Airborne remote sensing in forestry: Sensors, analysis and applications[1]

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This paper discusses the aspects of airborne remote sensing that are critical to forestry applications, the imaging characteristics of the most common sensors currently available, and analytical techniques that make use of the great amount of information content in airborne imagery. As the first paper in the CIF technical meeting to which this issue of the Forestry Chronicle is devoted, the paper is intended to provide an overview and context for subsequent papers and not a presentation of specific research methods or results.

Key words: airborne remote sensing, forestry, photography, digital cameras, hyperspectral sensors, radar, laser remote sensing, image analysis

Cet article discute des différents aspects de la télédétection aéroportée qui touchent particulièrement son utilisation dans les sciences forestières, des caractéristiques des images produites par les senseurs couramment disponibles, et des techniques d'analyse qui permettent de tirer parti de la grande quantité d'information contenue dans ces images. Cet article, le tout premier de la conférence technique de l'IFC rapportée dans ce numéro, a pour but de présenter un cadre général et une vue d'ensemble du sujet, plutôt que des méthodes de recherche ou des conclusions.

Mots-clés: télédétection aéroportée, foresterie, photographie, caméras numériques, capteurs hyperspectrals, radar, télédétection laser, analyse d'image

1.0 Introduction

In forestry, traditional information needs to manage the resource for economic gain now represent just one component in a complex set of applications that increasingly have biological and ecological significance at a variety of scales. Reporting to international agencies is required on the quantity and status of our forests. Provincial agencies require diverse information in order to balance resource extraction and employment goals with environmental and multiple use goals. Forest companies and other stakeholders require local, site-specific information for cost-effective management of their investments. With increasing demands on forest resources, the types of information required to improve our understanding and management of these resources have multiplied in quantity and diversity. Forest management must therefore be interdisciplinary and multi-scale. Information derived from field studies, airborne remote sensing and satellite remote sensing must be integrated for a wide range of applications and users.

The purpose of this paper is to present the current status of airborne remote sensing capabilities in forestry. Emphasis is placed on remote sensing issues and techniques but links will be made with forest management applications. The paper is divided into three primary sections: 1) an overview of critical aspects of remote sensing that are commonly integrated in applications development in order to optimally match imaging and analysis technologies to information needs, 2) airborne sensors that are pertinent to forestry, and 3) a summary of new techniques for forest information extraction from airborne images. Each of these sections is not an exhaustive review of detailed specifications and research. The goal is to present an overview of aspects that are of importance in the cost-effective integration of airborne remote sensing in forestry applications. A numbering system has been adopted to aid in distinguishing the numerous major and minor topics of the paper.

2.0 Matching Information Needs To Imaging Capabilities

Effective data acquisition using airborne remote sensing requires a starting point of explicit understanding of the information type and level of detail needed for the application. Coupled with some knowledge of remote sensing capabilities, a project or research design can be conceptualized. The process is similar to integration of statistics in project design; if knowledge of the potential statistical techniques exists, then they can be incorporated into the design phase of the project and the power of the extracted information will be greater than if research design and methods are carried out and attempts made afterwards to integrate statistical analyses. Much of remote sensing has developed outside forestry and other applications domains, and it has often been represented as technically sophisticated. Consequently, it has often been forced into a "technology push" process of applications development for specific sensors and techniques. However, now that a diverse set of sensors and techniques are available, the process of integration of remote sensing at initial stages of projects, to provide specific information in a cost-effective way, can be operationally adopted.

The following sections summarize the fundamental aspects of remote sensing that are common in project design. They are introductory and can be found in most textbooks on the subject (e.g., Jensen 1996, Lillesand and Kiefer 1999). Some details specific to video and digital cameras can be found in King (1995).

2.1 Sensor geometry and resolution considerations

Minimum mapping unit and ground pixel size

For a given application, the minimum mapping unit, the smallest area for which information is required, must be known. This may, or may not, be different from the smallest object that must

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be resolved. For example, a forest stand may be the minimum mapping unit, but the approach may be to characterize it based on analysis and inventory of individual trees. The minimum mapping unit determines the detail of the information used in decision making, while the object size determines the required resolution of the imagery (the term "resolution" is used informally here – definitions and techniques for evaluation of sensor spatial resolution are given in King (1992)). If individual overstory trees are to be analyzed, then several pixels should "fit" into each tree crown. Typically, for any object, an area of at least nine pixels, or a 3×3 window (if using square pixels), is required to adequately extract spectral and spatial information. For small tree crowns, a minimum nominal ground pixel size of 1m or less is commonly required, particularly if sample pixels for spectral analysis are extracted only from the sun illuminated side of the crown. For detection of object presence or absence only, the number of pixels required to "fit" in the object may be less if the object contrasts highly with the surrounding area. For example, fallen trees in a watercourse may be detected with only one pixel across their trunks because of their difference in brightness from the surrounding water and their linear shape.

