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Digital Change Detection Techniques in Remote Sensing

Peter Deer

DEPARTMENT ◆ OF DEFENCE
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

DIGITAL CHANGE DETECTION TECHNIQUES IN REMOTE SENSING

Peter Deer

Information Technology Division
Electronics and Surveillance Research Laboratory

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ABSTRACT

Technical Report

This report presents a review of digital change detection techniques using remotely sensed data, citing examples of their use for both environmental and military applications. It also discusses some issues germane to digital change detection: image registration and rectification, thresholding, and radiometric correction.

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Fax (08) 259 5619

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EXECUTIVE SUMMARY

Digital change detection techniques aim to detect changes in images over time. They can be used as a 'cueing system' to attract the attention of human analysts to 'interesting' digital images from the large number of available images. Change detection techniques rely upon differences in radiance values between two or more dates. These differences may be due to an actual change in land cover, or differences in illumination, atmospheric conditions, sensor calibration or ground moisture conditions. The calibration of data, or standardisation between dates, may be necessary, and the accuracy of the image registration is important.

There are a number of digital change detection techniques in relatively common use in the remote sensing community. They include post-classification comparison, multi-date classification, image differencing, image regression, image ratioing, vegetation index differencing, principal components analysis and change vector analysis. Unfortunately, few quantitative comparative studies of change detection techniques are available, and there is conflict between the results of these studies. It is concluded that there is no universally 'optimal' change detection technique: the choice is dependent upon the application.

There is a significant body of open literature on the military use of commercial remotely sensed digital imagery, but little has been published on the military use of change detection techniques.

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Author

Peter Deer
Information Technology Division

Peter Deer has a BSc (Mathematical Physics and Applied Mathematics, University of Adelaide), a Graduate Diploma in Operations Research (South Australian Institute of Technology), and a Graduate Diploma in Applied Remote Sensing (University of Adelaide). He is also a graduate of Cranfield Institute of Technology/Royal Military College of Science, UK. Peter is currently working in the field of digital image processing using remotely sensed data.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

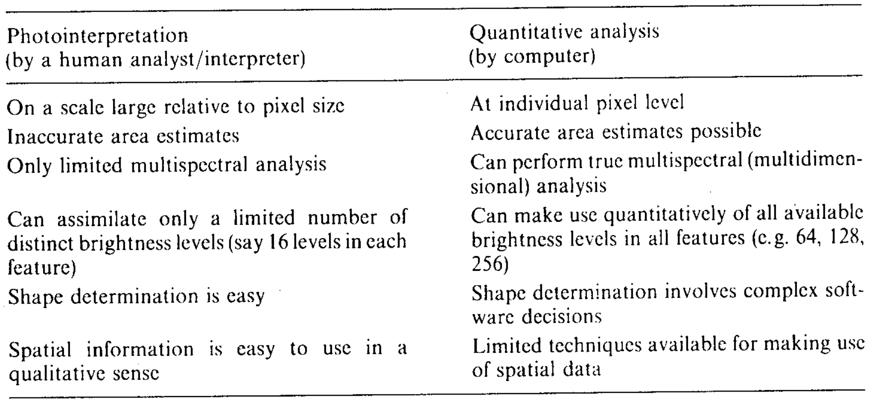
1 INTRODUCTION

1.1 General

It is now relatively commonplace for satellites, travelling at kilometres per second, at a height of hundreds of kilometres above the surface of the Earth, to capture and transmit 'images' of the Earth that we could not otherwise see, representing areas hundreds or thousands of kilometres square, at data rates of hundreds of megabits per second, and to do so continuously for years. It is also possible to capture imagery from airborne platforms, and these commonly use hundreds of spectral bands (hyperspectral imaging systems). We can use a variety of naturally occurring radiation sources (eg the sun, commonly at visible or infrared frequencies, or emissions from an object because of its temperature). We are, however, no longer constrained to naturally occurring radiation sources: we can illuminate the object (eg, with radar or lidar), and image at night and through cloud, light rain, haze and sometimes smoke. We can gain further advantage through our control of the radiation source, and synthesise antenna lengths to achieve much higher spatial resolutions than the physical laws would seem to permit. A noteworthy characteristic of these images is that they are captured in digital form.

The importance of this is that the imagery is amenable to processing by computers. This considerably changes and broadens both the nature and quantity of the processing that can be undertaken. Indeed, it can be strongly argued that it is a very limiting viewpoint to consider data of this type as 'an image'. It is a digital data file of numbers representing the strength of upwelling radiation in whatever frequency bands we desire, arranged in a well ordered spatial structure, containing much information about the nature of objects, that can be viewed as an image by a human analyst if so desired. But the budget of a nation can be viewed as a pie-chart, and the performance of the stock market can be viewed as a graph. These are both valid and useful views of the data, but they are limited views. There is much more underlying information than can be represented in these forms. So too is it with digital imagery. The human eye-brain has many remarkable qualities and attributes (most particularly, in this context, its ability to discern patterns and shapes in spatial data), but it has a number of limitations (such as an inability to input more than three spectral bands, to process numerically, or to make adequate use of a large number of brightness values). The following table, from Richards (1986), summarises the relative strengths of a human analyst and a digital computer.

Table 1. A Comparison of Human Analysts and Computers. *Reproduced from Richards (1986)*



Photointerpretation (by a human analyst/interpreter)	Quantitative analysis (by computer)
On a scale large relative to pixel size	At individual pixel level
Inaccurate area estimates	Accurate area estimates possible
Only limited multispectral analysis	Can perform true multispectral (multidimensional) analysis
Can assimilate only a limited number of distinct brightness levels (say 16 levels in each feature)	Can make use quantitatively of all available brightness levels in all features (e.g. 64, 128, 256)
Shape determination is easy	Shape determination involves complex software decisions
Spatial information is easy to use in a qualitative sense	Limited techniques available for making use of spatial data

It is worth asking ourselves "What happens to all these images?" The sheer number of them means that many are never even looked at. The SPOT imaging satellites alone, relative newcomers as they are, have, for example, generated over a million images. We might answer this question by stating that 'people should look only at the relevant images'. This is easy if we know which ones these are, because we wish to observe this particular rice paddy or that particular industrial complex, but it is not so easy if what we are looking for can move, we don't know where it is, and it may not even be anywhere at all.

The problem of knowing which images to look at can be alleviated somewhat, with digital imagery, by having a computer 'look at' all images, and directing the attention of a human analyst to the 'relevant ones'. Excepting the special case in which we know both where and when to look, the two principal methods of determining which are the 'relevant ones' are to either understand the image content, or to determine those images in which change has occurred over some appropriate time interval. The latter method goes under the rubric of digital change detection, and there exists a reasonable body of literature on the use of digital change detection techniques, for environmental applications, in remote sensing. The former method is less successful and well established, with the reported research commonly bearing titles including 'image understanding'. The remainder of this paper will concentrate on the use of digital change detection techniques.

1.2 *Change Detection*

Change detection is the process of identifying differences in the state of an object or phenomenon by observing it at different times. The basic premise in using remote sensing data for change detection is that changes in the object of interest will result in changes in radiance values or local texture that are separable from changes caused by other factors, such as differences in atmospheric conditions, illumination and viewing angle, soil moisture, etc. It may further be necessary to require that changes of interest be separable from expected or uninteresting events, such as seasonal, weather, tidal or diurnal effects.

Clearly, the aspects of change that are of interest are:
(a) has it occurred? (detection)
(b) where? (location and extent)
(c) what change occurred? (identification)
(d) what are the causes and implications of this? (analysis)

The term 'change detection' is variously and loosely applied in the literature. It invariably involves the first of these aspects, normally the second, and sometimes the third. The fourth aspect is normally left to the human analyst (although Dreschler-Fischer *et al*, 1993, attempts to capture this process in the knowledge rules of an expert system).

