36(5)	closed woodland-thickets (A.karroo D. lycioides, Euclea undulata, Lycium spp.,E. crispa) on linear dolomite ridges, occ. covered with dark brown soil but mostly exposed dolomite rocks and boulders	A	closed woodland thickets on dol. ridges
25	67	37^1/G14B(1)	See 37^3 but even denser (thicket formation)	A	thicket on dol.
26	65	39^6/G36(6)	closed, shrubby woodland - thicket (A. karroo, R. lancea, Diospyros lycioides, M. heterophylla) on dark brown soil overlying and between exposed rugged dolomite BR (isolated distrib.)	A	closed shrubby woodland on brown soils - dol.
30	73	37^4/G14B(4)	open to intermediate, mixed, woody shrublands (T. camphoratus, O. europaea ssp. africana, Rhus spp.) on dolomite BR but rather intermediate than open formation class	B^1	intermed. woody shrubland on dol.

AVERAGE OF MEANS - VISIBLE (BANDS 4 AND 5)	AVERAGE OF MEANS - INVISIBLE (BANDS 6 AND 7)	VEGETATION-LANDSCAPE UNIT/SPECTRAL CLUSTER CODE	DESCRIPTION OF GROUND COVER OF VEGETATION - LANDSCAPE UNIT OR SUBUNIT/SPECTRAL CLUSTER	CLUSTER CLASS GROUP	GENERALIZATION OF SPECTRAL CLUSTER
30	71	37^5/G14B(5)	open to intermediate, mixed, woody shrublands (T. camphoratus, O. europaea ssp. africana, Rhus spp.) on dolomite BR	B^1	intermed. woody shrubland on dol.
31	73	37^6/G14B(6)	open, mixed, woody shrublands (T. camphoratus, O. europaea ssp. africana, Rhus spp.) on dolomite BR and occ. calcrete outcrop (transitional to 16c)	B^1	open woody shrubland on dol.
32	74	39^2/G36(2)	Sparse to open, grassy R. lancea woodland on dolomite BR	B^1	sparse R. lancea woodland on dol.
30	79	39^3/G36(3)	open, mixed, woody T. camphoratus shrubland on calcrete and dolomite BR	B^2	open T. camphoratus shrubland on calc.
29	76	37^8/G14B(8)	closed, mixed, shrubby woodlands (O. europaea ssp. africana, Rhus spp., T. camphoratus) on frequently exposed dolomite BR slabs	B^2	closed shrubby woodland on dol.
30	77	37^2/G14B(2)	closed, mixed, woody shrublands (dominated by T. camphoratus) - thickets; on dolomite BR (often exposed) and occ. calc. outcrops	B^2	closed woody woodland on dol.
27	74	39^{3x}/G36(3)	(unsupervised) v. sparse, grassy shrubland (widely scattered A. karroo) on dolomite BR slabs (soils dark brown)	B^2	sparse shrubland on brown soils - dol.

AVERAGE MEANS - VISIBLE (BANDS 4 AND 5)	AVERAGE OF MEANS - INVISIBLE (BANDS 6 AND 7)	VEGETATION - LANDSCAPE UNIT/SPECTRAL CLUSTER CODE	DESCRIPTION OF GROUND COVER OF VEGETATION - LANDSCAPE UNIT OR SUBUNIT/SPECTRAL CLUSTER	CLUSTER CLASS GROUP	GENERALIZATION OF SPECTRAL CLUSTER
32	79	16c^3/G14A(3)	closed *T. camphoratus* - *Rhus ciliata* shrublands on red, base soils overlying pure calcrete bedrock (exposed)	B^2	closed *T. camphoratus* shrubl. on red soils
33	81	16c^4/G14A(4)	woody species (i.e. transitional to V-L 37 but also structurally transitional to V-L 38; *Olea europaea* ssp. *africana*, *Rhus pyroides*, *R. lancea*, *Ziziphus mucronata*) on calc. and some exposed dolomite BR	B^2	closed *O. europaea* ssp. *africana* shrubland on calc.
34	82	39^4/G36(4)	open, grassy *R. lancea*, *Acacia karroo* woodland on dolomite BR slabs, often exposed	B^2	open *R. lancea* woodland on dol.
35	82	16c^2/G14A(2)	woody species (i.e. transitional to V-L 37) (*O. europaea* ssp. *africana*, *Rhus pyroides*, *R. lancea*, *Ziziphus mucronata*) on calcrete and some exposed dolomite BR	B^2	closed *O. europaea* ssp. *africana* shrubland on calc.
34	77	16c^6/G14A(6)	intermediate *T. camphoratus* shrublands (+ widely scattered *O. europaea* ssp. *africana*, *R. lancea*, *R. ciliata*) on red-brown, base soils overlying calcrete BR (often exposed)	B^3	intermed. *T. camphoratus* shrubland on red - brown soils
35	79	37^7/G14B(7)	open, mixed, woody shrublands(*T. camphoratus*, *O. europaea* ssp. *africana*, *Rhus* spp.) on dolomite BR and occ. calcrete outcrops (transitional to 16c)	B^3	open woody shrubland on dol.

AVERAGE OF MEANS - VISIBLE (BANDS 4 AND 5)	AVERAGE OF MEANS - INVISIBLE (BANDS 6 AND 7)	VEGETATION-LANDSCAPE UNIT/SPECTRAL CLUSTER CODE	DESCRIPTION OF GROUND COVER OF VEGETATION - LANDSCAPE UNIT OR SUBUNIT/SPECTRAL CLUSTER	CLUSTER CLASS GROUP	GENERALIZATION OF SPECTRAL CLUSTER
38	80	39^1/G36 (1)	short, closed grassland with very sparse, solitary woody species on shallow brown soils overlying dolomite BR	B^3	grassland on brown soils
37	86	$16c^1$/G14A(1)	closed *T. camphoratus* shrubland; red, base soils overlying pure calcrete BR (often exposed)	B^4	closed *T. camphoratus* shrubland on red soils
40	93	$16c^5$/G14A(5)	sparse to open, grassy *T. camphoratus* shrublands on red, base soils, shallowly overlying calcrete BR infrequently exposed	D	sparse *T. camphoratus* shrublands on red soils
44	95	pans/G calc. (pan)	small pans and calcrete depressions; sparse, short grasslands on calcareous soils and calcrete, highly exposed	D	grassy pans, calc.
48	98	38/G92	short, open to closed, shrubby woodland (parkland) (*O. europaea* ssp. *africana* and *R. lancea*) on shallow, brown soils (frequently absent) over calcrete	D	*O. europaea* ssp. *africana* - *R. lancea* parkland on brown soils - calc.
18	109	streams/G red veg. 1	streams, with actively growing, closed *Cyperus* "grasslands", *Phragmites* - *Typha* reedbeds, on alluvial, peaty, heavy soils	C	streams with sedges
35	103	"faults"/ G red Veg. 2	closed *A. karroo* - *D. lycioides* woodland - thicket on raised, calcrete lineaments (sometimes covered by dark brown soils) or "faults"	E	closed *A. karroo* woodland on lineaments

AVERAGE OF MEANS - VISIBLE (BANDS 4 AND 5)	AVERAGE OF MEANS - INVISIBLE (BANDS 6 AND 7)	VEGETATION-LANDSCAPE UNIT/SPECTRAL CLUSTER CODE	DESCRIPTION OF GROUND COVER OF VEGETATION-LANDSCAPE UNIT OR SUBUNIT/SPECTRAL CLUSTER	CLUSTER CLASS GROUP	GENERALIZATION OF SPECTRAL CLUSTER
35	113	calc. roads on faults/G roads	scraped tertiary roads and farm tracks on raised lineaments or "faults", bordered on either side by intermediate to closed, woody shrublands (*Olea*, *Euclea* spp., *T. camphoratus*, *Rhus* spp., *B. albitrunca*, etc.)	F	calc. roads on lineaments
61	107	17c/G37A	low to short closed grassland with very widely scattered solitary trees and large shrubs on alluvial to red-brown soils	G	grasslands on alluv. or catchments
69	122	Calc. roads/ G.C. rd.	calcrete-surfaced roads through V-L 16c, 37 and 39; roads tertiary and secondary with scraped verges	H	calc. roads on lineaments

closed woodland-thicket on linear dolomite "step" ridges covered in places by dark, brown soil. Dominant (height and cover) species are *Acacia karroo, Euclea* spp., *Olea europaea* ssp. *africana, Boscia albitrunca*, *Rhus* spp. and *Diospyros lycioides*. Species present in V-L's 39^{4} and 39^{5} are similar, but the linear "step" ridges are topographically unique to the latter. It is understandable that these two subunits are low in reflectance values. Although V-L 39^{5} would seem structurally and floristically very different to the other subunits in V-L 39 (especially the dominant subunit 39^{2}: sparse to open, grassy *Rhus lancea* woodland), striking mosaicism prevails and V-L 39^{5} is very much a part of V-L 39 which cannot even be adequately mapped at this scale of map product.

V-L's 37^{1} and 37^{3} are almost identical and, furthermore, are dominant subunits of V-L 37. Both occur in close association with the Ghaap Plateau Escarpment and in the initial field surveys were not distinguished from each other. V-L 37^{1} may possibly be more structurally dense than V-L 37^{3}. Both subunits are short, closed, mixed shrubby woodland-thickets (*Olea europaea* ssp. *africana, Rhus undulata*, *R. tridactyla, R. lancea, R. pyroides, R. ciliata, Euclea undulata, E. crispa* ssp. *ovata, Tarchonanthus camphoratus, T. minor, Rhigozum obovatum, Acacia mellifera, Maytenus heterophylla* and many more). These subunits occur on shallow, brown soils overlying frequently exposed rugged dolomite bedrock. V-L's 39^{5} and 39^{4} are structurally (and floristically, to a large degree) moderately dissimilar to V-L's 37^{1} and 37^{3}. V-L's 37^{1}, 37^{3}, 39^{5} and 39^{4} are geographically distributed in close association with one another. While the human eye can easily detect environmental dissimilarities between the four subunits in the field, it is understandable that similarities in reflectance level have resulted in the grouping together of cluster centres. The broad resource class of "Dense Ghaap Plateau vegetation on dolomite bedrock" may be applied to this group.

6.3.2 GROUP B

The pixels classified into Group B in the Ghaap Plateau Training Area, representing ground cover falling within V-L's 16c, 37 and 39, all have moderate to low reflectance values in the visible (4 and 5) and invisible (6 and 7) bands respectively, i.e. areas which appear relatively dark on the hardcopy false colour composite image. These pixels are therefore divided spatially, in terms of purely vegetal subunits, between tall, closed

Tarchonanthus shrublands (V-L 16c, Plate 5 in Paper 1), short, closed, shrubby *Olea-Tarchonanthus-Rhus* woodlands (V-L 37, similar to the vegetation in Plate 9, Paper 1, but denser and lower) and high, sparse to open, woody *Tarchonanthus-Rhus* shrublands (V-L 39, structurally similar to the vegetation in Plate 4, Paper 1). From Table 4 it is apparent that the composition of the indistinct sub-groups within the bispectral plot group B is for the main part, false.

One look at the hardcopy false colour composite image shows that, in terms of reflectance (here seen as various shades of blue-purple-black), the majority of the ground cover areas of V-L's 16c, 37 and 39, are related. In real terms, they all belong to the Ghaap Plateau Ecological Region, all are shrublands or woody shrublands but vary in density from sparse (almost pure grassland) to closed (almost a thicket) structural formation. The same group of species/growth forms (analysed more in terms of foliage colour than taxonomy) is present throughout, though the species cover-abundance values vary considerably from one V-L to the next. The species which are important in terms of cover-abundance in all three V-L's are:

a) *Tarchonanthus camphoratus* (foliage light grey): abundant in V-L 16c; common in V-L 37; uncommon in V-L 39

b) *Rhus* species (foliage mainly olive green): common in V-L 16c; abundant in V-L 37; common in V-L 39

c) *Olea europaea* ssp. *africana* (foliage grey): occasional to uncommon in V-L 16c; abundant in V-L 37; occasional in V-L 39

d) *Acacia* spp. (foliage bright to dark green): sparse in V-L 16c; uncommon to common in V-L 37; common in V-L 39

e) open graminoid layer (yellowy green): uncommon in V-L 16c; occasional in V-L 37; common to abundant in V-L 39.

In terms of soil/geology complex, V-L's 16c, 37 and 39 are similar. In all three V-L's the geology is often exposed.

a) V-L 16c has red, base soils overlying calcrete bedrock

b) V-L 37 has red-brown base soils overlying calcrete and dolomite bedrock

c) V-L 39 has brown soils overlying dolomite bedrock, often intersected by raised calcrete lineaments ("faults").

An analysis of which clusters represent dominant (area) pixel numbers is given in the discussion of the subgroups.

In terms of ground cover, V-L's 16c, 37 and 39 are interrelated, with V-L's 37 and 39 closer to each other than to V-L 16c. Both the FCC image and the computer-generated classification show this trend. The bispectral plot of the mean reflectances of signatures shows this trend even more clearly with the gradient from V-L 16c to V-L's 37 and 39. While V-L 16c is relatively well grouped, V-L 37 and 39 are almost totally integrated. Several sub-groupings can be found in Group B of the bispectral plot:

1. Subgroup 37^4, 37^5, 37^6 and 39^2: V-L's 37^4, 37^5 and 37^6 consist of open to intermediate, mixed, woody shrublands on dolomite bedrock. V-L 39^2 consists of a very sparse to open, grassy woodland on dolomite bedrock. The dominant ground cover type of V-L 39 is totally confused with the less dense vegetation types of V-L 37, where some calcrete uncharacteristically occurs. The "mixed pixel" problem may be applicable to the confusion between V-L 39^2 and V-L's 37^4, 37^5 and 37^6.

2. Subgroup 39^3, 37^8, 37^2, 39^{3x}, $16c^3$, $16c^4$, 39^4 and $16c^2$: This large subgroup shows a gradient from V-L 39^3 to V-L $16c^2$, with possible subdivision into V-L's 39^3, 37^8 and 37^2; V-L's 39^{3x} and $16c^3$; V-L's $16c^4$, 39^4 and $16c^2$. This sub-group cannot be explained in any straightforward manner, as spectral clusters representing ground covers as different as *Tarchonanthus*-dominated shrublands; sparse, grassy shrublands and closed, mixed, woody shrublands appear tightly clustered together. (Soil/geology varies from red to dark brown soils and from calcrete-dominated (white) to pure dolomite (black) bedrock.) The "mixed pixel" problem is certainly present here; variability remains too large, regardless of any further subdivisions.

3. Subgroup $16c^6$, 37^7 and 39^1: V-L 39^1 is slightly further placed from the two former clusters, but this subgroup generally does not show the tight clustering evident elsewhere in Group B. V-L's $16c^6$ and 37^7 are similar in that V-L $16c^6$ is an intermediate *Tarchonanthus* shrubland (light grey foliage), with widely scattered *Olea europaea* ssp. *africana*, *Rhus lancea* and *R. ciliata* (dark green to grey foliage), occurring on red-brown base soils overlying calcrete bedrock, i.e. 100 m^2 grassy patches occur between shrubs/trees. V-L 37^7 is an open, mixed woody shrubland (dominated by *Tarchonanthus camphoratus*, *Olea europaea* ssp. *africana* and several *Rhus* spp.), occurring on brown soils overlying dolomite bedrock with occasional calcrete

outcrops. The grassiness is obvious in V-L 37^7. Though neither is truly transitional, V-L $16c^7$ is moving towards the V-L 37 "complex" and V-L 37^7 is moving towards the V-L 16c "complex". The reflectance ranges in these two clusters are adjacent to each other. The ground cover units are also adjacent to each other. The "mixed pixel" problem, within and between V-L's $16c^6$ and 37^7 in this case, is evident.