Ground pixel size and image coverage

Generally, increased image coverage requires a reduction in image resolution. For large area mapping, high detail cannot be achieved, unless very large sensors such as large format photography (23 cm square) are used. Digital sensors range in size from less than a centimetre to just over 4 cm, and can therefore not achieve coverage and resolution equivalent to photography. One of these parameters must be traded off against the other. For example, if high detail (small pixels) is required, image coverage must be compromised. Mapping of an extensive area then requires a large amount of processing to produce mosaics comprised of large numbers of images. In addition, as resolution increases, the statistical variance of land cover types tends to increase and mapping using statistical classifiers may have reduced accuracy. High-resolution imagery is therefore more suited to sample-based modelling of forest variables than to mapping over large areas. The types of applications that can be addressed with airborne remote sensing tend to fall within the range from very high resolution (0.02 – 1 m ground pixel size), large scale (equivalent to 1:1000 – 1:10 000), small coverage (tens of metres to just over 2 km), sampling and modelling to medium resolution (1 – 5 m ground pixel size), medium scale (1:10 000 – 1:50 000), medium coverage (1 – 10 km), regional mapping. Current satellite imagery is generally used for larger mapping projects that do not require high resolution. However, some new (e.g., IKONOS launched in September 1999) or planned satellite sensors may replace aspects of the medium resolution/coverage applications of airborne remote sensing. Integration of high resolution airborne imaging and lower resolution satellite imaging is also becoming more common in "scaling up" applications such as landscape gap analysis (Slaymaker *et al.* 1995) and criteria and indicators reporting (e.g., Fournier *et al.* 1997, Hall, J.P. 1999).

Geometric processing and positional accuracy

If remotely sensed imagery and derived information products are to be integrated into a map base or GIS, geometric processing of the imagery is necessary. In cases of relatively flat terrain, or where pixel positional accuracy requirements are not strict (about ±10 m or larger), distortions due to the sensor lens, aircraft rotations, and topography may be neglected. Simple georeferencing of the imagery to the map base using an affine transformation may be adequate. However, if positional accuracy requirements are moderate to strict, the following processes may be required. Radial and tangential lens distortions may be removed or reduced by using a high quality optically corrected lens, or they may be accurately measured using targets in a geometric calibration and later removed in image processing. If aircraft rotations produce positional errors that are significant for the intended applications, then instruments such as inertial navigation systems (INS) may be incorporated into the imaging system. They measure aircraft attitude (wing tilt, pitch of the nose, and rotation about the vertical axis) at each exposure of the sensor. These attitude measurements are used to remove the corresponding image warping and scale distortions. An alternative to this approach is to maintain the camera in a vertical position using a gyro or gimbal mount. However, mounts that respond quickly and accurately to aircraft rotations are quite expensive. Where topographic variations cause positional errors that are significant for the applications' needs, they can be removed or reduced if a digital elevation model (DEM) of equal, or better, spatial resolution as the imagery is available. An existing DEM can be used, or if stereo imagery is acquired, a DEM can be derived using photogrammetric processing. In the latter, geometric calibration of the sensor for lens focal length and distortions, as well as the sensor principal point (where the optical axis intersects the image plane), should be conducted if positional accuracy to better than two or three pixels is required. In addition, if abundant ground position data are not available (typically the case in forestry), the position of the sensor in-flight must be known. It is commonly measured using a global positioning system (GPS) to any level of required accuracy from tens of metres using a single receiver, to 1 to 5 metres using differential processing of two receivers, to several centimetres using survey level kinematic techniques. These match quite well the varied requirements of forest management activities from inventory (about 20 m error tolerance – Leckie (1994)) to large-scale sampling (centimetre level accuracy). The above sensor geometry and position parameters are linked to the ground geometry and position in DEM production. Whether the DEM is produced from the imagery, or is already available, it is then used to determine spatial errors in each pixel's position and the imagery is ortho-rectified to a planimetric projection.

In all of the above geometric processing and calibration techniques, cost is associated with accuracy. The user must determine the positional accuracy requirements of the resulting imagery for the intended applications. Some operators offer graded pricing for products of different levels of accuracy.