Satellite remote sensing offers a potentially powerful method of monitoring changes in imagery at higher temporal resolution and lower costs than those associated with traditional methods (Martin, 1989). The attributes of remotely sensed satellite data include a synoptic view, a high frequency of revisitation, relative cheapness, and its digital nature (rendering machine assistance or analysis possible). The capabilities of different sensing technologies can be utilised, to some extent, to overcome problems of day/night observation, obscuration by smoke, rain, cloud, haze etc. Additional advantages from a military perspective include an ability to overfly denied areas with relative invulnerability, and regular scheduled overflights that give no indication of specific interest (ie, with passive remote sensing systems, it is not usually possible to tell when an area is being imaged).

A number of researchers have used remotely sensed satellite data for change detection, and a number of approaches and techniques have been developed.

1.3 *Aim of this Paper*

The aim of this paper is to discuss the use of digital change detection techniques using remotely sensed satellite data. This aim will be pursued by:

a. discussing digital change detection techniques, and reviewing their use in the literature (Section 2);

b. examining military applications of remotely sensed satellite data (Section 3); and

c. describing the reported military use of digital change detection techniques (Section 4).

The intended audience for this report is the community of Defence image analysts, and the intended level is introductory. It was hoped at the outset of this study that a discussion of the applications of digital change detection techniques would be able to cite exclusively military examples: the paucity of such examples precluded this, and thus the examples offered in Section 2 are derived essentially from the environmental monitoring domain.

2 DIGITAL CHANGE DETECTION TECHNIQUES

2.1 *Introduction*

There are two basic approaches to digital change detection. The first approach involves the comparative analysis of independently produced thematic labellings or classifications of imagery from different dates. The second approach is to undertake simultaneous analysis of multi temporal data. Within these two approaches there are a number of methods and techniques. These are described below. As befits a document of this nature, the descriptions of techniques are relatively general, and their mathematical development has been avoided. References are provided for the reader who wishes to pursue any of these techniques in greater detail.

2.2 *Review of Techniques*

2.2.1 *Post-Classification Comparison*

This is the most obvious method of detecting change. It involves the classification of each of the images independently, followed by a comparison of the corresponding pixel (thematic) labels to identify areas where change has occurred. The process of classification itself can be undertaken in either a supervised or an unsupervised manner. A supervised classification is when a human analyst indicates a number of areas of an image, and identifies what they are (through collateral knowledge). The computer then identifies the characteristics of the data that comprise each type or area, and classifies the remaining image pixels in accordance with the identified type to which they are most similar. In an unsupervised classification, the computer clusters or partitions the data without prior knowledge of classes, and thematics labels are applied, through collateral knowledge, at a subsequent stage.

The major disadvantages of post-classification comparison are:

(a) Classification techniques are relatively expensive (in both time and cost). There is normally a substantial requirement for 'ground truthing' to reduce uncertainty and error. Unsupervised classification techniques, whilst possibly reducing the costs, are prone to higher error rates.

(b) Any subsequent classification and comparison is effectively constrained to the initial set of class labels.

(c) A classification process results in a class label being assigned to a pixel (provided some threshold condition of 'closeness' or 'typicality' is satisfied). The labels assigned are normally discrete, and information about the certainty of the assignment is normally not kept. A pixel may just fall into one category on one date, and just fall into a different category on a second date. A post-classification comparison will indicate a class change, but there may be, according to the probabilities associated with the individual classifications, only a small indication of change that is not statistically significant.

(d) Errors in classification have a compounding effect (Pilon *et al*, 1988; Quarmby and Cushnie, 1989). Consider images on two dates of the same area, with no change having occurred. Assume perfect image to image registration. Let the accuracy for each independent classification be 90% (a generous allowance). A pixel-wise comparison of the two classifications could reveal that up to 19% of the scene has undergone change (1-{0.9*0.9} = 0.19). We know that no change has occurred, yet this method could indicate that up to 19% of the scene has changed: this is an alarmingly high false detection rate! Clearly, this simple analysis assumes no correlation between the two sets of erroneous classifications, and is offered for illustrative purposes only. Not-withstanding this, Stow *et al* (1990) found that a change map produced from two independent classifications exhibited similar accuracy to the product of multiplying the individual accuracies.

The comparison of separately classified images can be carried out visually, or by computer. As previously discussed, computers are better at quantitative analysis, but humans are able to discern patterns and shapes much better, and the effect of misregistrations may be much reduced (registration is discussed later in this paper) . If the comparison of images is to be carried out by computer, it may be assisted by the use of a geographic information system (GIS).

Riordan (1980) produced unsupervised classifications of 1973 and 1978 Landsat MSS data and compared the classifications to detect non-urban to urban change, and reported an accuracy of 67 per cent. Joyce *et al* (1980) concluded that post-classification comparison 'appears suitable for detecting land cover change with Landsat MSS data in sites where large areas of forestland are being converted to cropland'. Gordon (1980), however, used this method to monitor land use change in Ohio and, after a rigorous quantitative assessment, observed '... we must conclude that substantial errors are associated with the use of Landsat data for land cover and change analysis'.

Jensen *et al* (1987) used post-classification comparison with unsupervised classification of aircraft MSS data for wetland change detection, but achieved limited success.

2.2.2 *Direct Multi-Date Classification*

This method is based on a single analysis of a combined data set of two or more dates to identify areas of change. To illustrate, in a study involving two dates, and using Landsat MSS imagery, a single data set of eight bands is produced. It may then be analysed in either a supervised or an unsupervised mode. In the supervised approach training sets pertaining to change and no-change areas are used to derive statistics to define sub-spaces of the feature (normally spectral) space. In the unsupervised approach, spectral classes are determined by cluster analysis, and subsequent inspection should reveal where changes have occurred. In either case, change classes are expected to display significantly different statistics from no-change classes. Weismiller *et al* (1977) used a clustering technique combined with layered spectral/temporal classification to detect change in a Texas coastal area.

2.2.3 *Image Differencing*

In this technique, images of two different dates are spatially registered (discussed later). The corresponding pixel values are then subtracted to produce a new image which represents the change between the two times. Pixels exhibiting a significant radiance change can be expected to lie in the tails of the distributions of the difference image, whereas the remaining pixels should be grouped about the mean. The technique may be applied to a single band (in which case it is called univariate image differencing) or to multiple bands. Some form of radiometric standardisation is normally applied to reduce the effects of illumination angle and intensity (including path effects) and viewing angle.

Weismiller *et al* (1977) found that change detection based on the method of image differencing worked well in the Texas coastal zone environment (although many small areas of change were not identified accurately). Miller *et al* (1978) applied Landsat image differencing successfully to the mapping of changes in tropical forest cover in northern Thailand. Williams and Stauffer (1978) utilised this technique to monitor gypsy moth defoliation in the forests of Pennsylvania, Brera and Shahrokhi (1978) used it for the analysis of desertification in the Sahara, and Vogelmann (1988) investigated the detection of change in temperate forests. Singh (1989) mentions his earlier use (1986) of this technique for monitoring changes attributable to shifting cultivation in a tropical forest environment.

2.2.4 *Image Regression*

In this method, pixel values from one time are assumed to be a (normally) linear function of pixel values at some other time. The function that relates the pixel values can be determined, for example, using a least squares regression Pixels that have changed between the two dates will exhibit values that differ significantly from that predicted by the determined function. Thresholding is applied to detect areas of change. This technique accounts for differences in the mean and variance between pixel values for different dates, so the effects of different atmospheric conditions and sun angle are reduced. Use of this method has not been widespread. Singh (1986), however, used it for forest change detection, and found it to be superior to a number of other methods. Hanaizumi *et al* (1991) used a technique involving both regression and segmentation.