V-L 39^1 is a short, closed grassland, with woody species, *Rhus lancea* and *Acacia karroo*, solitarily distributed. V-L 39^1 occurs on shallow, brown soils overlying dolomite bedrock slabs. In terms of vegetation structure and species presence/absence, V-L 39^1 is very far removed from V-L's 37^7 and $16c^6$ but, in terms of cluster centre distance (based on reflectance range), there is a moderate association. One wonders how this is possible when one considers the hue differences on the FCC image. This is obviously a "mixed pixel" problem. As is the case with V-L $16c^1$, it could be argued that V-L 39^1, on its own, could be regarded as a separate subgroup of Group B.

4. <u>Subgroup $16c^1$</u>: This ground cover type is the most extensive in V-L 16c and is also the most extensive subunit in the computer classification of V-L 16c (colour-coded blue). It is pleasing to note that V-L $16c^1$ is slightly distanced from the nearest cluster in the bispectral plot Group B. V-L $16c^1$ consists of a closed *Tarchonanthus* shrubland on red, base soils, shallowly overlying pure calcrete bedrock (often exposed).

The following two points are relevant with regard to Group B:
Firstly, it is possible that a subdivision of this group should not be attempted as Group B clearly forms a relatively tight group. Two other subgroupings were investigated:

a) 37^5, 34^4, 37^6, 39^2, $16c^6$, 37^7 and 39^1 as subgroup 1;
 39^3, 37^8, 37^2, 39^{3x}, $16c^3$, $16c^4$, 39^4, $16c^2$ and $16c^1$ as subgroup 2
b) 37^4, 37^5, 37^6 and 39^2 as subgroup 1;
 39^3, 37^8, 37^2, 39^{3x} and $16c^3$ as subgroup 2;
 $16c^6$ and 37^7 as subgroup 3;
 $16c^4$, 39^4 and $16c^2$ as subgroup 4;
 39^1 as subgroup 5;
 $16c^1$ as subgroup 6

The resource classes generated by these two subgroupings were no better than those generated by the subgroupings discussed in detail. The diagnosis of

Group B requires some level of subgrouping and possibly the dendrogram method of analysis would result in an objective subgrouping.

Secondly, given the real and reflective relationships between V-L's 16, 37 and 39, it is understandable that some confusion will result on the ground, the FCC image and in the computer classification. Interrelationships do exist; the degree of interrelationship is dependent on scale. At the reconnaissance level there is a considerable amount of lumping of subgroups, whether based on landscape, vegetation or reflective criteria. The computer classification of a training area of this size, however, forces one to a semi-detailed level of investigation and dictates that these vegetation-landscape subunits be recognized and separated. Some of the subunits are intrinsically similar in reflectance levels but the computer classification has, in the majority of cases, exaggerated the closeness evident in the field. It may be concluded that some units are naturally too closely related to expect the Landsat system to portray their separability, and that others are presumably inseparable as a result of the Landsat system error referred to as the "mixed pixel" problem.

6.3.3 GROUP D

This group consists of three clusters, representing ground cover areas containing ground cover classes: "pans" (not mapped), V-L 38 and V-L 16c^5. The three are relatively well-spaced. All three units are colour-coded light blue and patches of white in the computer classification. It could be argued that the three cluster centres should each be separate monocluster groups.

V-L 16c^5 consists of sparse to open, grassy, *Tarchonanthus* shrublands on red, base soils shallowly overlying calcrete bedrock, less exposed than is usual for V-L 16c. In the computer classification V-L 16c^5 is scattered in small patches throughout V-L 16c. "Pans" are small "saucer" depressions in the calcrete bedrock supporting a sparse, short grassland on calcareous soils (in the central areas) and exposed calcrete (outer slopes). These pans are often surrounded, to a distance of 30 m to 100 m, by an intermediate woodland (*Olea europaea* ssp. *africana*, *Rhus lancea*, *Ziziphus mucronata*, in higher density than usual for V-L 16c, and *Tarchonanthus camphoratus*, in lower density than usual for V-L 16c, sometimes even absent). V-L 38 consists of an open to closed *Olea-Rhus lancea* woodland (parkland) on very shallow, brown soils (frequently absent) overlying calcrete bedrock

(Plate 9). This unit also includes the Klein-Boetsaprivier area where much of it consists of sedges and occasional thickets of *Phragmites australis* and *Typha capensis*.

All three units are structurally and floristically dissimilar. While they occur on calcrete, the exposure percentage varies per unit and other than in the case of the "pans", will not dominate reflectance. The "mixed pixel" problem is in evidence here, i.e. integrated reflectance levels close enough to result in classification confusion.

6.3.4 MONOCLUSTER GROUPINGS

All remaining groups are monocluster groupings, well-separated from each other, emphasizing their uniqueness in spectral reflectance levels. All have moderate to high reflectance levels, in the invisible bands (6 and 7, infra-red to far infra-red) or in both visible (bands 4 and 5) and invisible bands.

Group C, representing the vlei-marshy "streams" traversing the Ghaap Plateau, shows up as bright red on the FCC image, owing to the active growth of Cyperaceae beds and solid stands of *Phragmites australis* and *Typha capensis*. This vegetation remains in the active growing stage throughout the summer months owing to the availability of moisture, either concentrated in the "streams" or because of the high moisture retention capabilities of the brown-grey clay soils.

Groups E and F, "faults" and calcrete lineaments traversing V-L's 16c, 37 and 39 but especially V-L's 16c and 39, though separated, are not too far removed from each other and can be discussed together. They are also reddish-black in the FCC image due to the active vegetation growth. The "faults" are known to have concentrations of underground water (hence the high number of boreholes positioned on or adjacent to these lineaments) which has resulted in the establishment of closed *Acacia karroo - Diospyros lycioides* woodland thickets of considerable height (Plate 12) in group E. The presence of dark-brown soils, high in humus concentration, is common. This group occurs mainly in V-L 39.

In "calcrete roads 'on faults'" (Group F), the lineaments tend to be not as high but much wider (50 m to 100 m as opposed to 10 m to 20 m) and support an intermediate to closed, woody shrubland (*Olea europaea* ssp. *africana*, *Euclea* spp., *Rhus* spp., *Tarchonanthus* spp., *Boscia albitrunca* and others) on frequently exposed calcrete. In both groups, exposed dolomite bedrock occurs on either side of the fault. This group occurs most commonly in V-L 16c where, owing to the nature of the calcrete surface, many tertiary roads and farm tracks have been built on the lineaments by merely scraping away the top 100 mm of soil-calcrete mixture. Both units contrast markedly with the vegetation through which they "run", not only because of the density (cover) and height of the vegetation they support, but also because of the species composition. As noted above, this is due to the availability of underground water.

In contrast to Group F ("calcrete roads on 'faults'"), Group H "calcrete roads", with the highest reflectance levels in both the visible and invisible bands, consists of calcrete-surfaced roads cutting through all V-L units. The majority of these are secondary and tertiary roads, colour-coded white in both the FCC image and the computer-generated classification and can be found in Fig. 6. It is interesting to note that changes/new additions/omissions to the topographical map-positioned roads (based on aerial photographs obtained 10 to 12 years ago) can be made simply by using an overlay from the FCC image of the same scale.

Group G represents the cluster centre of pixel groups positioned largely in the ground cover areas classified as V-L 17c (low to short, closed grasslands on "alluvial" to red-brown soils of large catchment areas, similar to the vegetation in Plate 8, Paper 1) and is uniquely classified as yellow and white colour-codes in the computer-generated classification. It is interesting to note that the pixel groups representing grasslands V-L 17d, though not signaturized in this training area and therefore not discussed further, do not cluster near or within this cluster centre, but rather with V-L 38.

6.3.5 COMMENTS

The relationships between V-L's 16c, 37 and 39 notwithstanding, there is confusion between the various vegetation-landscape units in Groups A and B when the criterion of reflectance emanating from the terrain cover is considered. Some of the confusion appears to result from actual, though surrogate, relationships within and between heterogeneous vegetation types.

For the greater part, however, the confusion appears to be due to the "mixed pixel" problem and has no basis in the real world. The mass of spectrally-based cluster centres of Groups A and B tends to hide the revealing fact that, through signaturization of many spectrally different low pixel number classes, the great majority of cluster centres account for a low percentage/area of the three ground cover units. If only the clusters representing most of the area are considered, then clusters $16c^1$, 37_1, 37^2, 37^3 and 39^2 are of concern. These five clusters are well separated from each other on the bispectral plot thus emphasizing their uniqueness and evidencing the correlation between Landsat spectral units and ground-based terrain cover classes stressed by so many authors. This fact tends to be obscured by all other minor spectral classes/minor vegetation-landscape subunits normally prevalent in heterogeneous natural ecological units. In the bispectral plot, cluster centres representing major portions of V-L's 16c and 37 are found lying at opposite extremes, with V-L 39 equidistant between these two. Removal of all minor spectral classes would result in the three cluster centres being well-spaced. Classification errors may be due to a combination of the true natural heterogeneity of natural ecosystems, the strong reflective relationships between the Ghaap Plateau terrain classes and a Landsat system error.

In this spatial stratification study, the statistical grouping of the cluster classes makes it difficult to isolate the groups further according to some common, more generalized parameter or set of parameters applicable to all cluster centres in the group or sub-groups.

In the study by Todd *et al.* (1980), the cluster centres were grouped in this way to form several resource classes. These resource classes did not follow one theme throughout, but were found to vary from one group to the next, i.e. vegetation, topography or geology. The purpose of their mapping of Landsat data was to derive land-cover classes. In the present study, multicluster Groups A, B and D could not be explained in the same way as no common environmental/landscape parameter or set of parameters (be they geology, vegetation height, percentage cover, foliage colour, number of strata, floristics, topography, soils or moisture regimes) could be found throughout the group. In a number of cases all but one cluster may have fitted a given resource. The possible reason for this is that a classification system based on reflectance values of approximately 260 000 individual, separately classified picture elements, representing the surface area of the Ghaap Plateau training area, does not necessarily have to relate to landscape units of the area in question. These units are by their very nature, broad categories.

Several of the subgroups within a group (e.g. Group B) have a common resource class applicable to all cluster centres present in the subgroup, especially resources such as geology and topography. None of these, however, is based upon any vegetational characteristics, a resource which should be the most obvious environmental parameter applicable to the class, especially physiognomy. The classification places terrain units such as "calcrete roads" (Group H), crossing several V-L units, and "calcrete roads on 'faults'" (Group F) as being quite different from each other (see bispectral plot Fig. 9), yet terrain units/landcover classes as dissimilar as sparse shrublands, closed woodlands and panveld (V-L's 16c^3, 38 and "pans", Group D, respectively) group together. On comparison of the bispectral plot and the table of cluster groupings, it is obvious that it is not possible to generalize the cluster groupings into broad resource classes. When this was done with Group A, the resulting resource class was too weak and indistinct. The problem of "mixed pixels" alluded to earlier, may well be responsible for these anomalous situations.

Where a known terrain unit shows a strong colour-code mosaic in the classification, reference to the bispectral plot may show that the cluster centres lie adjacent to one another. If this is not so, then the colour-code assignment is, in all probability, valid. Cluster centres too similar to be separated (i.e. lying adjacent to one another) cannot be pooled simply on the basis of their spectral similarity. Group B is such a group.

Usually pooled spectral classes are assigned a new colour-code or are given the colour-code of one of the similar classes. The result of this is a more "tidy" unit in the computer classification and a misleading impression of accuracy. A system followed by Mayer & Fox (1981) is the comparison of spectral classes to one another by means of a separability matrix. Spectral classes were pooled or deleted on the basis of their separability. Decisions were made as follows:

a) A class exhibiting confusion with two or more classes was deleted,

b) If only two classes were similar, they were pooled.

It is clear that in this study there were instances where these conditions prevailed. Before pooling or deletion become options, however, the geographical areas concerned must be identified and the environmental parameters reviewed. Spectral similarity alone should not be a primary criterion in the decision-making process. If the cover types are sufficiently similar and a meaningful resource class can be created without threatening the "real world" classification scheme, then pooling or deleting can be justified. In this study, reflectance similarity was greater than environmental similarity. Forcing a "tidier" computer classification using Mayer & Fox's (1981) method was not an option. The true diversity would have been oversimplified.

7. THE PROBLEM OF MIXED PIXELS

Although difficult to prove statistically, it is possible that problems in the correct classification or assignment of pixels to the correct cluster centre were directly due to a Landsat system error. Interpretations of unacceptable pixel classifications could not be explained by any primary environmental parameter nor by complex combinations of these primary parameters. Roller & Visser (1980) encountered these problems in their study of forest cover types. In many cases they could ascertain why confusion of classes occurred, and found the Landsat system highly accurate in classifying small, unique groups of pixels in heterogeneous landscape types; the findings of this study concur. In certain instances, no plausible explanation could be given and they concluded that the mixed pixel problem may be evident.

The colour-coding of the computer classification and/or the grouping of cluster centres in the bispectral plot gives the investigator accurate indication of which units are being confused. Consider the following example: in a group of four units, three may show some distant or close relationship, but the fourth unit does not fit into the group in any plausible way. In the computer classification, the three related as well as the fourth, unrelated unit, have the same or similar colour-coding. In the bispectral plot the four units form a tight grouping. Owing to their inherent relationship, one would expect the three vegetation-landscape units to be classified by the computer as being the same unit, or very strongly related. If each unit were separately signaturized and colour-coded, e.g.

red, yellow and blue, then each unit would probably be dominated by its specific colour-code, but would contain many pixels of the other two colours as well. This situation was evident in several areas in each of the training area computer classifications. The reflectance levels are so similar that no unit is uniquely classified, and hence the integration. In this case, the confusion of the units is acceptable since they do have an inherent similarity. One might find, however, that there are scattered patches of these colour-codes throughout. These could be a result of isolated patches of vegetation-landscape similar to one of the three units. If this is not so, then the mixed pixel problem applies. Cihlar *et al.* (1978) overcame the problem of scattered, incorrectly classified pixels by applying a strong spatial filter which reassigned the isolated pixels to themes dominating the neighbourhood. By so doing, the reason for the misclassification is side-stepped which may not always be advisable.

The three related units have been discussed, but what of the fourth which bears no relationship to the other three vegetation-landscape units? In the computer classification this fourth unit may be colour-coded any one of the codes red, yellow or blue or contain a good mix of all three (if not signaturized). If a training site was positioned within this unit and colour-coded after signaturization as say, green, then some of this unit's pixels would also contain green colour-coding. Subsequent signaturization need not necessarily result in an overall improvement in classification accuracy, and could even result in a deterioration in some areas. The computer classification and the bispectral plot indicate a strong relationship between this unit and the other three, showing that in terms of mean reflectance per pixel, there is a considerable overlap in range of values. In terms of environmental parameters, it is difficult to imagine any reason at all for this unit grouping with the other three. The theory of mixed pixels has relevance here, and some shortcoming of the Landsat system itself is indicated.

7.1 TERRAIN UNIT SCALE AND LANDSAT RESOLUTION

Short (1982) is one of few authors who mentions the concept of mixed pixels and gave the following definition: "The averaging of radiances from different objects within each IFOV [instantaneous field of view] gives rise to the concept of mixed pixels." It will be argued that there are two types of mixed pixel problems and that the reasons for their existence encompass

Landsat system error, heterogeneity of the natural environment, resolution decisions and scale of terrain units.

The constituents of a terrain feature type are:

a) On the microscale: cover of rock, soil, litter, grass, shrubs, trees and shadow,

b) On the mesoscale: vegetation structural groups (growthform x cover), consisting of pockets of grassland, shrubland, thickets, pans, etc.,

c) On the macroscale: the formation class (structural group x height x dominant floristics) and potential boundary problems between two single component formations.

Every formation class consists of microscale and mesoscale terrain features. The spectral reflectance from any area of the earth's surface can be highly variable depending on the specific mix of terrain features and can lead to contiguous units having similar or dissimalr reflectance values, accurately or inaccurately so in terms of environmental parameters under consideration.

The mixed pixel problem can be cover class dependent and will vary from one geographic region to another. In nature, systems are seldom homogeneous and ground features (especially biotic forms) are seldom randomly or uniformly distributed. There is also the natural variability of most environmentally-based cover classes, radiating from some central point outwards to where the variability of one cover class becomes the variability of another. Ground features in a cover class vary in their proportionality and the proportionality is scale and feature dependent. All these aspects affect the reflectance of the cover class, both in specific values recorded and the range over which these values stretch. The resolution is fixed for a satellite type or satellite series.

The term "mixed pixels" (assignment of pixels to several cluster centres) refers to two distinct problem areas, which are directly resolution (pixel) and cover-class type dependent:

a) the intrinsic pattern of a cover class is larger than 0,45 ha (a pixel, the basic Landsat system unit is approximately 0,45 ha) - non-random, non-uniform distribution and variability of individual ground features. This has been designated the "between mixed pixel" or "straddling" problem.

b) when the intrinsic pattern of a cover class is smaller than 0,45 ha - random, uniform distribution and variability of individual ground features. This has been designated the "within mixed pixel" problem.

The "between mixed pixel" problem is portrayed diagramatically in Fig. 10. If intrinsic environmental pattern distribution is larger than the pixel size and pixels fall wholly within and straddle one or another ground feature, resulting reflectance values vary greatly from one pixel, or group of pixels, to another over the geographical distribution of the cover class type. In this case, classification accuracy is affected in that pixels from the single cover class type are assigned to several reflectance-based cluster centres, and upon colour-coding of the several cover classes, is noticeable in the intermingling of several colour-codes within the cover class. This has been referred to as the "between mixed pixel" problem, and occurs in highly heterogeneous cover types, not necessarily in terms of vegetation, but also in terms of soil, geology, topography and possibly moisture.

This situation should not be confused with what vegetation ecologists refer to as a vegetation type containing a mosaic of plant communities (although the possibility exists, but generally the scale is different) as, in computer classification a vegetation type with good PCC will show the various major plant communities as a number of clear, separate, well-classified, sizeable, colour-coded units. Of course, there is a gradient between a vegetation-landscape type containing a number of clearly defined subunits (true mosaicism, such as closed, tall *Olea* shrublands and open, high *Acacia* woodlands) and one which is defined as being highly heterogeneous in terms of the various environmental parameters present (such as pockets of grassland, panveld, *Olea* thickets and *Tarchonanthus* shrublands). Again, it is a matter of scale, and what is true for reconnaissance level mapping aided by Landsat imagery, will probably not be true for the investigator working at detailed levels (1:10 000) with enlarged aerial photographs, where the highly heterogeneous cover type is defined as one portraying true mosaicism at, say, a minor or sub-community level. Obviously this discussion is only applicable to certain scale levels generally highly suited to the use of Landsat MSS digital data sets.

Although the satellite resolution is fixed, it may be changed, to some extent, in direction of coarseness (lower resolution) by combining pixels

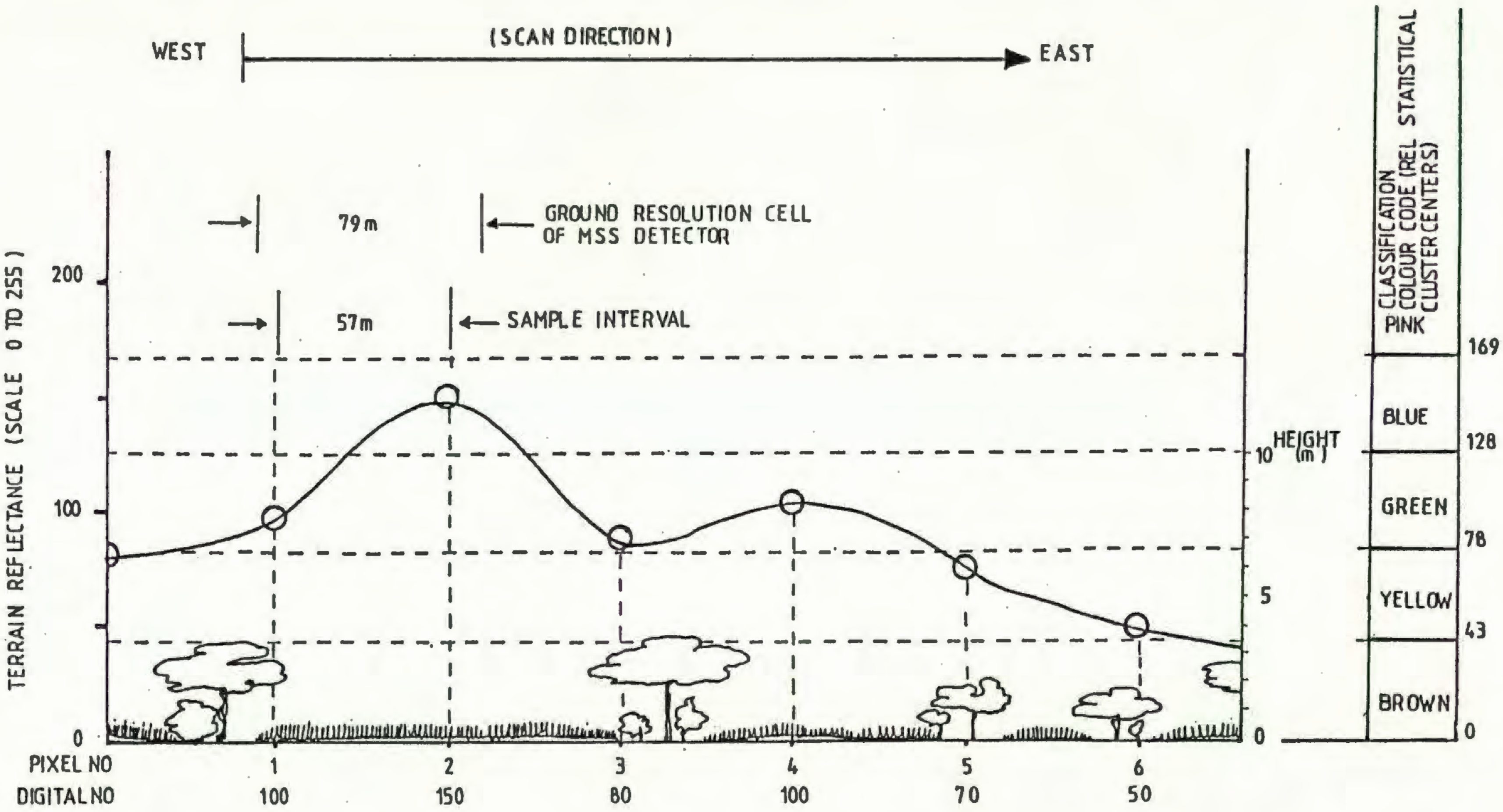


Figure 10 Plot of terrain reflectance along a scan line. The reflectance curve produced is sampled at intervals of 57 m to generate the digital number for each pixel. Low numbers denote low reflectance and high numbers high refectance. The example depicts the typical "between mixed pixel" problem within a single vegetation-landscape unit and the boundary effect between vegetation-landscape subunits and units. (Partly from Sabins 1978).

together in, say, a 3 x 3 or 4 x 4 matrix - referred to as the per-field analysis, as opposed to the per-point analysis, Armstrong (1975). In this manner the size of the basic unit of reflectance measured on the earth's surface is increased. The result of this step may be two-fold (Short 1982):

a) Statistical variance of the spectral response values decreases with coarseness (lower resolution): classification accuracy improves.

b) The proportion of mixed pixels (and degree of mixing) increase with the coarseness: classification accuracy worsens.

Short (ibid) stated that a poorer resolution could increase the classification accuracy by smoothing out environmental heterogeneities of cover classes (by lowering the variance). Of course, this would depend very much on the type of cover class. This type of improvement in classification accuracy is only applicable to the "between mixed pixel" problem.

The "within mixed pixel" problem is diagramatically shown in Fig. 11. Where the intrinsic pattern of the cover class is smaller than the pixel size, classification inaccuracies of a much more serious nature may result. The reflectance value recorded for any given pixel is, in itself, a mean value of all the reflectance emanating from the exposed ground cover feature types present within the 0,45 ha sample of the earth's surface. A given pixel is capable of any reflectance value scored on the scale between 0 and 255. A pixel in the Kalahari Thornveld could have the following microscale level terrain feature types or objects, e.g. clump of olive green *Acacia erioloba*, scattered large whitish *Tarchonanthus camphoratus* and dark grey *Grewia flava*, intervening browny-green grassy areas and high percentage of exposed red, base, Kalahari sands. All the various reflectance values per potential exposed ground cover feature, in accordance with the area that each covers within the 4500 m² area of the pixel (its proportion) results in a reflectance value (digital number) of, say, 137 for the four MSS Bands. This figure falls within a range of reflectance values which has been given the colour-code bright red.

Another pixel, many pixel-distances away in the Ghaap Plateau, contains the following exposed ground cover feature types: a uniform, open stand of *Tarchonanthus camphoratus* (whitish) with scattered *Ziziphus mucronata* (bright green) and *Rhus lancea* (pale yellow-green) trees on red, loamy soils shallowly overlying calcrete bedrock (chalk-white and highly reflectant) often exposed, and occasional exposure of dolomite bedrock slabs. A good covering

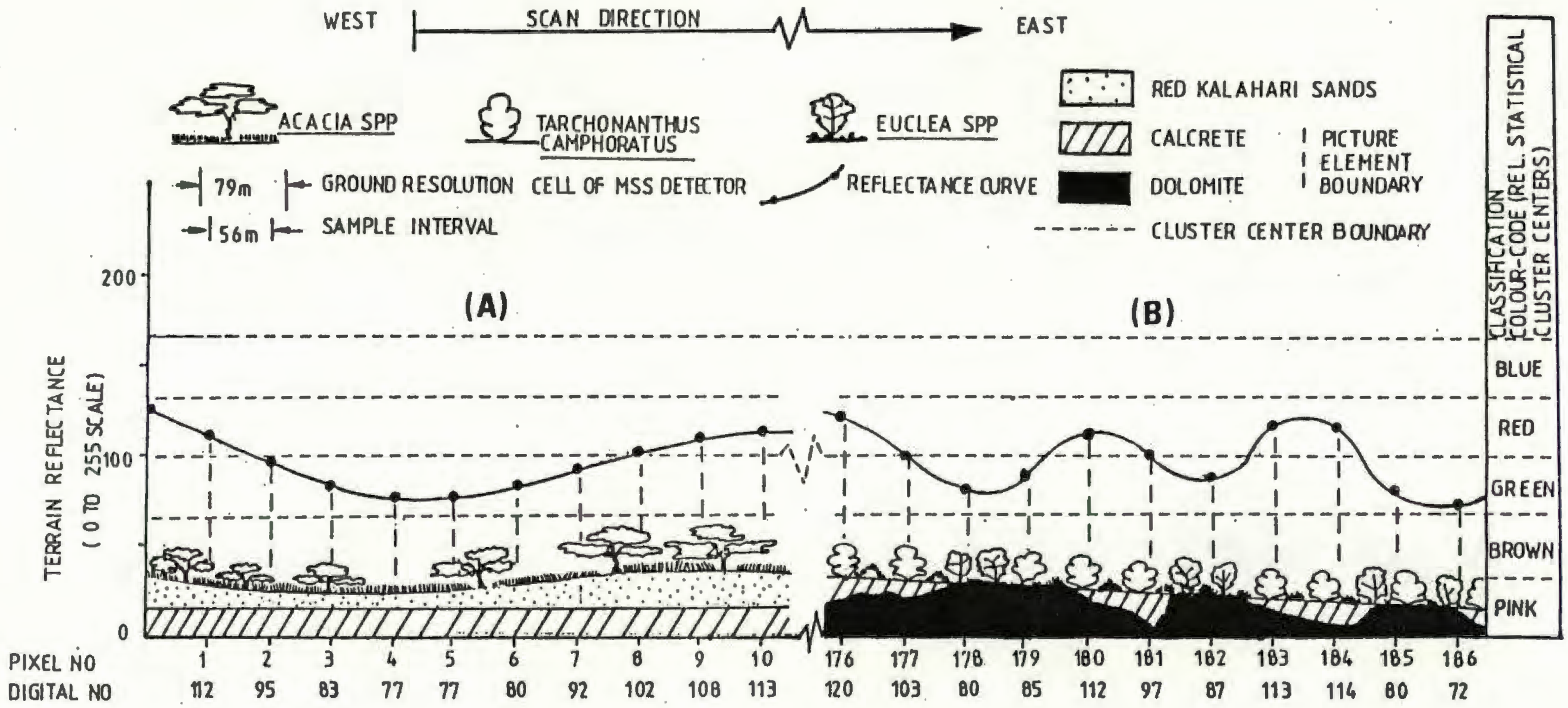


Figure 11 Plot of terrain reflectance along a scan line. The reflectance curve produced is sampled at intervals of 57 m to generate the digital numbers for each pixel. (A) and (B) depict two different vegetation-landscape units. The two examples depict the "within mixed pixel" problem, where a) pixels within the same vegetation-landscape unit are classified as being dissimilar, and b) pixels in different vegetation-landscape units are classified as being similar.

of dark green grasses exists and the soils are moist. On obtaining a mean brightness (intensity) for all the reflectance values emanating from the various ground cover feature types, for the four MSS bands, the resulting mean reflectance value (weighted average of all the ground feature types mentioned above) may be identical or very close to that obtained for the Kalahari Thornveld pixel described previously, i.e. 137. In this case, the Ghaap Plateau Shrubland pixel will also be colour-coded red. This would then be an example of a "within mixed pixel" problem and is directly due to the Landsat system itself (surrogate reflectance data of the earth's surface). No amount of classifications based on a pixel by pixel analysis will separate the two and reflect the real world difference between these two discrete vegetation types.

If the two pixels described above originate from two vegetation-landscape types or major plant community types which do not display any mosaicism but are relatively homogeneous over their geographical distributions in terms of environmental parameters/reflectance characteristics resolved by the MSS, then the confusion between the two units becomes extensive, i.e. they would solve with the same training limits. Thus, the clustering of vegetation-landscape units, or parts thereof, is dictated by their reflectance and may not be in agreement with the the investigator's preferences. The importance of good, detailed ground reference data is thus obvious.