2.2.5 *Image Ratioing*

Image ratioing consists of calculating the ratio of the values of corresponding pixels of registered images of different dates, on a band by band basis. If no change has occured, it is expected that the ratio of corresponding pixels, in corresponding bands, will be near unity. If change has occured in a particular pixel, the ratio it is expected to be either considerably more than or considerably less than unity (depending on the 'direction' of the change). Some data standardisation or radiometric correction between dates may be necessary. Todd (1977) used image ratioing to determine urban change in Atlanta, Georgia, and determined that 91.4% of land cover change was correctly identified. Weydahl (1991) states that ratioing is less sensitive than differencing to multiplicative noise in SAR imagery.

The main criticism of this method centres on the statistical distributions of the ratioed images (Robinson 1979). Because functions of the standard deviation are normally used to threshold change, non-symmetric distributions will result in unequal areas on either side of the mean. Therefore, the error rates on either side of the mean will not be equal. This is clearly undesirable. Further work appears indicated on the nature of the distributions of ratioed images, and on more robust thresholding proposals.

2.2.6 Vegetation Index Differencing

Digital spectral radiance values can be analysed independently on a band by band basis, or in combinations of two or more bands. One of the most commonly used band combination techniques involves the calculation of vegetation indices. These have been developed to enhance spectral features on the basis of the strong absorption of red and strong reflectance of near-IR by vegetation. They are most commonly either linear combinations of bands, or band ratios. It has been found that the ratio of near-IR to red reflectance is significantly correlated with the green leaf biomass (Tucker, 1979). There are a number of vegetation indices in use (refer to Guoling, 1989, for a complete treatment) with a common one being the normalised difference vegetation index (NDVI):

(near-IR minus red reflectance)/(near-IR plus red reflectance).

It is considered that normalising or ratioing spectral bands negates the effect of any extraneous multiplicative factors in sensor data that act equally in all bands (Lillesand and Kieffer, 1979), but it should be noted that it may enhance random or coherent noise that is not correlated in different bands (Singh 1989). Qi *et al* (1993) advocate a correction to account for first-order soil background effects when using vegetation indices.

For change detection purposes, the difference between vegetation (or indeed any other) indices between two or more dates should give a reasonable indication of change in the vegetation canopy (or other condition of interest). Coiner (1980) used vegetation index differencing to study desertification, but provided no accuracy assessment or comparison with other techniques. Nelson (1983) assessed this method quantitatively in the study of gypsy moth defoliation in Pennsylvania.

2.2.7 *Principal Components Analysis*

The principal components transformation (sometimes termed the Hotelling or discrete Karhunen-Loeve Transformation) is a linear transformation which defines a new, orthogonal co-ordinate system such that the data can be represented without correlation. Both the correlation and covariance matrices in the new co-ordinate system are therefore diagonal.

The transformation that achieves this can be found from the eigen vectors of either the covariance or correlation matrices of the original data. The axes of the new, orthogonal co-ordinate system are defined by the eigen vectors. Each individual pixel is transformed by vector multiplication of its original vector and the eigen vectors, resulting in coordinates in the new space (ie a new pixel vector). Each eigen vector can be thought of as a new 'band', and the coordinate of an individual pixel can be thought of as its brightness in that 'band'. The amount of the total scene variance that is represented by each new 'band' is given by the eigen value of the corresponding eigen vector.

PCA can also be applied to image data sets comprising bands from two or more dates (ie to multi-temporal image data) (eg Lodwick, 1979; Byrne *et al*, 1980; Richards, 1984; Ingebritsen and Lyon, 1985; Fung and LeDrew, 1987). There is a high correlation between image data for regions that have not changed significantly and a relatively low correlation between regions that have changed substantially. Provided the major portion of the variance in a multi-temporal image data set is associated with constant cover types, regions of localised change will be enhanced in the higher components of the set of images generated by a principal components transformation of the multi temporal, multi spectral data (Richards, 1986), whilst brightness changes between the two dates attributable to atmospheric conditions or sun angles can be expected to be represented in the first PC.

It was stated earlier that PCA can be undertaken using either the covariance matrix or the correlation matrix, but it should be noted that the principal components so derived will be different. A detailed treatment of this matter is given in Singh and Harrison (1985). Fung and LeDrew (1987) state that the use of correlation PC is 'especially useful in multi-temporal analysis because standardisation can minimise the differences due to atmospheric conditions or sun angles'.

Fung and LeDrew (1987) used PCA on a primarily urban and agricultural area with MSS data from two dates, and found that the correlation PC were, in order, essentially indicating greenness, brightness, change in greenness between the two dates, and change in brightness. Ingebritsen and Lyon (1985) generally found the PC to be brightness, greenness, change in brightness and change in greenness, although they noted that the order after brightness was determined by the amount and nature of the change between dates. Deer and Longmore (1994) found that the order of PC of like-season imagery in southern Australia was brightness, greenness, change in brightness and change in greenness, and noted that there are similarities between principal components analysis and vegetation index differencing for applications involving changes to vegetation.

2.2.8 Change Vector Analysis

Multi spectral remotely sensed image data can be represented by constructing a vector space with as many axes or dimensions as there are spectral components (bands) associated with each pixel. A particular pixel in an image is plotted as a point in such a space with co-ordinates that correspond to its brightness values in the appropriate spectral components. The data values associated with each pixel thus define a vector in the multi dimensional space. If a pixel undergoes a change from time t_1 to time t_2, a vector describing the change can be defined by the subtraction of the vector at t_1 from the vector at t_2. This is called the spectral change vector. It may be calculated from either the original or transformed (for example, PCA) data, and using either individual pixels or clusters formed by a spectral clustering or spatial segmentation algorithm. If the magnitude of the computed spectral change vector exceeds some specified threshold criterion, it may be concluded that change has occurred. The direction of the vector contains information about the type of change. Change Vector Analysis is illustrated in figure 1.