Open to closed Ghaap Plateau Shrublands often experience the "within mixed pixel" problem, for, while being dominated by tall *Tarchonanthus camphoratus,* the variability of the intershrub component leads to variable mean reflectance values per pixel. Dominant species can also reduce the reflectance variability within the pixel. The underlying rock, soil, litter, grasses, etc., if exposed would lead to a different mean reflectance than that which would result from the 0,45 ha dominated by the grey-white foliage of *T. camphoratus.* The dominant species smoothes uneveness caused by the diverse terrain feature types, thus resulting in a better mean value. A species which is dominant over a large area helps the generalization of the vegetation type. Soil background will play a similar role.

A possible solution to the "within mixed pixel" problem is a decrease in the size of the resolution cell (increased resolution), in which case a different series of satellites would have to be used such as the French SPOT system. While the "within mixed pixel" problem may be thus solved, hitherto unknown classification problem may result, such as highly mixed colour-coding.

It is not known to what extent the "within mixed pixel" problem prevails in either classified training area but, there is a good possibility that many thousands of individual pixels scattered throughout the training areas, each with complex mixtures of ground cover features, are coded one colour or another, not because they contain the vegetation-landscape parameters typical of the unit, but rather the ground cover feature spectrum gives rise to an equivalent mean reflectance value (integrated spectral response, Walsh (1980)).

The problem is the multitude of scattered, individual pixels of similar colour-code distributed throughout the various spectral units. The effect is similar to that of a "noisy" image. Both "mixed pixel" problems could be in operation, but an adequate explanation is not forthcoming. A possible explanation of classification problems concerning patch or area confusions is that of boundary effects between terrain features.

7.2 DISCUSSION

Both types of "mixed pixel" problems serve as a reminder of the complexity of the natural terrain surface. It is this fact that prompted Smedes (1975) to state that the remote sensing "map" is more accurate than the "ground-truth" map; the former faithfully reproduces the true complex variation of ground cover features as they are interspersed in space and time. Obviously all thematic maps, whether depicting the distribution and type of vegetation or some other theme in a geographical area, are simplified generalizations which include a certain degree of subjectivity and loss of detail and accuracy. It is most unusual for a cover type to be continuous over larger areas. Detail shown is scale-dependent. Certainly the computer-generated classifications bear out this fact; the natural complexity of any given vegetation-landscape unit is clearly obvious from the patchiness and mixing of colour-codes in the classifications, most of which can be traced to variability in the environmental parameters, and thus the ground cover features in the unit. This wide range of pixel values can be associated with one cover type solely due to variations in slope angle and aspect (Holben & Justice, 1980), which involves only one environmental parameter: topography. Despite this, Smedes' statement is not wholly correct; those parts of the classification affected by the mixed pixel problem, especially the "within mixed pixel" problem, result in the remote sensing "map" depicting ground cover classes where they do not exist. Generally, the percentage of pixels (area) showing this type of error is small, especially as many of these pixels are solitary or in small groups scattered widely throughout the study area or "map". Occasionally the error is a serious one, when the number of pixels is relatively large and contiguous, leading to the false extension of a vegetation-landscape unit to some distant region bearing no relationship to the unit. Thus Smedes' statement must be viewed with caution, since in rare cases, the "ground truth" map may show a major error in the remote sensing "map". Generally, the "ground truth" map plays a major role in the identification and description of cover class types, but not in the accurate delineation of boundaries.

A discussion of the merits and demerits of the per-point (pixel by pixel) and per-field (groups of pixels) classification methods is pertinent. There is a mass of spatial information in Landsat MSS imagery (Swain 1983). During visual interpretation of FCC imagery, the human brain analyses features such as size, shape, orientation, texture and intricate patterns in the formulation of cover types, their geographical distribution, their possible identity and relationships with each other. Although the human eye performs poorly on the quantitative level, visual interpretation of the FCC image is very successful. In the production of FCC images a mean value per pixel matrix (e.g. 16-pixel matrix) is obtainable or not every line is necessarily produced. This "sampling" results in the smoothing of the patterns, hues and textures, possibly making for easier visual interpretation.

Normally automatic recognition, machine processing techniques analyse Landsat MSS digital data on a pixel by pixel basis, thus omitting one of the most important aspects of the data, its spatial organization (Armstrong 1975). The statistical definition of texture is also extremely difficult. Most of the processing methods used in the analysis of MSS digital data have centered around its spectral information content. This is because the characterization of spatial features, stretching over several to many thousands of pixels, is computationally difficult, expensive and most certainly beyond the scope of the investigations discussed in this paper. In the methods used here, viz. pixel by pixel classification, or individual point classification, each pixel is analysed and classified without any consideration of the surrounding pixels. Thus the pixels, though contiguous, stand in isolation during classification and the added information of associated pixels is not used. The superiority of the human eye in the recognition of pattern and interpretation of FCC imagery is contained in the dictum: "The whole is greater than the sum of its parts". "Per field" classifications have the potential to give better classification results but, when misclassifications do occur using this method, the mistakes are larger and possibly more serious. Increased or decreased resolution (smaller or larger-sized pixels respectively) may reduce some mixed pixel problems. A comparative study between Landsat MSS and Landsat Thematic Mapper (TM) would be an interesting project.

8. ACCURACY

8.1 INTRODUCTION

Accuracy denotes the degree to which ground cover classes were recognised and mapped by using Landsat digital data (Walsh 1980). Jarman (1981) rightfully stressed the importance of being able to specify the accuracy of the final product produced from Landsat digital data. In this study the final product is obviously the colour-coded "maps" of surrogate data representing the vegetation-landscape units and sub-units in the two training areas. The statement of accuracy denotes the level of success or failure (the soundness) of the techniques applied to the data and its potential usefulness to other users. This discussion is applicable only to researchers interested in mapping terrain cover types, especially natural vegetation and its associated macro-environmental parameters, in the arid to semi-arid regions of South Africa, at the reconnaissance level of investigation. The "accuracy" obtained in this investigation is applicable to the techniques used and the region of application.

In a discussion of the logic of mapping macro-environmental parameters, a valid point, which is directly applicable to the accuracy assessment of the "maps" produced here using machine processing of Landsat digital data, was made by Varnes (1974, in Robinove 1981): "The essence of mapping is to delineate areas that are homogeneous or acceptably heterogeneous for the intended purpose of the map". The computer-classified maps must be assessed in the light of this statement. They depict "areas" which are both homogeneous and heterogeneous. Most of the heterogeneous areas are acceptably so. Of more importance, are they heterogeneous within the limits set by "the intended purpose of the map", i.e. do they correspond with the delineated vegetation-landscape units in the maps prepared from ground reference data (field surveys, aerial photographs and available supportive information maps)? The landscape approach improves the accuracy of the classification markedly in that the data is given maximum opportunity for correct classification.

Any assessment of accuracy in this study requires a comparison of the computer classification of the Landsat data representing the Kalahari Thornveld and Ghaap Plateau Training Areas, and the vegetation-landscape for the same areas. This comparison has been discussed in detail in sections 4 and 5. The answer to whether there is good correlation between reflectance data as recorded by the Landsat satellite's multispectral scanner system and the features on the terrain surface was decidedly "yes". The subject of the accuracy of supportive information maps versus the accuracy of Landsat imagery has been discussed in Paper 1 where it was concluded that it is sometimes problematical to assess the validity of using Landsat imagery as a tool in mapping terrain features, when that which is being assessed is, in fact, more accurate than the "yard-stick" being used. In addition, Fox *et al.* (1985) found that small "incorrectly classified" pixel groups within a spectral unit were in fact often correctly classified and that the ground reference data was lacking.

The accuracy assessment made here is of the Landsat computer-generated classification "map" and the FCC image-assisted vegetation-landscape map. This situation is probably more realistic in that the sampling superiority of the Landsat system had already been taken into account. It had already been ascertained that, in terms of detail, Landsat data is superior in: (a) the identification of number of cover types present, (b) depicting the true heterogeneity (mosaicism) of any given cover type, (c) accurately depicting the true spatial and geographical boundary positions of the cover types, (d) related cover types, and (e) depicting not only vegetation, but also soils, geology, topography, state (quality) and possibly climatic conditions. In terms of accuracy assessments, the computer classification can be directly compared to the vegetation-landscape map, with consideration given to such aspects as the classification methods used, software and mixed pixel problems.

It should be noted that no quantitative accuracy assessment was undertaken in this study. Usually one of several recognized, pixel-based methods is employed. The degree of inaccuracy can be assessed by the production of confusion tables (Nagy *et al.* 1971; Mayer & Fox 1981), where the number of pixels per cover type is given, and the number of pixels belonging to a specific cover type which have been assigned to another type is shown. Usually not all pixels are appraised, but range from 1% to 5% of all classified pixels. Roller & Visser (1980) described a similar, but essentially quantitative method to the one used in this paper. Using contingency tables, resource classes derived from the computer classification were compared with the original forest types on the field-derived map. These techniques were not available to the author at the time of investigation. Quantitative accuracy assessments essentially sample pixels and check them for classification correctness by comparison to "ground truth" maps (prepared or already available), verified in the field or compared to known ground reference data (see Sweet *et al.* 1980; Smedes *et al.* 1970; Walsh 1980; Short 1982; Todd *et al.* 1980). Quantitative accuracy testing involves statistical analysis and confusion matrix calculations.

8.2 ASSESSMENT OF ACCURACY

The procedure followed for the evaluation of the accuracy of the computer-generated classification in this study is outlined below:
35mm photographic colour transparencies of the various classification attempts, training sites selected for signaturization and FCC imagery of the training areas were projected on the internal screen of a carousel-type slide projector. Clear overlays of various supportive maps and the vegetation-landscape map were prepared at a reduced scale to allow for a direct 1:1 comparison. The prepared overlays were attached to the screen surface thus superimposing the slide and overlay(s). This is similar to the interactive procedure followed at the SAC, Hartebeeshoek, where computer-generated material appears on a separate desk-top comtal display screen. Classifications were diagnosed in detail. Qualitative and semi-quantitative assessments were made of patterns, aerial differences, boundary positions and pixel misclassifications or confusions. In this way a reasonably

detailed comparison between the control map and the computer classification could be undertaken.

In the semi-quantitative case, pre-selected sample sites used for describing the terrain cover classes in the field could be checked for similarities or differences. The stratified, non-random sampling of the field units became a technique for the stratified, non-random sampling of the computer classification. Rudd (1971) adopted a similar, but quatitative, verification procedure for use on aerial photographs. (An almost identical procedure was used by the author in the visual interpretative investigation of the 1:250 000 FCC imagery where supportive information maps and prepared ground reference map overlays were superimposed on a light-table surface (Paper 1)). In this study, the positions of ground sample sites were located on the computer classification and were enlarged to incorporate approximatley one hundred of the classified pixels surrounding the sample site. This cluster approach subsequent to the detailed bispectral plot analysis led to a subjective yet controlled assessment of purely qualitative comparisons. Obviously this system does not constitute a pixel-by-pixel accuracy assessment, but it does allow for accurate positioning of areas of comparison on the classification map. This facilitated the accuracy assessment of not only the sample sites, but of the whole computer classified training area. Although the system may seem general, it must be remembered that the vegetation-landscape units are broad generalizations of a complex environment and that the final mapping scale was at the reconnaissance level of 1:250 000. Accuracies of 1 km to 2 km are quite acceptable, but the detail in the Landsat data does allow this level of accuracy to be increased with the collection of very little extra ground reference data.

Rudd (1971) maintained a statistical aspect to this procedure by fitting a grid to the classification map and using a table of random numbers to select sample sites. He then obtained "ground truth" for each sample (by using aerial photographs at a scale of 1:30 000) and compared this with the classified map category, thus arriving at a percentage accuracy for each map category and for the overall map. Although this procedure could have been followed here, the sample size was not considered sufficiently large after sample sites falling on or near boundaries (designedly so positioned in the field) had been removed from the data set. Furthermore, returning to the field for the sole purpose of increasing the sample size merely for a statistical test of accuracy, could not be justified. In addition, it was found that inaccuracies, misclassification and confusion seldom occurred in the vicinity of boundaries, but rather within extensive, heterogeneous (mosaic) vegetation- landscape units. It was felt that the procedure followed by the author gave sufficient indication of the accuracy of the computer-generated classification. The method also allowed for the interpretation of the "where and why" of occurrence of the vegetation-landscape units which is embodied in the statement that most interpretation-orientated analyses of Landsat data have as their goal the identification and classification of ground cover types (Short, 1982), which of course gives rise to questions of accuracy. The detailed results of the overlay procedure have been given in Section 6.

The accuracy was assessed at three separate levels:

(a) overall pattern accuracy (the correspondence of area, including the position of the boundary)

(b) details shown within the overall pattern (mosaicism)

(c) the uniqueness or discreteness of each separate cover type.

The clustering efficiency of the classification was ascertained by analysis of the bispectral plot. The unique clusters (single cluster centre groups) were easily evaluated by referring to the ground reference data. If a single ground cover type occured in the area then the classification was deemed accurate. The second step in the evaluation was to consider where else the colour-code of this cluster occured in the classification. If it occured only in ground cover areas classified the same, or, with only a very small fraction of pixels with this colour-code scattered throughout the classified area then the clustering procedure was deemed accurate. This situation occurred several times, e.g. hydrophilic grasslands, calcrete roads, lineaments, drainage lines and streams, burns and areas supporting an open, dwarf *Acacia haematoxylon* woodland. Unfortunately, these clusters account for not more than 4% in both training areas, although they represent approximately 30% of the classified ground cover units.

The multicluster groups showed where several unique ground cover classes contained considerable percentages of pixels classified as highly similar in reflectance. This resulted in: (a) several dissimilar ground cover types having the same colour-code over all or parts of their distribution and

(b) other ground cover types containing a confused mixture of colour-coded pixels. Each cluster in the multicluster group is represented by pixels emanating from positions in the computer classification which relate to positions on the ground classification containing environmental parameters resulting in their classification into two or more vegetation-landscape units. The identity and positions of these pixels is made clear to the investigator by their colour-codes. It should be remembered that in terms of acceptable levels of accuracy in any classification of Landsat MSS digital data, a given cluster should represent only one ground cover type, while any given vegetation-landscape unit may be represented by several clusters, if several classes have been signaturized separately to allow for mosaicism within that vegetation-landscape unit, e.g. the Ghaap Plateau Training Area. This homogeneity of the cluster itself was analysed for the degree of accuracy. A cluster with relatively high numbers of pixels from two or more different ground cover types was regarded as being incorrect and added to the inaccuracy of the classification as a whole, e.g. the confusion of V-L's 16c, 37 and 39.

The supervised technique was employed on the Kalahari Thornveld Training Area. As the results show, the classification was unsatisfactory on the whole, and qualitatively judged, was no higher than 60%. The results were mixed; some cover types were unique, and others showed complete confusion with unrelated or distantly related cover types. The reasons for this have been discussed in detail (Sections 6 and 7). Discussion and interpretation of these results were undertaken in an attempt to improve the classification of the Ghaap Plateau Training Area. The detailed nature of the ground reference data was considered a serious disadvantage, no matter how commendable this fact may be. Secondly, since natural ecosystems are far from homogeneous, it became apparent that many more spectral classes required signaturization, i.e. the range of acceptable reflectance values according to which pixels could be "dumped" into a cluster centre had to be narrowed.