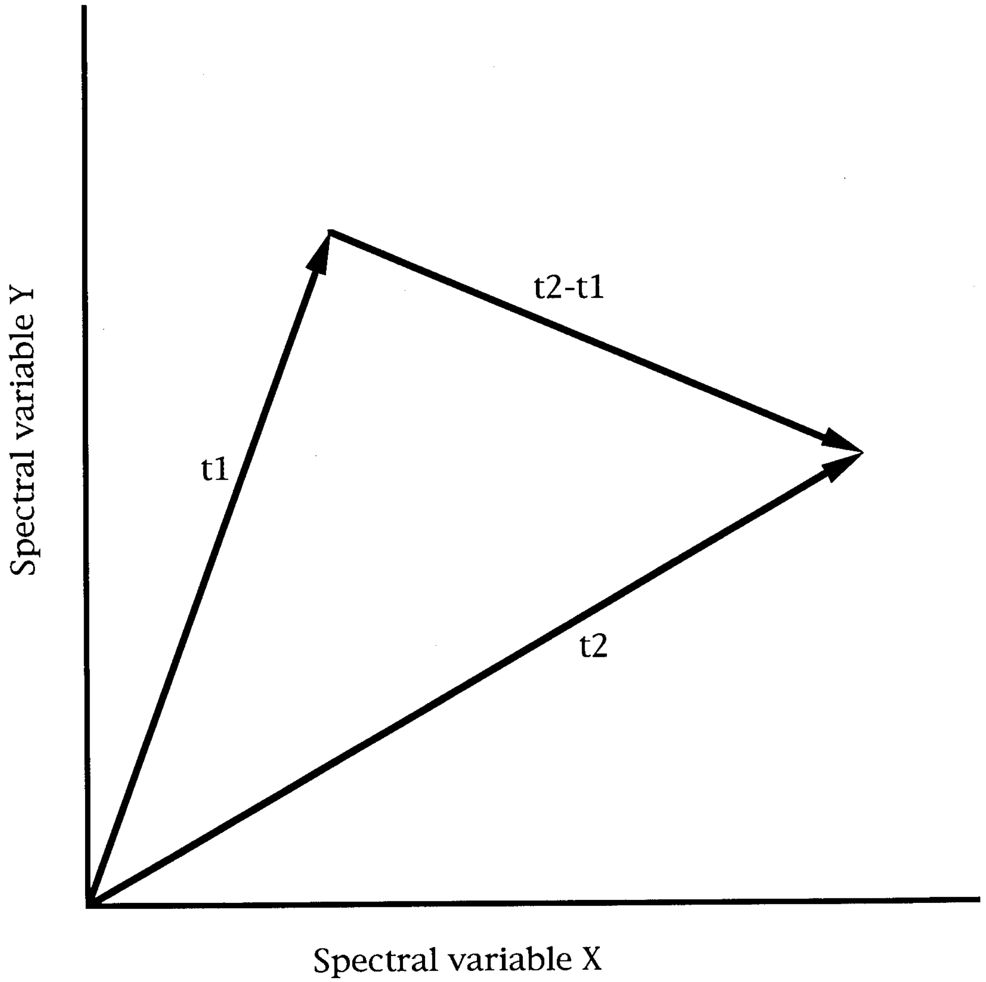


Figure 1. Change Vector Analysis. The spectral vector representing the values of a particular pixel at times t_1 and t_2 are shown as t1 and t2 respectively. The spectral change vector, for the particular pixel, is shown as t2-t1.

This method was applied to forest change detection in northern Idaho (Malila 1980) and in South Carolina (Colwell and Weber 1981), and to general change in the Ann Arbor, Michigan area (Virag and Colwell 1987). Lambin and Strahler (1994) recently reported a further development of this method, and used it to monitor land use in West Africa. Unfortunately, little or no accuracy assessment was undertaken in any of these studies.

2.2.9 Statistical Tests

These involve examining the statistics of two or more image files, of the same area, taken at different times. Eghbali (1970) used the Kalmogorov-Smirnov test to determine whether two samples (two dates of imagery of the same location) had been drawn from the same population. With this method, the maximum difference between the cumulative distributions of the two data sets is calculated. If it is above some threshold, change is concluded to have occurred. Coiner (1980) used the correlation coefficient between the data sets of two dates as an indicator of change. Townshend *et al* 1992 used the semivariance (the sum of the squares of the differences in pixel values) of multi date NDVI images.

These techniques do not yield much useful information on the nature of the change, or its specific location within the image: they merely indicate that a statistically significant change has occurred somewhere in the image or region under examination. They offer some advantage, however, in that they are likely to be less affected by image misregistration.

2.2.10 New Techniques

There seems to be some potential for new change detection techniques to emerge from areas such as computer vision, image understanding, knowledge-based systems or fuzzy logic. For example, Choo *et al* (1989) sought to identify change in an image sequence using shape analysis. Researchers in the computer vision area use local texture features for segmentation, and it would seem that multi temporal images so segmented would be amenable to change detection. Although not focussed on change detection, Matsuyama (1987) provides an excellent review on the growing use of artificial intelligence (AI) techniques for remote sensing. Blonda *et al* (1991) report that a rule-based fuzzy logic approach gave better results than a maximum likelihood classifier on a multi temporal data set (the objective was classification, not change detection). Some recent work on 'fuzzy' classification algorithms (ie classification using a fuzzy set membership approach) would seem to offer some promise of improvement in the accuracy of post classification comparison (see, for example, Wang, 1990; Nishida *et al,* 1993; or Al-Sultan and Selim, 1993).

2.3 *Comparison of Techniques*

The majority of the literature reviewed in this section deals with the use of one change detection technique in a particular application. Few comparative studies are available, and the majority of these do not support their conclusions by quantitative analysis. Colwell and Weber (1981) used post-classification comparison, change vector analysis and visual estimates for forest change detection, but no ground reference accuracy assessment was done. Howarth and Wickware (1981) qualitatively compared the image ratioing and post-classification comparison methods for environmental change detection. Toll *et al* (1980) used univariate image differencing, post-classification comparison and principal component differencing for urban change detection, but again, only qualitative analysis was undertaken. Weismiller *et al* (1977) used image differencing, post-classification comparison and multi-date classification for change detection in a coastal zone environment, but the results were not compared with coincident ground truth.

Using quantitative accuracy assessment, Nelson (1983) found that vegetation index differencing was superior to both image differencing and ratioing for detecting gypsy moth defoliation. Banner and Lynham (1981), however, found vegetation index differencing less accurate than the multi-date classification approach. Singh (1989) summarises some previous work (Singh, 1986) on the objective evaluation of automated methods for forest change detection. Univariate image differencing, image ratioing, normalised vegetation index differencing, image regression, principal component analysis, post-classification comparison and multi-date classification were compared. A number of local spatial processing techniques such as image smoothing, background subtraction, edge enhancement and texture defined by standard deviation were also investigated. A thresholding technique was applied and a number of standard deviation threshold levels were tested in the upper and lower tails of the distribution in order to find a threshold value which produced the highest change classification accuracy. The conclusions were as follows:

(a) The regression method using Landsat MSS band 2 produced the highest change detection accuracy.

(b) Image ratioing and image differencing produced the next highest change detection accuracies.

(c) The various local spatial processing techniques did not improve the change detection accuracy.

(d) The post-classification comparison approach produced the lowest change classification accuracy.

Fung and LeDrew (1988) combined an investigation of thresholding with the change detection techniques of image differencing, image ratioing and principal components analysis. They concluded that principal components analysis gave the best overall results, but noted that some specific change categories were identified with greater accuracy by other techniques. Jiaju (1988) also found principal components analysis superior to image differencing and image ratioing. Stow *et al* (1990), on the other hand, found that image ratioing produced higher change detection accuracies than did principal components analysis. Martin (1989) concluded post-classification comparison gave better results than either multi-date classification or principal components analysis for change detection in the rural-urban fringe.

Thus it would appear that there is no universally 'optimal' change detection technique: the choice is dependent upon the application (and possibly on the specific data set). This view is supported by Virag and Colwell (1987), who state 'The procedure that is most appropriate to use in a given situation depends upon the specific application (type of environment, targets of interest), and the amount of detail required'.

2.4 Other Issues

There are several potential problem areas confronting any attempt to undertake digital change detection. They are image registration and rectification, selection of threshold values, and radiometric correction/calibration. These are discussed below.

2.4.1 Image Registration and Rectification

Image registration is 'the process of geometrically aligning two or more sets of image data such that resolution cells for a single ground area can be digitally or visually superimposed' (Swain and Davis, 1978). Image rectification is 'the process of correcting distortions in remotely sensed imagery so that its geometry accurately represents the geometric features of the Earth's surface' (Harrison and Jupp, 1989).

That is, registration and rectification aim to remove the geometric distortions that exist between image and image, and image and map, respectively.

There are numerous sources of geometric distortion in remotely sensed imagery. These sources include (Richards, 1986):

(a) rotation of the Earth,
(b) sensor scan rate,
(c) sensor field of view,
(d) curvature of the Earth,
(e) sensor non-idealities (*sic*, non linearities?),
(f) variation in the platform altitude, attitude and velocity, and
(g) panoramic effects related to imaging geometry.

Figure 2, reproduced from Harrison and Jupp (1989), shows the effects of imaging geometry alone, for an otherwise geometrically perfect aircraft sensing system (ie with no other sources of geometric distortion). The effect is similar for satellite systems, although reduced due to the generally lower off-nadir viewing angles.

Relief displacement can also have an effect, particularly in areas of significant relief variation, at the edges of imagery, or if the imaging system is employing off-nadir viewing. This is particularly so in the case of synthetic aperture radar (SAR) imagery.

The literature is in common agreement that digital change detection requires accurate spatial registration of the multi temporal images (eg Singh, 1989; White, 1991). If high accuracy is not achieved, widespread changes will seem to occur over the entire scene which are in fact artefacts caused by misregistration of the images (Milne, 1987). The accuracy needed, or conversely, the errors observed if 'high accuracy' is not achieved, does not appear to have attracted much serious scientific analysis. One quantitative study that has been reported on this subject is Townshend *et al* (1992), who found that, in some cases, misregistrations of the order of 0.2 of a pixel resulted in errors in change detection accuracies of 10%. It should be noted, however, that they used only one change detection method (and an uncommon one at that).

Therefore some or all of the geometric distortions inherent in imagery must be removed or reduced before comparison of multi temporal imagery is possible by other than visual means. The two principal methods of removing geometric distortions are:

(a) model the nature and magnitude of the distortions, and then use these models to correct the imagery; and/or

(b) establish empirically derived mathematical relationships between pixel addresses in an image, and either pixel addresses in another image (registration), or map coordinates (rectification).

It is also sometimes appropriate to correct for topographic effects (by use of digital elevation models). This is common in the case of radar imaging because of the viewing angles used.

The subject of image registration/rectification is quite complex, and will not be addressed further in this report. Due, however, to its importance to digital change detection, general mapping, and many other problems of defence interest, a separate report on this subject is proposed (Deer and Newsam, in preparation).

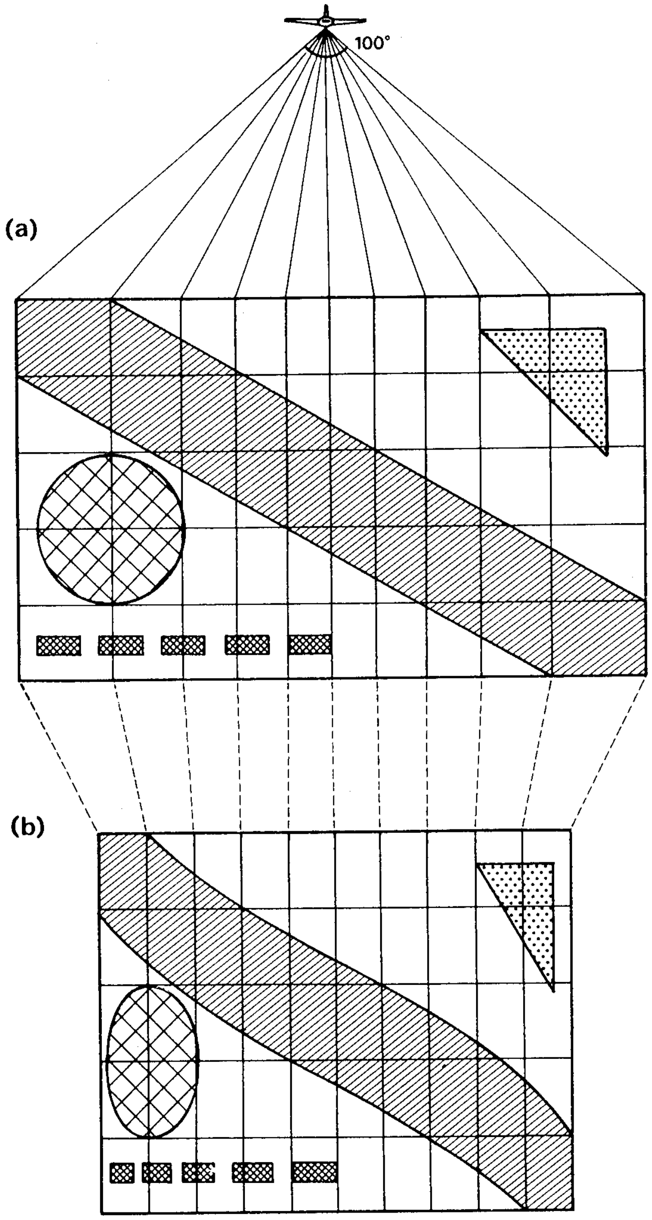


Figure 2. Effect of scan angle in aircraft imagery. **a** Panoramic distortion: pixel width increases significantly away from a vertical view. **b** Resulting image distortions: image features have lateral distortion when displayed with constant pixel width. *Reproduced from Harrison and Jupp (1989)*

2.4.2 *Selection of Threshold Value*

Most of the digital change detection techniques described in this paper require the selection of a threshold value in order to determine when change is considered to have occurred. The two main methods currently in use for selecting the threshold value are:

(a) inter-actively, whereby the analyst adjusts the value until satisfied with the result; and

(b) using some statistical measure, such as standard deviation from a class mean.

The former method is clearly not suited to autonomous change detection by computer, but it may be with some modification. This would require some 'training class' information to be provided to the computer. A human analyst could identify a number of instances of the desired change occurring. The computer would determine the characteristics of that change, through statistical analysis or a learning algorithm, and then identify further instances of 'change' exhibiting the same characteristics. This approach does not appear to have been studied explicitly, and there seem to be a number of problems confronting it.

The overall subject of selection of threshold values is addressed further in a number of publications (eg Fung and LeDrew, 1988).

2.4.3 *Radiometric Correction/Calibration*

Some digital change detection techniques (eg image differencing, change vector analysis) give improved results if the radiometric data are corrected and/or calibrated. It was stated earlier that a fundamental premise of using remotely sensed data to detect change was that changes in the object of interest will result in changes in radiance values that are large compared to radiance changes caused by other factors, such as differences in atmospheric conditions, illumination angle and soil moisture. If the change detection technique is sensitive to these other factors, they need to be either corrected for or otherwise taken into consideration.

If meteorological information at the time of the data acquisition is available, atmospheric corrections can be made to the raw data. Topographic information can also be used (eg Pons and Sole-Sugranes, 1994). It has, however, been more common in the past to attempt to standardise one data set to another rather than to try and apply the complex modelling that is required to correct for variations in atmospheric transmission and path radiance (Milne 1987).

Changes in the solar illumination angle of a surface brought about both by the time of day of the image acquisition and by the apparent summer-winter migration of the sun have an obvious effect on the digital numbers recorded by the sensor system. As many satellite systems are in a sun-synchronous orbit, and pass over the same latitudinal band at the same local ground time on each overpass, there are no variations in the data caused by daily changes in solar elevation for each latitude. However, seasonal changes in sun angle effect both the intensity of energy received at a surface and the component of shadow included in the reflectance values recorded. Graetz and Gentle (1982) showed that for rangeland environments around Western New South Wales, the dynamic range of Landsat digital count values was 2.6 times greater in summer than in winter and that the shadow component associated with a metre high salt-bush plant increased from 8% in summer to 35% in winter!

Surface reflectivities vary with the stage of phenological development reached. Phenologic change associated with events such as crop growth or the ephemeral flush of vegetation in a semi arid environment after rain may obscure long term changes to surface types and to environmental conditions in general. Whilst there are software routines to correct for sun angle changes, the only truly effective way of dealing with the effects of seasonal phenological change is by selecting data collected on or near anniversary dates (Milne, 1987). That is, deal with the problem by selecting data sets that do not exhibit it!.

The comparison of pixel values derived from different sensors can lead to incorrect results unless some form of calibration is used to standardise the responses of multi spectral scanners involved. Tables have been published, for example, by Robinove (1982) and Ahern (1985) to convert the digital numbers for individual bands on each of the Landsat multi spectral scanners to radiance or reflectance values.

Another method of calibration between different dates and/or sensors is by reference to regions in the image in which no significant change is believed to have occurred. A regression approach (Virag and Colwell, 1987; Vogelmann, 1988) or image histogram matching (Richards, 1986) may then be applied. Figure 3, reproduced from Richards (1986), shows the use of image histogram matching to reduce illumination angle (and, to a lesser extent, phenological) effects.