In the initial phase of the classification of the Ghaap Plateau Training Area, the supervised technique was used, but a higher number of spectral classes were signaturized. This classification was thought to be more successful than that of the Kalahari Thornveld Training Area, but there was still room for much improvement. The next phase was incorporation of the unsupervised technique within the ground cover areas coinciding with the boundaries of the three most extensive vegetation-landscape units: V-L's 39, 37 and 16c. Each V-L was subjected to a separate unsupervised classification. These "mini" classifications showed clearly which cover types could be separated and which could not, possibly involving mixed pixel problems owing to the statistical inseparability of the reflectance-based clusters or cluster centres. For example, within V-L 39 are numerous, narrow, exposed, dolomitic ridges supporting a closed, mixed, shrubby woodland. This part of the mosaic of major plant communities present in V-L 39 was confused with the extensive major plant community of closed, mixed, shrubby woodland on rugged dolomitic bedrock areas, i.e. 39^{8} with 37^{3}. This confusion can be clearly seen in the bispectral plot Fig 9. The application of the hybrid techniques, however, resulted in a major classification improvement. The classification accuracy of the Ghaap Plateau Training Area was qualitatively assessed to be in the region of 75%. While this may appear to be greater than that of the Kalahari Thornveld Training Area, the classification was still regarded as unsatisfactory. Furthermore, a direct comparison of the qualitative percentage accuracy of the two training areas is not valid; if the Ghaap Plateau had been classified using the supervised technique only, an estimated 40% classification accuracy would have been achieved. The Ghaap Plateau Training Area is environmentally very different and displays much more spatial complexity. It is estimated that a quantitative pixel-by-pixel accuracy assessment in both training areas would have scored below 50%.

8.3 DISCUSSION

Various vegetation-landscape units in the training area showed varying degrees of accuracy in their classification. Overall classification accuracy percentages tend to hide the fact that the level of accuracy is variable. In this study, the more homogeneous cover types were reasonably accurately classified, while heterogeneous cover types showed much lower levels of accuracy. This was also shown by Walsh (1980), when he determined the individual percentage accuracy of each of the major cover types present in his study. The accuracy evaluation should be carried out on the automatic computer classification of the whole study area since accuracies can be expected to be high within those areas used for training purposes. In order to extrapolate the classification to the entire study area, a high degree of success must be obtained in the training areas as accuracies can be expected to drop a further 15% to 20% at best (Smedes *et al.* 1970). This "gross signature extension" was not considered worthwhile in this study. From the results obtained in the training areas, the author regards this type of signature extension is unreasonable and unrealistic, especially when dealing with extensive, natural to semi-natural ecosystems. Short (1982) found signature extension to be both inaccurate and ineffective. It must be acknowledged that the qualitative assessment of the success of the classification obtained here is subjective to some degree; investigators may not concur on what is "good" and what is not. The limits of "good" and "poor" depend on initial expectations from the technique of automatic classification processing. Despite this, the classification obtained here can be considered adequate for first-approximation, reconnaissance level mapping only. The results are more of interest to the computer classification analyst (research- and development-orientated) than to the vegetation landscape mapper involved in recording what vegetation is present, where and why. The computer classification "map" is not a suitable product in this regard (Plates 2 and 11).

In order to obtain increased accuracy in the second computer classification, a much larger portion of the Landsat data was used as a training sample. One should be careful of an "over-kill" situation in applying the supervised technique, where the investigator uses a sample of the data so large that a major portion of the training area has already been designated. Obviously, the more spectral classes that are signaturized, the more accurate the classification will be. In heterogeneous cover types, there is a temptation to continue sampling until all possibilities have been accounted for.

There is a tendency to disregard heterogeneous training sites. Generally areas with a high degree of spectral homogeneity are sought within spectral cover classes, regardless of the environmental homogeneity. Heterogeneous areas or spectral classes are not chosen to help build statistical models because of their dilution of the clusters which result. This strategy disregards the natural heterogeneity of natural vegetation-landscape units, which results in a gradient of spectral classes being produced. Obviously the accuracy (correct classification) improves if heterogeneous cover classes are omitted from analysis. Nagy *et al.* (1971) warned against the choice of ideal, unrealistic training sites, e.g. exceptionally homogeneous areas in terms of the primary environmental parameters, as these sites are representative of only a small portion of the data/ground cover.

Limitations in the software force the investigator to select a sample of the spectral classes and dominant terrain cover classes. Dominant terrain cover classes of interest to the investigator may not be represented as dominant multispectral classes and vice-versa. This fact has implication for both supervised and unsupervised methods of classification. In the supervised approach, one is forced to signaturize some spectral classes representing known terrain cover classes of interest and importance but, which will not lead to unique computer classification. At the same time, using the unsupervised technique (logical division of the pixels into clusters) dominant and "unique" spectral classes will be isolated, but they may not relate to actual terrain cover classes of interest, or, they may form only small parts of a much larger cover class (as is the case with cover classes portraying strong mosaicism).

The results of objective, quantitative accuracy tests should be viewed with caution. This is not a reflection on the accuracy tests themselves, but rather on the methods employed in the classification in the first instance, and the quality and quantity of ground reference data (control maps) in the second instance. Classification of terrain cover types using machine processing techniques based upon statistical methods "are usually achieved only through an iterative process" (Nagy *et al.* 1971). The investigator decides on the logical number of terrain classes that may be present in the image and specifies the number of clusters desired, the number of iterations to be used and the number of standard deviations from the mean in each band (Robinove 1981). Each unsatisfactory classification of the data set results in a further partitioning of the data; more "homogeneous" spectral classes, usually viewed as more "representative", are signaturized and the statistical data set increased while the classification procedure is repeated until the required classification accuracy is attained (usually in the order of 85% "correctly" classified pixels). This procedure was followed in this study and although the classifications were viewed as not very successful, the procedure was halted when the "fit" was reasonable. Clearly a certain amount of subjectivity is implied in this process.

Frequently the accuracy assessment is undertaken on highly manipultated data, which has resulted in new, simplified, broad-based resource classes originally consisting of several classes whose identity and distribution were individually sought (if the a *priori* approach is employed). The objective of the original investigation is changed to accommodate the resource class map thus produced and the accuracy assessment scores high in relation to the manipulated end product. Frequently authentic cover type variations cannot be accommodated owing to lack of ground reference data. The only alternative left to the investigator is the simplification of the spectral classes to suit the nature of his data.

Some investigators improve on the classification accuracy by combining several confused cover types to produce a single cover class. It should be made quite clear that this step could be detrimental to the fulfilment of the objectives of the study. In this study, as will often be the case in the classification and mapping of the natural - seminatural ecosystems, it is not possible to combine cover types until the level of statistical recognition is attained without violating good vegetation ecological practices. In the mapping of vegetation-landscape units at the reconnaissance level, if the aim is to separate vegetation units on both the structural and floristic levels, it is not acceptable to combine say, Kalahari grassland and Ghaap Plateau grassland types or, even Kalahari sparse woodland and Kalahari grassland types, simply to satisfy the statistical nature of the data.

The fact that almost all the pixels were classified also has no bearing on the success of the computer classification, but rather means that a "home" was found for nearly each and every pixel classified. The wider the tolerance limits (range of reflectance values) of a given spectral class, the greater the chances of any given pixel having a chance of being placed in a cluster.

In the hierarchical classification of vegetation units, all units are not of the same level. A major plant community cannot, therefore, be placed on the same hierarchical level as that of a vegetation formation type in order to satisfy the partitioning of the reflectance-based statistical sample. This aspect of classification should be considered in the analysis of accuracy. If the investigator has a detailed knowledge of the environmental parameters of the study area, the functional dynamics and relationships between these cover types (i.e. an hierarchical scheme), then the "classification" accuracy should be viewed in two ways:

a) Are all the pixels classified correctly? (classification accuracy, estimates of percentage error in the size of each cover class)? and

b) Do the computer-generated "map" units correspond with the ground reference map (control map) units? (mapping acccuracy; positional estimate of percentage error in cover class displacement)

All subunits belonging to a unit type should have the same colour-code. If pixels have been incorrectly classified, type (b) accuracy will be affected too. Usually hierarchical classification problems will be detected by the misclassification "in total" of the majority of pixels belonging to a unit or subunit (in terms of ground cover position). Most often authors disregard the hierarchical aspect of classification accuracy.

The various colour-codes cannot depict hierarchical relationships in themselves. It is only the investigator's interpretation of the spatial and geographical positions that gives meaning to the colour-coding. The positions of cluster centres and their groupings could be used for this purpose, but only if it can be shown that there is a direct correlation between reflectance levels and hierarchical relationships. In vegetation analyses, this would only be feasible in situations where the vegetation dominates the terrain surface (where it is the principle reflectance feature) and then only in terms of those parameters sensitive to Landsat sensor interpretation and recording, e.g. height, number of strata, projected canopy cover, colour of foliage of dominant species. The identification of most of the units is one aspect of accuracy; whether or not these units are linked in a satisfactory manner is an entirely different consideration.

The concept of accuracy is scale-related. Classification accuracies have been found to be higher at the broad level, with low accuracies after subdivision of the broad categories (Nelson & Hoffer 1979; Smedes *et al.* 1970). This is true only if pooled spectral classes can be accommodated in new, meaningful, broad-based resource classes, e.g. combining V-L's 37 and 39. By way of contrast Short (1982) stated that environmental variability increases with increased class size, leading to classification problems, e.g. V-L's 1, 4, 37 and 39 (see Section 6). The author's findings support Short's reasoning, e.g. V-L 17c. A measure of success was achieved only after the broad cover types were subdivided to accommodate the spectral class units, i.e. the computer classification forced the investigation from the broad-general to the narrow-particular (larger scale): V-L 37 became subunits 37^1 to 37^7.

Throughout this study the importance of good ground reference data was evident. Fundamental to the accuracy of the classification itself is the quality of the ground reference data (Boyle *et al.* 1988). In addition, the accuracy of interpretation and evaluation is directly dependent upon the quantity and quality of ground reference data. Good ground reference data allows for meaningful analysis of clusters generated in the classification. The evaluation, in turn, gives the investigator an idea of the system's practical value.

9. CONCLUSION

The computer-generated classification of the Ghaap Plateau Training Area was more accurate than that of the Kalahari Thornveld Training Area. The reasons for this are summarized as follows:

i) Experience gained from classifying the Kalahari Thornveld Training Area was of direct help in the classification of the Ghaap Plateau Training Area.

ii) Only the supervised method of training the classifier was used for the Kalahari Thornveld Training Area, while supervised, unsupervised and hybrid methods were used for the classification of the Ghaap Plateau Training Area.

iii) Many more spectral classes were used for training site signaturization in the Ghaap Plateau Training Area, resulting in more accurate partitioning of the pixels covering a wide range of reflectance values. Adequate spectral class signaturization is undoubtedly of utmost importance for the classification of units displaying any degree of mosaicism or heterogeneity.

iv) The Ghaap Plateau Training Area was more diverse in terms of combinations of environmental parameters per vegetation-landscape unit. This resulted in more information being available and a greater likelihood of the Landsat system being able to distinguish spectrally between units.

v) The greatest disadvantages of the Kalahari Thornveld Training Area were the uniformity of the vegetation (structure and floristics), the widespread presence of Kalahari sands and the general narrow-range,

> high reflectance levels of the whole training area owing to the dominant surface features being "white" Kalahri grasses and pinkish red sands. Kalahari Thornveld types and Kalahari sands were easily distinguishable from other ecological regions but inter-unit differences in the vegetation and sands were seldom spectrally unique. The uniformity of the vegetation canopy colour and the sands resulted in a general lack of pattern, hue and textural contrast.

The results of computer classifications are neither straightforward nor predictable. The broad, overall pattern of vegetation-landscape units is present in that two units, separated by some space, are identified, but they may be colour-coded the same, similar or dissimilar. It is often the parts of the whole that have to be interpreted in detail and at a scale of survey of 1:50 000; this data is often not available. One is forced to investigate minor pixel class assignments in more detail. Computer classifcation of training areas of 512 x 512 pixels (30 km x 40 km) leads more spontaneously to map products of between 1:10 000 and 1:50 000. In this case, additional ground reference data, not necessary at the reconnaissance level of mapping, is required.

What vegetation/landscape investigators refer to as "homogeneous" in natural ground cover systems, is always heterogeneous to a degree. The Landsat system is unable to generalize this natural heterogeneity in the same way as the human brain. The computer does not generalize the training area into broad categories, i.e. where an area is spatially dominated by a certain type of resource class, the computer does not automatically assign a single colour-code to the entire area. It is apparent that some classes were incompletely or inadequately defined in the initial signaturization stage. This resulted in groups of pixels belonging to certain spectral classes being assigned to other spectral classes. If these pixels were assigned to another vegetation-landscape unit type then they added to the confusion. The significance of this confusion may be of lesser or greater importance, depending on the relationships/correlation between the spectral class and on what is present in the terrain cover type, i.e. confusion between an alluvial floodplain grassland and a sedge wetland is more acceptable in terms of reflectance resource classes than confusion between Kalahari Sandveld grasslands and Ghaap Plateau mixed, woody shrublands (although the latter type of confusion rarely occurs).

In quantitative accuracy assessments, pixels sampled from the total number of pixels are used as data points for the assessment. A statement such as "the computer classification was 86% accurate" refers only to the fact that 86% of the pixels taken as data points were found to correspond closely to several highly discrete classes which represented several ground units of interest to the investigator. Possibly a better appreciation of the limitations and accuracy associated with various image analyses is required (Mead 1978). In the quantitative assessment of accuracy (i.e. how well the surrogate data classification represents the real world), there is the philosophical consideration of whether it is relevant to assess accuracy purely on a pixel-by-pixel basis. The underlying argument is whether it is acceptable to measure accuracy only in terms of the difference or similarity of individual, adjacent pixels without regard for the question whether the units are different or similar to their neighbours.

Throughout all products, regardless of the automatic recognition techniques employed, there is a recurring problem of precision in the classified training area. The bispectral plots show the spectral heterogeneity of the vegetation-landscape units in the form of distinct subgroups (spectral cluster centres). Upon comparison of the spectral groups and subgroups with terrain feature descriptions, it was found that further subdivision of the land cover, according to the spectral subgroups and groups, could not be justified. Spectral groupings, therefore, do not correspond to any great extent with land cover groupings. Retraining the classifier to improve spectral homogeneity will not result in an improved classification accuracy, no matter how tidy the classification may be forced to appear. The distinction between terrain information classes (vegetated land parcels) and spectral classes (pixels with a similar colour) must be retained if Landsat data is to be used successfully in the mapping of terrain information classes. The collection of some level of spectral data (e.g. soil colour and canopy colour) during field surveys is of help in this regard.

It has been stated that Landsat TM with its improved resolution over MSS will improve classification accuracy, especially in heterogeneous environmental units (Trolier & Philipson 1986). In attempting to discriminate between important forest types using various Landsat MSS and TM products, Benson & DeGloria (1985) found that the TM was inferior to the MSS. The TM was not tested in the present study, but it was felt that a decrease in resolution would be more likely to improve classification accuracy. The increased resolution of the TM may help to solve the "between mixed pixel" problems, but the greater problem of "within mixed pixels" is more likely to be solved by decreased resolution per field sampling unit and thus a much higher level of classification should result.