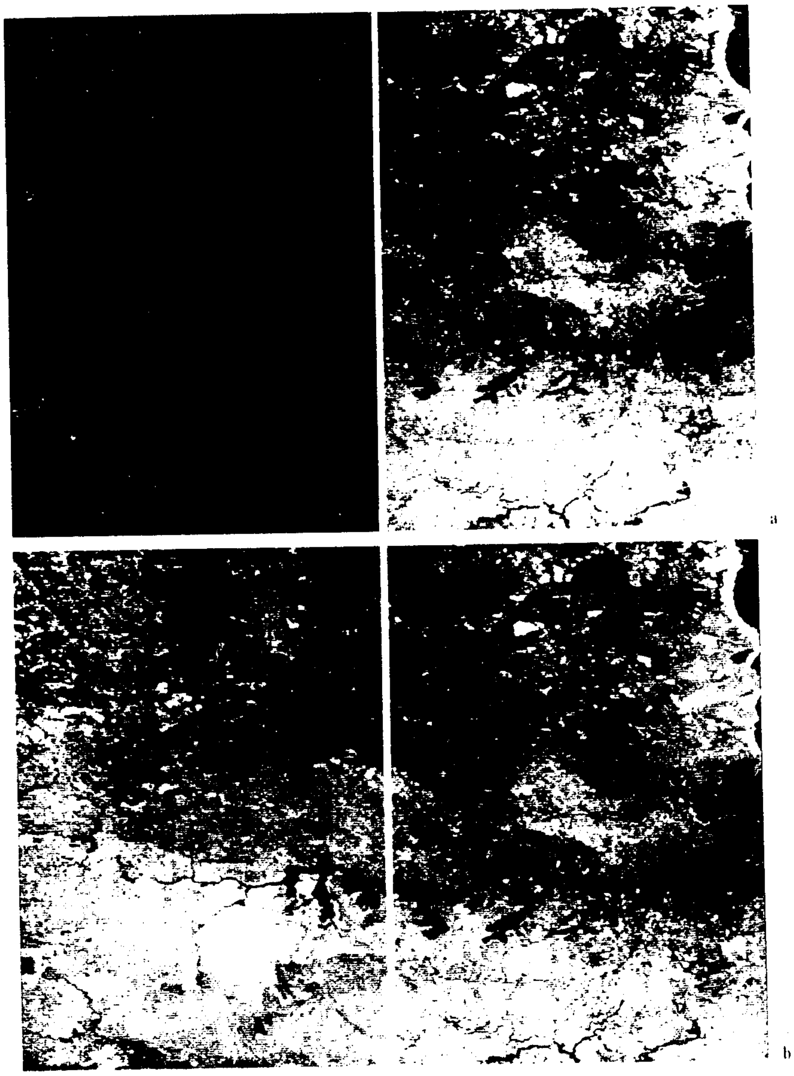


Figure 3. Histogram Matching. a Contiguous Landsat multi spectral scanner images showing contrast and brightness differences resulting from seasonal effects. The left hand image is an autumn scene and that on the right a summer scene, both of Sydney, Australia. **b** The same image pair but in which the histogram of the autumn scene has been matched to that of the summer scene. *Reproduced from Richards (1986)*

3 MILITARY USES OF COMERCIAL REMOTE SENSING SATELLITES

This section provides a general review of military uses of commercial remotely sensed imagery. It is included to provide some insight into how we might use remote sensing systems to advantage, and how a potential adversary might use them against us. Further, it challenges some common perceptions of the value of commercial remotely sensed imagery for military applications. In particular, the issue of spatial resolution is addressed.

3.1 *Review of General Military Use of Commercial Remote Sensing*

Ball and Babbage (1989) address the general requirement for geographic information in the defence of Australia, and the potential for commercial remote sensing systems to satisfy some of these information requirements. A general review of the potential of satellites for wide area surveillance of Australia can be found in a paper issued by the Royal Australian Air Force Air Power Studies Centre (Gale, 1992). The paper concludes that 'Space-based sensors are unlikely to offer a complete wide area surveillance solution in the timeframe examined here (15 years), ... ', but that '.... they are likely to be the means by which long term wide area surveillance capabilities are achieved'. Bernard (1991) discusses some possible military applications of the French SPOT system.

O'Connor and Bohling (1991) note that 'Operational reconnaissance technical organisations are burdened by increasing workloads due to the expanding capabilities for collection and delivery of large volume near-real-time multi sensor/multi spectral softcopy imagery'. This supports the earlier assertion that automated tools will be required to fully exploit the capabilities offered by current and future remote sensing systems. Their paper describes a system developed at (US) Air Force Rome Laboratory 'to provide an integrated collection of interactive exploitation tools to aid an image analyst within a softcopy imagery workstation environment'.

The extent of use of commercial remote sensing satellite imagery for map production and updating in the Gulf War is well covered in Wright (1992). Anson and Cummings (1991) address a number of uses of both military and civilian satellites in the Gulf

War, including wide area surveillance. It is suggested that key surveillance support was provided to the Gulf forces by commercial earth observation and weather satellites, with the Pentagon reportedly spending up to US$6m on Landsat and SPOT data alone. It is estimated that over 30 satellites were used (both military and civilian) . A table is provided listing the satellites used and their key characteristics. It is reproduced below as Table 2.

There are numerous studies of other uses of military interest, such as man-made object detection (Lu and Aggarwal, 1991), target detection using infrared imagery (Zhou, 1991), detection of ships using multi spectral imagery (Burgess, 1993), detection of surface-laid minefields (McFee *et al*, 1991), and tactical air mission planning (Gilmartin, 1991). There are a number of interesting case studies reported in Krepon *et al* (1990), including analyses of several ground force installations using commercial data sources. This is instructive in that it provides some insight into the nature and detail of intelligence that can be derived from commercial imagery by trained analysts. A table in the introduction (by Zimmerman) lists the generic classes of military targets that can be detected, identified or measured by the main commercial remote sensing systems. It is reproduced below (Table 3), and followed by a table (Table 4 , after Harrison and Jupp, 1989) showing the principal features of the main (visible and infra-red) commercial satellite systems, including the spatial resolution (pixel size), to aid in the interpretation of the table by Zimmerman.

Shettigara *et al* (1993) report on 'a pilot study to demonstrate some of the capabilities of remote sensing in intelligence gathering'. The report briefly reviews some of the papers mentioned above, then offers a more detailed discussion on some specific applications: pattern recognition and classification, object height determination, and image enhancement. It concludes 'The report clearly demonstrates the ability of multi spectral satellite images in enhancing and detecting targets of defence significance'.

Table 2. List of Surveillance Satellites. *Reproduced from Anson and Cummings (1991)*