May (1986) suggested that a possible way to improve classification accuracy, through increasing the statistical distance between similar spectral classes, is to register digitally, and integrate further ancillary data types to the original data base, provided they can be correlated with the vegetation, the primary information classes sought in the classification. Such ancillary data would range from soil types and elevation contours to moisture levels or even a cellularized vegetation map. Geometric registration of a second, contrasting Landsat MSS data base would presumably have the equivalent desired effect of reducing misclassification and consolidating spectral units, especially if the ancillary data mentioned are not readily available. The method of registration of a second image file is known as the multi-temporal or multidate method of analysis (Paper 3).

Much of the discussion about visual and automatic machine processing techniques, supervised and unsupervised classifications, and accuracy assessments, centres on the subjectivity/objectivity dichotomy. Hajic & Simonett (1976), on the assessment of the qualitative versus the quantitative appproaches in image analysis, suggested that the differences are actually on a continuum between the two approaches: "Computer studies which have no error analyis ... are *ipso facto* qualitative; manual studies which follow precise, repeatable decision rules and which assess interpreter error are quantitative." Furthermore, the implicit subjectivity of computer analyses of Landsat data has been mentioned.

It was argued by Nagy *et al.* (1971) that, in support of good statistical sampling practice, it may be wiser to classify the MSS data and only then, a *posteriori,* identify the classes produced. This procedure dictates that no prior ground reference data be used and that the unsupervised method of data analysis be employed. Nagy *et al.* (ibid.) contended that the a *priori* approach, with its use of ground reference data and supportive information maps prior and during computer classification, and the supervised method,

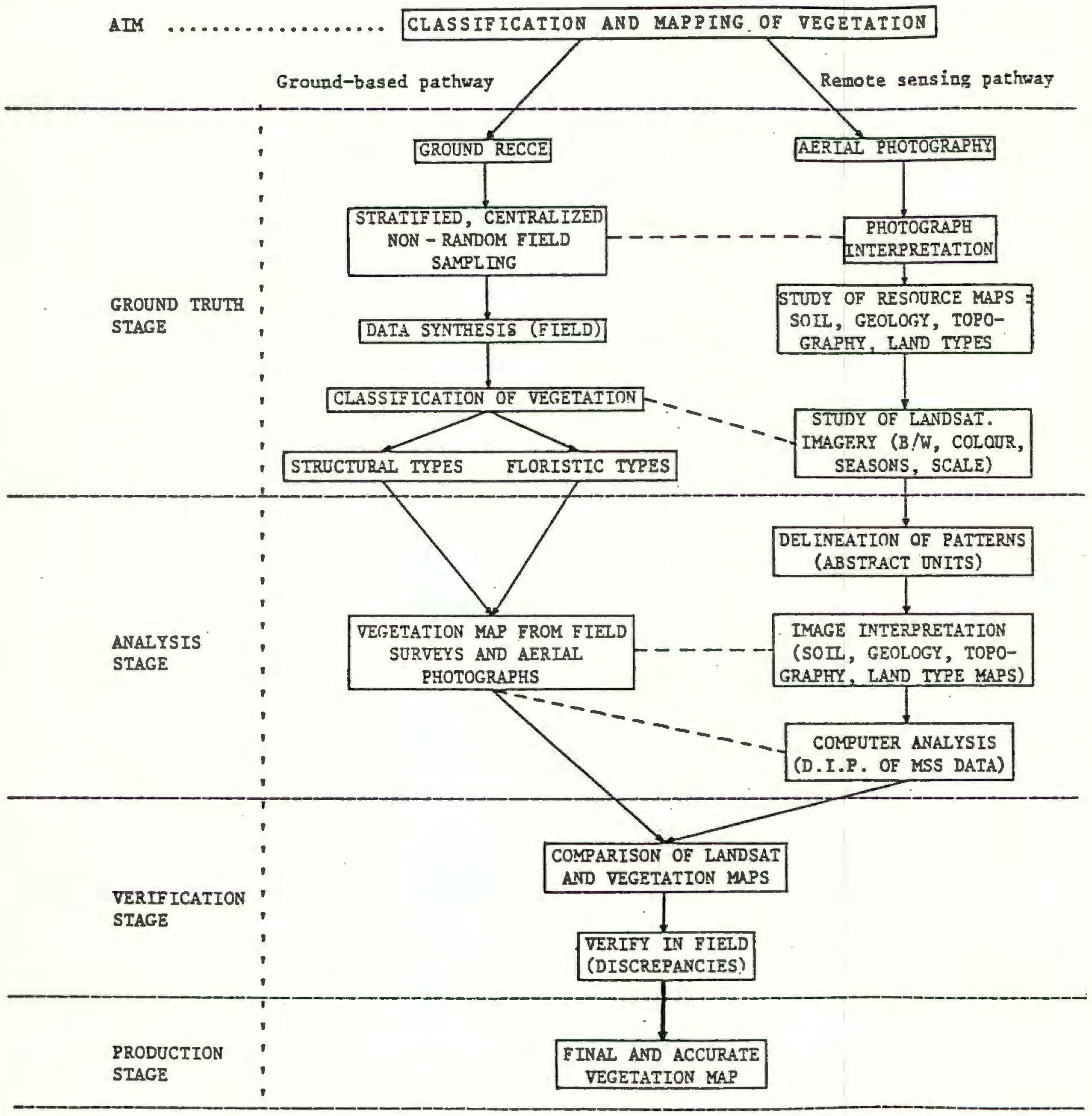


Figure 12 Steps and interrelationships in the "multi" approach to vegetation mapping.

almost always leads to an iterative process of computer classification until the desired results are achieved. While this may be so, there are disadvantages inherent in the a *posteriori* approach:

a) lack of correspondence between spectral classes and thematic map units required

b) a weaker incentive to undertake thorough ground reference data collection at sampling sites

c) the temptation to "make" terrain cover classes fit the classification product in hand

d) a low sampling density

e) sampling restricted to spectral units defined during classification

f) the possibility that the objectives of the study will not be met in the final map product.

This method is advisable when the objective is to test the feasibility of using Landsat data, *per se*; it is probably not applicable when the data is being used as a tool in the attainment of mapping accuracy. The basic aim of this study was to find out if computer classification of MSS data would lead to an improvement over the visual interpretation techniques in terms of the production of more accurate, less time-consuming and less costly vegetation maps. In this regard the approach was essentially a *priori* and at times, subjective and qualitative. Fig. 12 summarizes the concurrent steps followed in the production of the vegetation maps used in this study. It was felt that this approach was justified in terms of the aims of the study. Visual analysis of FCC imagery, with its higher accuracy levels, appears more practical. Cihlar *et al.* (1978) and Quirk & Scarpace (1982) drew a similar conclusion. Based on the findings of this study, it must be concluded that significant effort will be required to obtain discrete computer classifications of heterogeneous environments.

Appendix 1 Details of hardware and software used in the Satellite Applications Centre Image Analysis System (IAS).

SATELLITE REMOTE SENSING CENTRE IMAGE ANALYSIS SYSTEM

1. INTRODUCTION

The purpose of this document is to provide an overview of the Image Analysis System (IAS) of the Satellite Remote Sensing Centre (SRSC) of the South African Council for Scientific and Industrial Research (CSIR).

It is not intended to be a user's operating manual but rather to provide the reader with basic information on the capabilities and resources of the system.

The Image Analysis System as implemented at the Satellite Remote Sensing Centre is based on a hardware/software package supplied by Macdonald Dettwiler and Associates Ltd. of Vancouver, Canada [1,2]. The hardware configuration and software modules are continually being modified and extended as needs dictate.

Basicaly the IAS consists of a 32 bit minicomputer, usual computer peripherals , high resolution digital video colour display system, a high resolution photographic recording device and a powerful software package with a number of stand-alone applications programs that can perform the standard image analysis functions in an interactive or basic mode.

The IAS is concerned with four types of activity : the generation of standard LANDSAT precision products; the generation of non-standard Landsat precision products; the generation of certain other non-standard products; and general image analysis functions.

The general image analysis functions are a set of stand-alone applications programs which provide the building blocks for precision product generation. The production of non-standard precision products involves utilising a subset of these programs.

The generation of standard precision products also uses the image analysis functions, but their use is made transparent to the operator by means of a supervisor task. As the use of this supervisor task is primarily for internal operating methodology of the SRSC it will not be described in this document.

All applications programs including those which are used by the supervisor task and which can also be used in stand-alone mode are described in section 4.

2. IAS HARDWARE

2.1 SYSTEM DESCRIPTION

The following is a brief description of each of the major hardware devices that go to make up the IAS. Figure 2.1 shows a block diagram of the entire hardware configuration.

2.1.1. MINICOMPUTER

Perkin Elmer (Interdata) model 8/32D high performance 32 bit minicomputer with 512 kilobytes of core memory. Single (32 bit) and double (64 bit) floating point instructions are fully implemented in hardware.

2.1.2. VIDEO DISPLAY UNIT (VDU) WITH KEYBOARD.

The present configuration allows for up to four of these units. In general one is used as the system console and the others for individual user terminals. The system console is used for overall system control and for running the supervisor task to produce standard products. In practical terms the system can support up to two interactive IAS users on a time sharing basis.

2.1.3. MASS STORAGE DISK MEMORIES.

There are two mass storage media disk drive units of 256 megabyte capacity each. All operating software, image video data and other auxilliary data files are stored on these disks.

2.1.4. MAGNETIC TAPE DRIVES (CCT).

These provide for the reading and writing of 9 track 1600 bits per inch computer compatible tapes (CCT's). The prime drive operates at 125 inches per second and the other at 45 inches per second.

2.1.5. COMTAL 8000 IMAGE SYSTEM

This is a high resolution digital video colour display device with four 512 x 512 x 8 bit semiconductor image memories; four function memories (i.e. look up tables for realtime contrast enhancement of displayed image data): one pseudo colour memory (i.e. for maping image grey level intensities to selected colours); and two 512 x 512 x 1 bit graphics memories for providing graphics overlays on the displayed image. The system also includes a track ball to control the position of a target cross on the display screen.

2.1.6. COMTAL VISION ONE/20 IMAGE SYSTEM.

The Vision One/20 System has all the features of the Comtal 8000 System with the major addition of having a fully integrated LSI-11 microprocessor with its own powerful image analysis application firmware.

Control is accomplished via the dedicated alphanumeric keyboard or, as for the Comtal 8000, remotely via the interface to the 8/32 computer.

This means that unlike the 8000 System, once image data has been loaded via the IAS 8/32 computer, the Vision One/20 can be used off line to perform a wide range of image processing functions. These include real time interactive zooming; image combinations (i.e. differences and ratios); and a convolver using 9 unique coefficients for edge enhancement etc.

In addition to the trackball as described for the 8000 this system also contains a data tablet and stylus which can be used to input data to image or graphics memories. It can for example be used to digitize information from a map.

2.1.7. OPTRONICS MODEL C4300 COLORWRITE FILMWRITER.

This is a high resolution photographic film recording device for hard copy output of precision processed image data. Either monochrome or colour films can be produced as negative or positive transparencies.

The recording spot (pixel) resolution size can be set to 100, 50 or 25 micrometres. The maximum film size is 254 x 254 millimetres, which, at a 50 micrometres resolution, allows for 5000 lines of 5000 pixels each to be recorded.

In general a film size of 254 x 203 mm is used for LANDSAT products as this allows a full 185 km x 185 km scene to be recorded at full resolution at a scale of 1:1000000.

2.1.8. VERSATEC ELECTROSTATIC PRINTER/PLOTTER.

This can be used to provide a quick look hard copy halftone product of a 512 x 512 image at a resolution of approximately 100 lines per inch.

2.1.9. STANDARD ALPHANUMERIC LINE PRINTER.

This is used for output of processing summaries, classification statistics, numerical pixel values, histogram data, etc.

2.2. INTERACTION WITH OTHER SYSTEMS.

Although not shown in figure 2.1, for reasons of simplicity, some of the hardware units are shared with other SRSC computer systems by means of bus switches. These systems include those for direct reception of LANDSAT data, processing of LANDSAT bulk data stored on high density digital magnetic tape (HDDT) and for receiving and processing METEOSAT data.

The shared equipment includes both Comtal systems, the Optronics film writer, the printers and the 45 i.p.s. magnetic tape drive.

It should therefore be noted that the equipment is used to the maximum efficiency and that all units described as comprising the IAS are not necessarily available on a full time basis for pure image analysis functions.

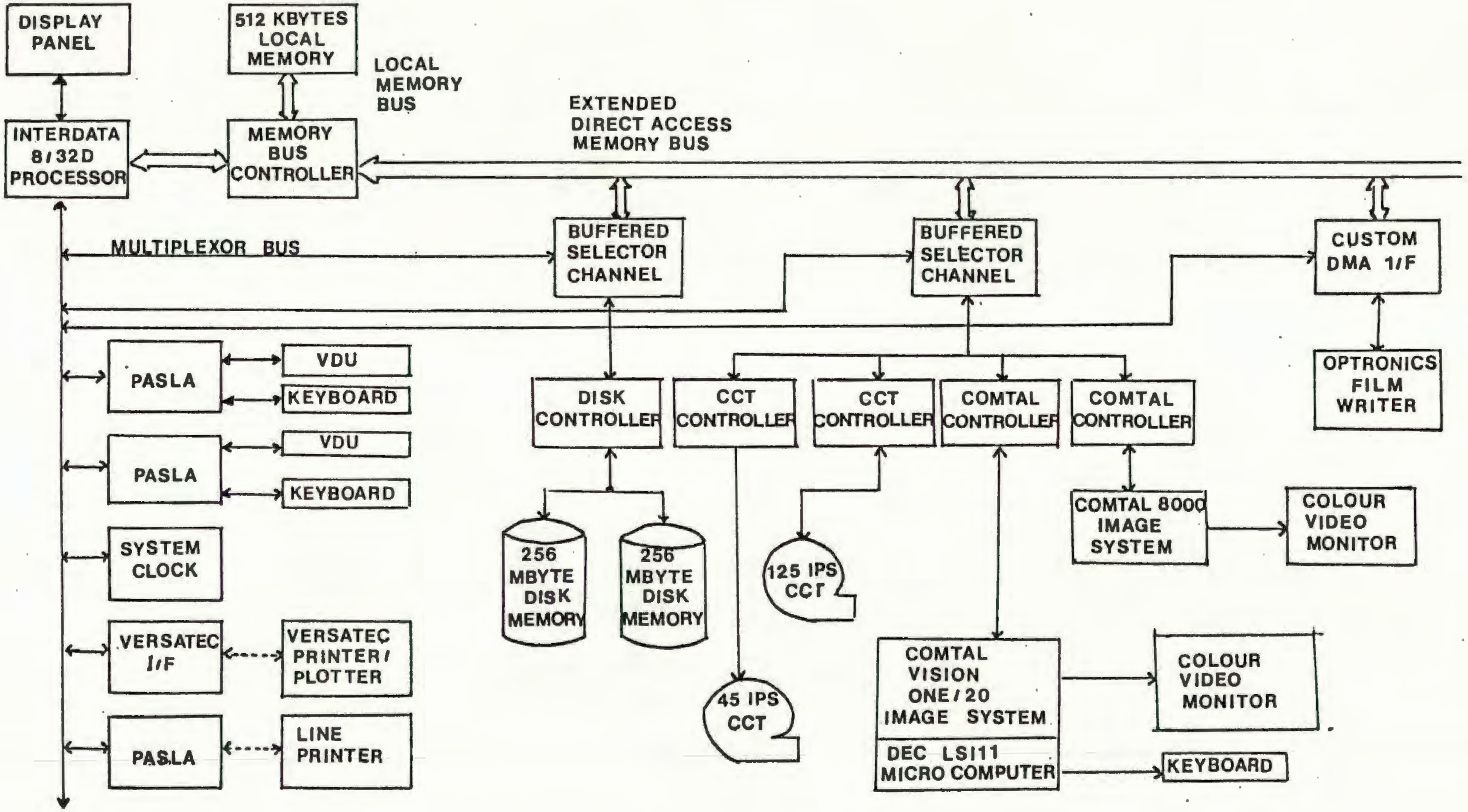


FIGURE 2.1 SRSC IMAGE ANALYSIS SYSTEM HARDWARE CONFIGURATION

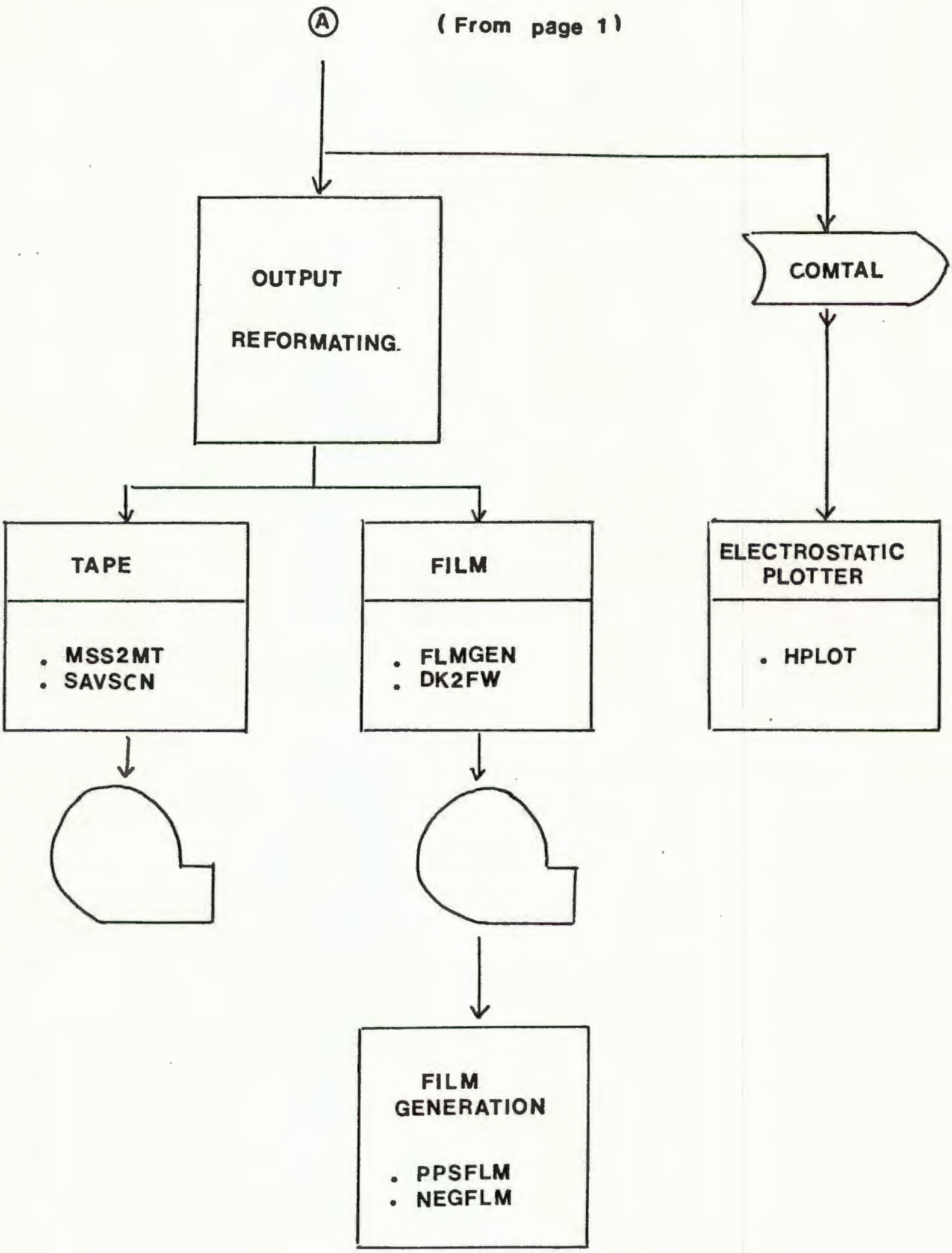
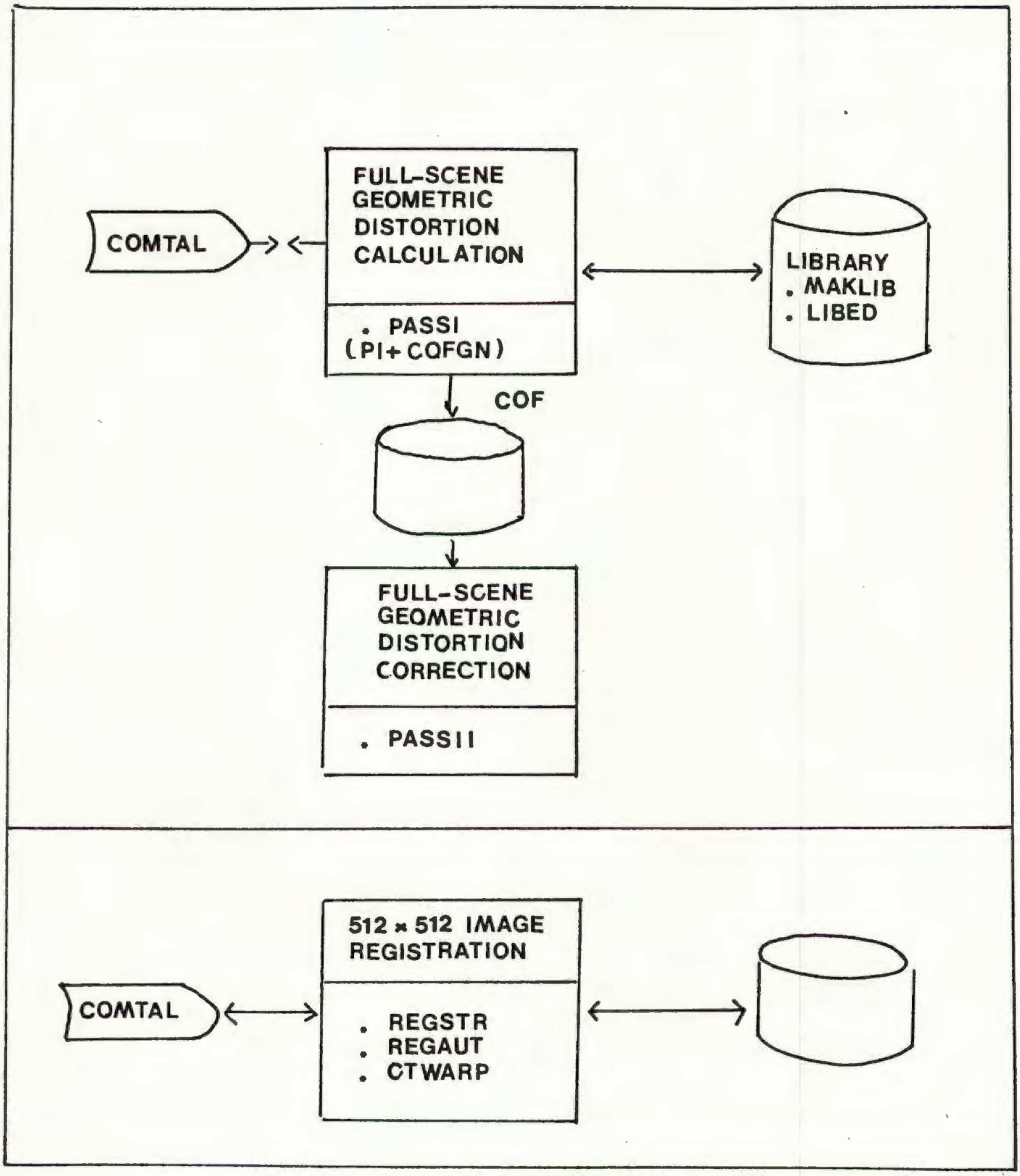


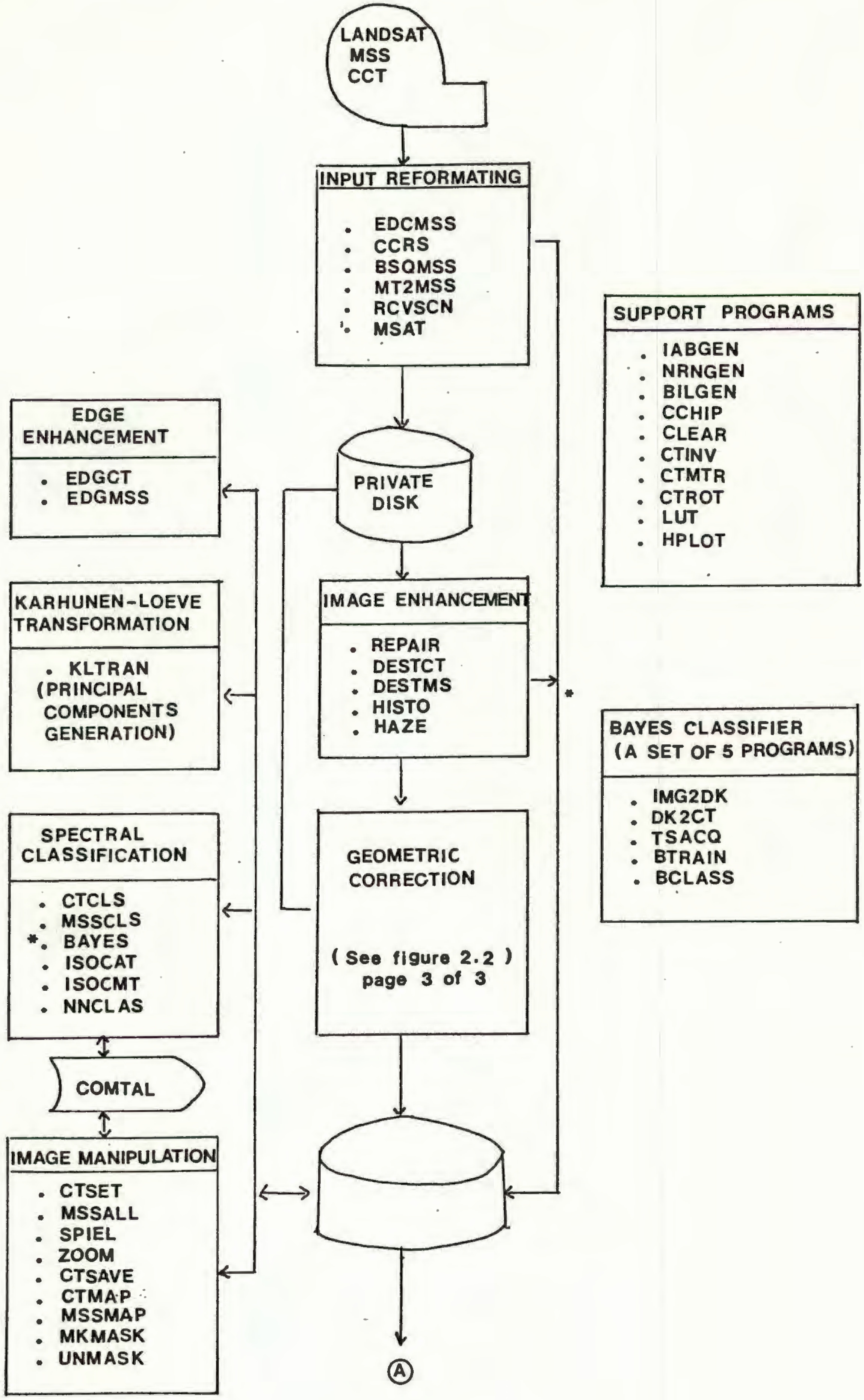
FIGURE 2.2 IMAGE PROCESSING SYSTEM FUNCTIONAL ANALYSIS (page 2 of 3)