SATELLITE	FUNCTION	ORBIT	OPERATOR	RESOLUTION	No. OF SATELLITES IN SERIES/ GULF OPS	LAUNCHES
MILITARY						
LACROSSE	Radar Surveillance (+ optical and sigint?)	LEO <700km	US DoD	metre-class	1/1	DEC 88 1991? 1992?
KH 11	Imaging reconnaissance (optical/IR/radar)	LEO <500km	US DoD	<25cm	8/1	#8-1987
KH 12	Advanced Imaging reconnaissance (optical/sigint)	LEO <450km	US DoD	?	?/?	#1-1990
WHITE CLOUD	Ocean Surveillance	LEO 100km inclined	US DoD	?	10+/?	#10-1987
MAGNUM	Electronic/signal Intelligence	GEO	US NSA	-	?	#2-1989
VORTEX (CHALET)	Radar surveillance Elint	?	US DoD	1.5m?	?	?
DEFENCE SUPPORT PROGRAMME (DSP)	Early Warning (Thermal IR)	GEO	US DoD	3km	22/5?	2nd generation -1987 3rd generation -1989
Defence Meteoro-Logical Satellite Programme (DMSP)	Weather observation (microwave/visible/ IR sensors)	LEO 800km	USAF	-	30/3-5	1960-1990
RORSAT	Radar ocean reconnaissance	LEO 250km	USSR	?	?	1987-2
EORSAT	Elint ocean reconnaissance	LEO 450km	USSR	?	?	1987-2
USSR Reconnaissance	Photographic reconnaissance	LEO 200km+	USSR	<25cm	?	1962-1990
ALMAZ	Radar reconnaissance (3 GHz SAR)	LEO 270km	USSR	15-30cm	2/1	1987-1989
CIVIL						
SPOT	Earth observation (visible imagers)	LEO 800km	SPOT Image (France)	10m HRV 20m pan-chromatic	2/2	1986 1990
LANDSAT	Earth observation (visible imagers)	LEO 700km	EOSAT (US)	20m	5/2	#4-1982 #5-1984
GOES	Meteorology (visible/IR)	GEO	NOAA (US)	1km	7/2	#7-1987
NOAA	Metorology (visible/microwave radiometers)	LEO 850km	NOAA (US)	-	11/?	#10-1986 #11-1988
METEOR	Meteorology (visible/IR radiometer)	LEO 800-1200km	USSR	>2km	?/2	#3-02 1988 #3-03 1989
OKEAN	Oceanography (radar/visible/IR)	LEO 600km	USSR	>1.5km radar	?/2	# 1983-87 #1-1988 #2-1990
RESURS-F	Earth observation (photo reconnaissance)	LEO 300km	USSR	5-8m	13/?	1987-1989 (14-30 day missions)
RESURS-O	Earth observation (visible/thermal IR)	LEO 600km	USSR	170-600m	5?/	#5-1988
DATA RELAY						
TRACKING AND DATA RELAY SATELLITE (TDRSS)	Data relay for LEO earth observatory surveillance satellites	GEO	NASA/ Spacecom (US)	-	4/3	#3-1988 #4-1989

Table 3. Analysis of Targets Using Commercial Imagery. *Reproduced from Krepon et al (1990)*

Target[b]	Detection[c]	General Identification[d]	Quantitative[e]
Bridges	MSS/TM	TM/XS	XS/P
Roads	MSS	MSS	TM/XS
Radars	P	P	
Railroads	MSS	P	
Supply dumps	MSS	P	P
Major headquarters	MSS	TM/P	P
Airfield facilities	MSS	TM	P
Aircraft	P	P	P
Rockets and artillery	MSS/TM	XS/P	
Missile sites (SAM)	MSS	MSS/TM	P
Surface ships	XS	XS	XS/P
Surfaced submarines	TM(?)	XS/P	P(?)
Vehicles	P(?)		

MSS: LANDSAT multi-spectral scanner; 80-meter resolution
TM: LANDSAT thematic mapper; 30-meter resolution
XS: SPOT extended spectrum sensor; 20-meter resolution
P: SPOT panchromatic sensor; 10-meter resolution

[a] MSS = multi-spectral scanner (LANDSAT); TM = thematic mapper (LANDSAT); XS = SPOT extended spectrum; P = SPOT panchromatic

[b] No attempt made to list all targets in original chart.

[c] A target of the given type is clearly present, but no details are apparent.

[d] Class of bridge, number of buildings, etc., can be discerned. There is little or no doubt that the target has been properly classified.

[e] Quantitative measurements of the target can be made; aircraft classified as to mission or type. Known types can be recognized using tables, silhouettes, etc.

Table 4. Some Commercial Satellite Sensing Systems. *Reproduced from Harrison and Jupp (1989)*

Satellite:sensor	Channels	Pixel size at nadir (m)	Swath width (km)	Repeat cycle	Lifetime
GMS:				Geostationary	1978–
VISSR	500–750nm	1250	hemisphere	hourly	present
	10.5–12.5 µm	5000			
NOAA:				2 per day	
AVHRR	580–680 nm	1100	2700	from two	1978–
	725–1100 nm			satellites	present
	3.55–3.93 µm				
	10.5–11.3 µm				
AVHRR/2	as for AVHRR plus				1981–
(NOAA 9)	11.5–12.5 µm				present
Landsat:				1 per 18 days	
for Landsats 1, 2 and 3				1 per 16 days	
for Landsats 4 and 5					
MSS	500–600 nm	80	185		1972–
	600–700 nm				present
	700–800 nm				
	800–1100 nm				
TM	450–520 nm	30	185		1983–
	520–600 nm				present
	630–690 nm				
	769–900 nm				
	1.55–1.75 µm				
	2.08–2.35 µm				
	10.4–12.6 µm	120			
SPOT:				1 per 26 days	1986–
MSS	500–590 nm	20	60 x 2		present
	610–680 nm				
	790–890 nm				
Panchromatic	510–730 nm	10	60 x 2		
MOS–1:				1 per 17 days	1987–
MESSR	510–590 nm	50	100 x 2		present
	610–690 nm		with 15 km		
	720–800 nm		overlap		
	800–1100 nm				
VTIR	500–700 nm	900	1500		
	6.0–7.0 µm	2700			
	10.5–11.5 µm				
	11.5–12.5 µm				
MSR	23.8 GHz	32 km	317		
	31.4 GHz	23 km			
NIMBUS:				1 per 6 days	
CZCS	433–453 nm	825	1566		1979–
	510–530 nm	(nadir)			1986
	540–560 nm				(interrupted
	660–680 nm				operation)
	700–800 nm				
	10.5–12.5 µm				

All of the papers and reports discussed above utilised data sources with spatial resolution in the range 10m to 1.1km. It should, however, be noted that data sources with higher spatial resolution are available. Panchromatic imagery from the Russian 'Kosmos' satellites is now being marketed by EOSAT (the world-wide marketing arm for Landsat and Indian IRS satellites). This imagery has a claimed spatial resolution of 2 metres. The US government has recently announced a relaxation of its policy on the commercial use of high spatial resolution surveillance satellite technology, and a number of companies in the US are planning to launch commercial optical surveillance satellites with one metre resolution in the next few years. One such proposal is the Lockheed CRSS system (due for launch in 1997).

It should also be noted that common perceptions about the efficacy of commercial 'low resolution' imagery for military purposes may not be entirely correct. There is a table that is frequently reproduced in the literature (eg Jasani, 1982; Richelson, 1984; Gale, 1992) that lists the resolution required for a number of military applications. Nyberg and Orhaug (1991) state that the origins of this table appear to lie in a reconnaissance handbook produced by McDonnell Douglas (McDonnell Douglas, 1982), but it is noted that the table has not been justified or supported by any study available for scrutiny. Gale (1992) and Shettigara *et al* (1993) express some disquiet about this table, and it is clearly at variance with the findings of Zimmerman in Krepon *et al* (1990) reported above. The standard table (reproduced, in this example, from Jasani, 1982) is included below as Table 5 for comparison with Table 3 (Zimmerman 's findings).

An interesting study of the use of low spatial resolution image data for military applications is reported in Stephens and Matson (1993). The sensing system used (NOAA AVHRR) has a spatial resolution of 1.1km (cf SPOT at 10m and 20m, and LANDSAT TM at 30m), and revisits at least once every 6 hours. Figure 4, reproduced from Stephens and Matson (1993), clearly shows the contrails of military aircraft in the Gulf War region. This is a clear reminder that it is not always necessary to detect the object itself: it is often adequate to infer the presence of the object from its effects.

Table 5. Required Resolution (in metres) for Different Interpretation Tasks.