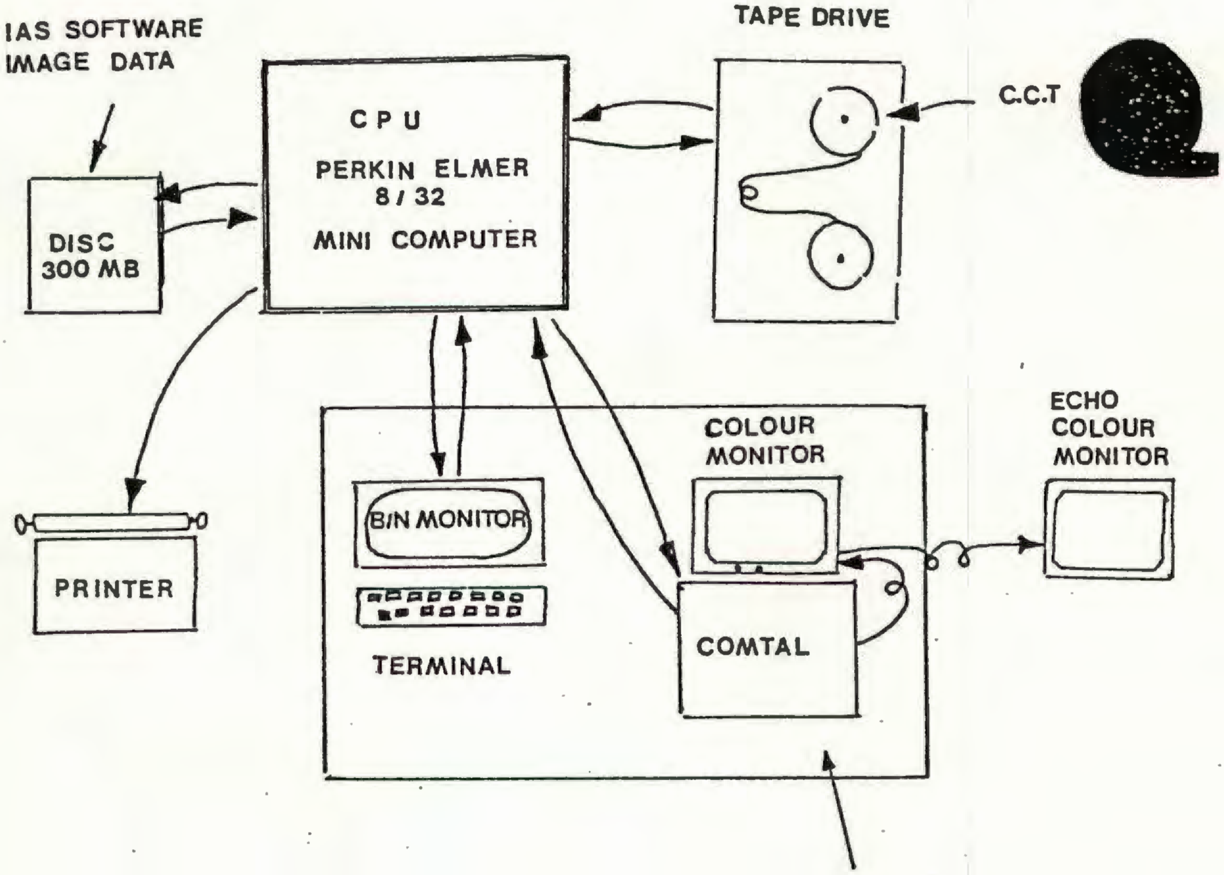
CP = CONTROL POINT DATA

COF= DISTORTION COEFFICIENTS

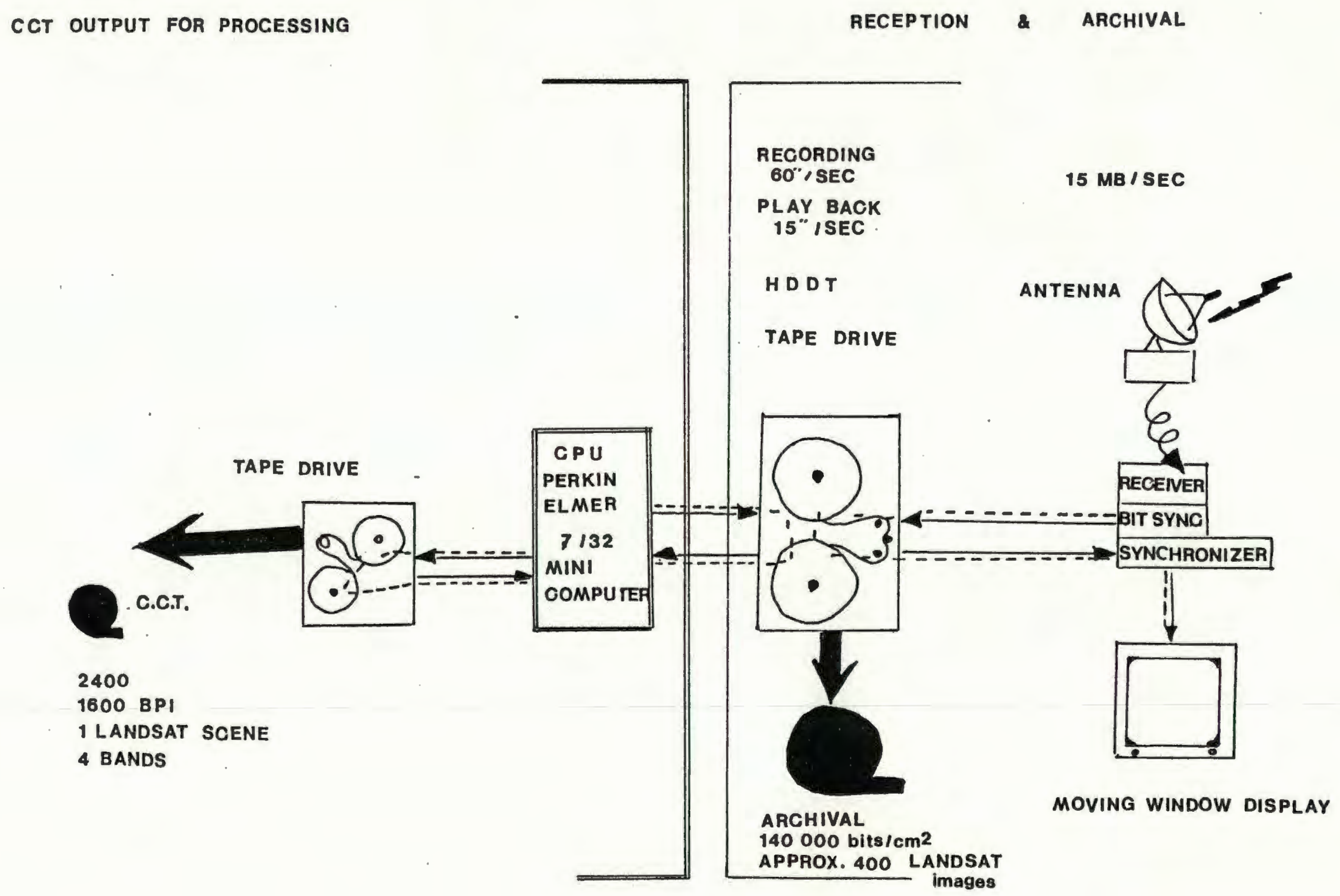
FIGURE 2.2 IMAGE PROCESSING SYSTEM FUNCTIONAL ANALYSIS
(page 3 of 3)


LANDSAT
MSS
CCT
INPUT REFORMATING
. EDCMSS
. CCRS
. BSQMSS
. MT2MSS
. RCVSCN
. MSAT
SUPPORT PROGRAMS
. IABGEN
. NRNGEN
. BILGEN
. CCHIP
. CLEAR
. CTINV
. CTMTR
. CTROT
. LUT
. HPLOT
EDGE ENHANCEMENT
. EDGCT
. EDGMSS
PRIVATE DISK
KARHUNEN-LOEVE TRANSFORMATION
. KLTRAN
(PRINCIPAL COMPONENTS GENERATION)
IMAGE ENHANCEMENT
. REPAIR
. DESTCT
. DESTMS
. HISTO
. HAZE
*
BAYES CLASSIFIER
(A SET OF 5 PROGRAMS)
. IMG2DK
. DK2CT
. TSACQ
. BTRAIN
. BCLASS
SPECTRAL CLASSIFICATION
. CTCLS
. MSSCLS
*. BAYES
. ISOCAT
. ISOCMT
. NNCLAS
GEOMETRIC CORRECTION
(See figure 2.2)
page 3 of 3
COMTAL
IMAGE MANIPULATION
. CTSET
. MSSALL
. SPIEL
. ZOOM
. CTSAVE
. CTMAP
. MSSMAP
. MKMASK
. UNMASK
A

I.A.S.



COMTAL (512 × 512)
1 MB LOCAL MEMORY
(1 BYTE / PIxEL) → 4 IMAGE PLANES
4 FUNCTION MEMORIES
(1 BIT PIxEL) → 4 GRAPHICS PLANES
1 PSEUDO-COLOUR MEMORY
TRACKBALL-CURSOR


CCT OUTPUT FOR PROCESSING
RECEPTION & ARCHIVAL
RECORDING 60"/SEC
PLAY BACK 15"/SEC
HDDT
TAPE DRIVE
15 MB/SEC
ANTENNA
RECEIVER
BIT SYNC
SYNCHRONIZER
MOVING WINDOW DISPLAY
ARCHIVAL
140 000 bits/cm2
APPROX. 400 LANDSAT images
CPU
PERKIN ELMER
7/32
MINI COMPUTER
TAPE DRIVE
C.C.T.
2400
1600 BPI
1 LANDSAT SCENE
4 BANDS

Appendix 2 A list of the training classes (supervised and unsupervised) and their relevant biotic and abiotic components, for the Kalahari Thornveld and Ghaap Plateau Training Areas.

1. KALAHARI TRAINING AREA

	TRAINING CLASSES	VEGETATION UNITS AND PHYSICAL FACTORS
1.1)	K49A.GRA	Open Acacia erioloba woodland (sometimes scattered Boscia albitrunca) on deep, red Kalahari sands. Mid north-facing and south-facing gentle slopes. 6m high dominant tree stratum.
1.2)	K52.GRA	Mixed, closed Terminalia sericea - Acacia erioloba - Boscia albitrunca woodland (height 7m) on pinkish-yellow depauperate sands. Crests on sandy hills.
1.3)	K52A.GRA	Acacia erioloba woodland, with Tarchonanthus camphoratus tall shrubland as substratum. Scattered clumps of tall Terminalia sericea. On level crests of sandy hills. Height 6-8m. Kalahari sands overlying calcrete.
1.4)	K54.GRA	Open, mixed Acacia erioloba - Tarchonanthus camphoratus woodland. Height 4,5-5,0m. Co-dominant spp. are Dicrostachys cinerea and Grewia flava. On deep, red Kalahari sands.
1.5)	K54X1.GRA	Same as K54.GRA, but on calcareous soils. (Alluvial)
1.6)	K46.GRA	Low, closed Acacia mellifera woodland. Thicket-forming from over utilisation of grass layer. Co-dominant species are Tarchonanthus camphoratus, Grewia flava. Widely scattered Acacia erioloba (sometimes forming localised clumps). Red Kalahari sands. Height 2-3m.

1.7)	K50A.GRA	Dwarf, open *Acacia haematoxylon* woodland. Co-dominant sp. *Dicrostachys cinerea*. Widely scattered *Acacia erioloba* (low) and *Terminalia sericea* (low). Deep, pale pink Kalahari sands. Height 2m.
1.8)	K43.GRA	Very open *Acacia erioloba* woodland or Kalahari grassveld with widely scattered *Acacia erioloba*. Deep Kalahari sands. Height of trees 4-6m.
1.9)	K42.GRA	Semi-closed *Tarchonanthus camphoratus* shrubland with scattered *Acacia erioloba* and *Rhus lancea*. Scattered, rare clumps of *Acacia mellifera*. Kalahari sand overlying calcrete. Height of shrub layer 2,5m, tree layer 5m.
1.10) 1.11)	K40X1.GRA K40X2.GRA	Mosaic Grassland with: widely scattered clumps of *Tarchonanthus camphoratus* and *Diospyros lycioides*. Widely scattered, low *Acacia erioloba* throughout. Also odd narrow lineaments with *Acacia karoo* (5m), *Diospyros lycioides*, *Tarchonanthus camphoratus*, etc. Pink Kalahari sands thinly covering dolomite bedrock slabs. Heights variable; shrubs 2,5m, trees 4-8m.
1.12)	K39.GRA	Mixed, closed *Tarchonanthus camphoratus* - *Rhus lancea* shrubland. Other common spp. are *Ziziphus mucronata*, *Grewia flava* and *Acacia karoo*. Shrubs 2-3m. Trees 4-6,5m. Solid calcrete with small depressions of dolomite bedrock slabs. Soil layer thin, often almost absent.

1.13) 1.14) 1.15)	K44X1.GRA K44X2.GRA K44X3.GRA	High, rounded Kalahari sand-covered quartzite hills with a mosaic of major plant communities; open, tall *Acacia erioloba* woodland (K44X2.GRA) closed, tall *Acacia erioloba* woodland (K44X1.GRA) or pure grassveld (K44X3.GRA). Scattered clumps of *Terminalia sericea*, with scattered *Acacia mellifera*, *Acacia haematoxylon* and *Dicrostachys cinerea*. Height variable, but generally 5-7m.
1.16)	K52X0.GRA	Fresh burn, high reflectance; Kalahari sands, leafless trees.
1.17)	K52X00.GRA	Old burn, low reflectance; Kalahari sands, coppicing *Terminalia sericea*, *Grewia flava*, *Boscia albitrunca* and stunted *Acacia erioloba*. Thicket-forming.
1.18)	K40X1A.GRA	See K40X1.GRA. Grassveld on dolomite bedrock slabs.
1.19)	K102.GRA	Closed *Tarchonanthus camphoratus* shrubland. Reddish loamy soil with andersite rocks and pebbles. Also scattered *Rhus ciliata* and widely scattered, low *Ziziphus mucronata*. Height 2-3m.
1.20)	K101.GRA	Mixed, closed *Acacia* - *Tarchonanthus* woodland. Spp. of importance: *Acacia tortilis*, *Acacia robusta*, *Tarchonanthus camphoratus*, *Grewia flava*, *Rhus ciliata*. Andersite hills; common rocks and boulders. Soil brown. Height 5m.
1.21)	K40X2A.GRA	Pure *Tarchonanthus camphoratus* tall shrubland. Pink Kalahari sand thinly covering dolomite bedrock. Height 2-2,5m.

2. GHAAP PLATEAU TRAINING AREA

2.1)	G36X1.GRA	Open woodland
2.2)	G36X2.GRA	Open woodland; rich soils
2.3)	G36X3.GRA	Open woodland; high ground
2.4)	G36X4.GRA	Open woodland; high ground
2.5)	G36X5.GRA	Lineaments
2.6)	G36X6.GRA	Exposed dolomite

This is a complex of closely-interrelated major plant communities of the Ghaap Plateau; northern section - open Rhus lancea woodland criss-crossed with lineaments supporting closed, mixed Rhus lancea - Acacia karoo woodland. The soil forms a thin layer over dolomite bedrock slabs (open Rhus lancea woodland); sometimes open dolomite, and sometimes thinly covered by a red, sandy loam. Lineaments are low limestone ridges, or past "water veins". These classes refer to geological types as well as physiognomic types.

2.7)	G14AX1.GRA	Closed Tarchonanthus camphoratus shrubland; southern section. Height 2-2,5m. This vegetation unit consists of a complex mosaic of interrelated major plant communities. Co-dominant species are the shrubs Rhus ciliata and Grewia flava with widely scattered Ziziphus mucronata (4m), Rhus lancea (5-7m), Diospyros lycioides (3,5m) and Olea europea (3,5-5,5m). Almost pure calcrete with scant soil cover. Odd exposures of dolomite bedrock associated with dark brown soils.
2.8)	G14AX2.GRA	
2.9)	G14AX3.GRA	
2.10)	G14AX4.GRA	
2.11)	G14AX5.GRA	
2.12)	G14AX6.GRA	
2.13)	G14BX1.GRA	Similar to the above vegetation unit but closed, mixed Tarchonanthus camphoratus shrubland (height 3-4,5m). Occurring on a stronger exposure of dolomite. Soils dark brown. Species as above but more common and include species such as Euclea crispa, E. undulata, Rhus tridactyla, R. undulata and many others. This vegetation unit occurs up to the edge of the Ghaap Escarpment.
2.14)	G14BX2.GRA	
2.15)	G14BX3.GRA	
2.16)	G14BX4.GRA	

2.17)	G37A.GRA	Grassveld with widely scattered Acacia karoo and Rhus lancea. These trees often absent over large areas. Soils dark brown. Patches of calcrete and dolomite bedrock. Some areas experience water-logging; marshland grass species.
2.18)	GCALCRD.GRA	Secondary calcrete-surfaced roads.
2.19)	G92.GRA	Tall Olea europea - Rhus lancea woodland. Other species are Rhus pyroides, Lycium hirsutum, Ziziphus mucronata, Maytenus heterophylla, etc. Thin layer of grey-brown soil over calcrete. Height 6-8m.
2.20)	G14BX5.GRA	Refinement of G14B complex. Mainly geological types, but with the possibility of being combined with variations in the moisture regime of subsoil layers.
1.21)	G14BX6.GRA	
2.22)	G14BX7.GRA	
2.23)	G14BX8.GRA	

Appendix 3 Relationship between map scale, smallest recognizable map unit (in ha) and number of spectral units used in numerical classifcation of digital remote sensing data. (From Jarman *et al.* 1981, in Jarman 1981).

Final map scale	Smallest map unit recognized = 2 print characters		Units used in classification	
	No. of pixels	(ha)	No. of pixels	(ha)
General and General Reconnaissance >1 : 1 000 000	3 200	1 408,0	1 600 (40 x 40)	704,0
Reconnaissance 1 : 250 000	200	88,0	100 (10 x 10)	44,0
Semi-detailed 1 : 50 000	8	3,5	4 (2 x 2)	1,8
1 : 20 000	2	0,8	1	0,4
Detailed 1 : 10 000	1	0,4	1	0,4
Ultra-detailed <1 : 500	Beyond the limits of resolution of current Landsat series			

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