Reproduced from Jasani (1982)

Target	Detection[a]	General identification[b]	Precise identification[c]	Description[d]	Analysis
Bridge	6	4.6	1.5	0.9	0.3
Communications					
Radar	3	0.9	0.3	0.15	0.04
Radio	3	1.5	0.3	0.15	0.15
Supply dump	1.5	0.6	0.3	0.03	0.03
Troop units	6	2	1.2	0.3	0.08
Airfield facilities	6	4.6	3	0.3	0.15
Rockets and artillery	0.9	0.6	0.15	0.05	0.01
Aircraft	4.6	1.5	0.9	0.15	0.03
Command and control headquarters	3	1.5	0.9	0.15	0.03
Missile sites (SSM/SAM)	3	1.5	0.6	0.3	0.08
Surface ships	7.6	4.6	0.6	0.3	0.08
Nuclear weapon components	2.4	1.5	0.3	0.03	0.01
Vehicles	1.5	0.6	0.3	0.05	0.03
Land minefields	9	6	0.9	0.03	–
Ports and harbours	30.5	15	6	3	0.3
Coasts and landing beaches	30.5	4.6	3	1.5	0.08
Railway yards and shops	30.5	15	6	1.5	0.6
Roads	9	6	1.8	0.6	0.15
Urban areas	61	30.5	3	3	0.3
Terrain	–	91	4.6	1.5	0.15
Surfaced submarines	30.5	6	1.5	0.9	0.03

Source: "Reconnaissance Handy Book", p.125, published by McDonnell Douglas Corporation, USA.

[a] Requires location of a class of units, object or activity of military interest.
[b] Requires determination of general target type.
[c] Requires discrimination within target types of known types.
[d] Requires size/dimension, configuration/layout, components construction, count of equipment, etc.

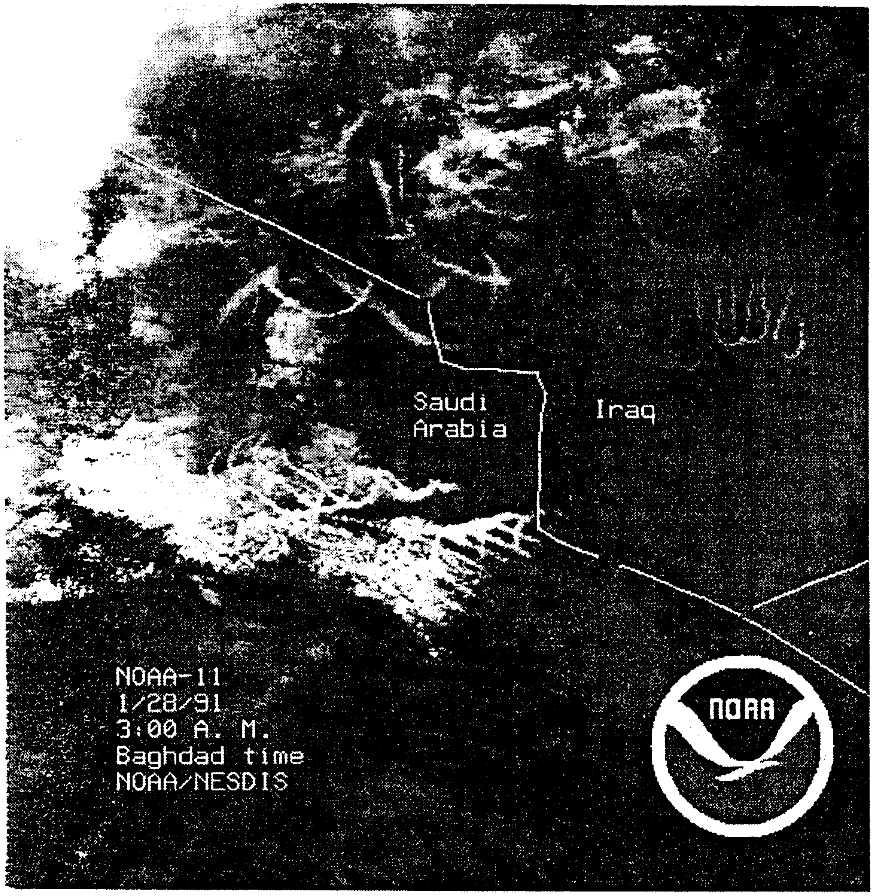


Figure 4. NOAA Channel 4 Image Showing Aircraft Contrails. *Reproduced from Stephens and Matson (1993)*

A further concern sometimes expressed about the use of satellite remote sensing data is the time it takes to get it into the hands of analysts and military field commanders. The US DoD has recently developed a mobile receiving station ('Eagle Vision'), after recognising the need for such a system in the Gulf War (Felsher, 1994). A contract was signed with SPOT IMAGE on 28 April 1994 to provide image data transmission direct to Eagle Vision mobile receiving stations, for global use for defence applications. In a separate development, a newly formed company called Teleos (EOSAT and TELESPAZIO) has announced plans to use portable ground stations designed to acquire multiple source remote sensing data from different satellites (Felsher, 1994). These developments, combined with the ability of some current and most proposed future satellites for 'steerable' off-nadir viewing, should allay some of the fears of potential military users about data availability. Of course, concerns relating to the ability of the satellite operator to turn the satellite off, or to selectively deny data, justifiably remain (as demonstrated by the restricted availability of SPOT data over Saudi Arabia/Kuwait/Iraq during the Gulf War (Roos, 1991)).

4 MILITARY USE OF DIGITAL CHANGE DETECTION

There are few references in the open literature to the military use of change detection techniques using remotely sensed digital imagery. It is not known whether this is because there have been few uses, or because few of the uses have been reported. The United States Army Multispectral Imagery Product Guide (1990) lists change pairs (using the image differencing technique described earlier) as one of 'the most important baseline reference products from which the other remaining products are derived'.

Ekblad and Olsson (1990) used the single band image differencing technique with Landsat TM data to detect preparations for an underground nuclear weapons test near Astrakan in the (then) USSR. Their approach was based upon the detection of road and track system development, and would therefore be applicable to any application which resulted in similar development (eg development or extension of military-industrial facilities).

Banner (1991) discusses the use of a change detection technique for monitoring the Soviet withdrawal from Afghanistan in 1988 and 1989. SPOT panchromatic images of Kabul were acquired for two dates (November 1987 and November 1988). The method used was to display the images of the different dates in different primary colours. Aircraft movements at Kabul airport and a large military camp (at the time housing the Soviet 108 Motorised Rifle Division) were examined. The study concluded that 'the change detection enhancement was quite effective in finding areas of change between the two images', but noted that 'the imagery is not really suitable for monitoring military ground forces if anything more than very superficial information is required'.

Elliott (1992), in discussing the use of imagery for military applications, makes brief mention of two change detection techniques, but cites no examples of their use.

5 CONCLUSION

Digital change detection techniques aim to detect changes in images over time. They can be used as a 'cueing system' to attract the attention of human analysts to 'interesting' digital images from the large number of available images. Change detection techniques rely upon differences in radiance values between two or more dates. These differences may be due to an actual change in land cover, or differences in illumination, atmospheric conditions, sensor calibration or ground moisture conditions. The calibration of data, or standardisation between dates, may be necessary, and the accuracy of the image registration is important.

There are a number of digital change detection techniques in relatively common use in the remote sensing community. They include post-classification comparison, multi-date classification, image differencing, image regression, image ratioing, vegetation index differencing, principal components analysis and change vector analysis. Unfortunately, few quantitative comparative studies of change detection techniques are available, and there is conflict between the results of these studies. It is concluded that there is no universally 'optimal' change detection technique: the choice is dependent upon the application.

There is a significant body of open literature on the military use of commercial remotely sensed digital imagery, but little has been published on the military use of change detection techniques.

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19. Abstract

This report presents a review of digital change detection techniques using remotely sensed data, citing examples of their use for both environmental and military applications. It also discusses some issues germane to digital change detection: image registration and rectification, thresholding, and radiometric correction.