2.2 Sensor radiometric considerations

While inventory-type mapping is still generally conducted using medium-scale black and white panchromatic aerial photography, most other applications make use of multispectral information in colour photos or in a digital sensor. The most important aspects regarding spectral information content are the spectral sensitivity range, the number of spectral bands within the given range, the bandwidth of the spectral bands, and spectral / radiometric calibration.

Spectral sensitivity range

The useful spectral ranges of optical sensors depend on their composition and on the atmosphere. The latter determines which wavelengths can be sensed through its absorption, transmission, scattering and emission characteristics. Sensors have been designed that respond to EM radiation in the wavelength ranges that the atmosphere transmits well. For example, silicon-based sensors and film are used in the visible (400–700nm) and near infrared (NIR, 700–1000 nm). Less common PtSi, PbS, InSb, and HgCdTe compounds are used in either the mid-IR (1–5 µm) or thermal IR (8–14 µm). Each compound is not equally sensitive at all wavelengths, but typically has a region of peak sensitivity flanked by decreasing sensitivity at shorter and longer wavelengths. Imaging in the region of high sensitivity is optimal and will produce high brightness and contrast, while images acquired in low sensitivity regions will be of lower brightness and contrast and relatively greater noise.

Number of spectral bands

Knowledge of the spectral reflectance characteristics of targets is critical in determination of the number of appropriate spectral bands and their centre wavelengths. If information to be extracted from the imagery can be obtained in a few spectral bands, then simple sensor designs are appropriate. An example would be automated classification of water, bare soil/rock and vegetation for % cover estimates of all vegetation. These three classes can typically be well distinguished through statistical analysis of two spectral bands, one in the visible (usually in the red) and one in the NIR. In contrast, for detection of subtle reflectance differences between vegetation species or health states, multiple measurements at several to many wavelengths may be appropriate. Currently, a wide variety of sensors is available with numbers of spectral bands ranging from one to about 300.

Spectral bandwidth

The precision with which the electromagnetic spectrum is imaged by a sensor is termed the spectral "bandwidth." In broad terms, it is the wavelength range of a given spectral band. As above, imaging of cover types or conditions that vary widely in reflectance does not require narrow bandwidths. Low cost cameras and filters of wide bandwidth (>25 nm) should suffice. However, as above, subtle reflectance differences may only be evident at specific wavelengths. In such cases, narrow bandwidths are required. Sophisticated hyperspectral sensors and some advanced digital camera sensors are capable of imaging with bandwidths as narrow as 2 nm, while off-the-shelf film and digital cameras have bandwidths of about 100 nm.

The relation between spectral bandwidth and spatial resolution

Filtering a sensor to image in narrow spectral bands reduces the total amount of radiant energy incident to the detector to levels where electronic and atmospheric noise can become significant. In such cases, the time during which the sensor "integrates" energy must be increased. In airborne remote sensing, the aircraft platform is advancing at rates typically between 30 and 70 m/s. During the exposure period, the aircraft advances a given distance, which, if more than about one-half the ground pixel size, produces visible image smear. This results in a trade-off between spectral and spatial image quality. For narrowband imaging (high spectral quality), the shutter speed must be reduced, and the ground resolution element imaged in the flight direction during exposure of the sensor will be increased (lower spatial quality). Given that the ground resolution across the swath (perpendicular to the flight direction) is not affected by aircraft advance during exposure, rectangular ground resolution elements result that have their longer dimension parallel to the direction of flight. For bandwidths of 2–10 nm image pixels can essentially be two to four times longer in the direction of flight than across the swath (e.g., 1 m by 3–4 m). Also, the longer exposures required for narrowband (<10 nm bandwidth) imaging limit image pixel sizes to larger than about 0.5 m, while in wideband (>25 nm bandwidth) imaging, pixel sizes as small as 2cm with exposure times up to 1/5000s are possible.

Spectral and radiometric calibration

For precise spectral information analysis requirements, including reflectance modelling of ground objects, spectral calibration is required to determine the centre wavelength and sensitivity curve for each spectral band. This may be conducted in the lab using lamps with known spectral emission characteristics. It is typically conducted for sophisticated hyperspectral sensors where many bands of narrow bandwidth must be calibrated. For low cost film and digital cameras that use filters placed in the optical path, the manufacturer typically supplies a spectral transmission curve for each.

Absolute radiometric calibration is a process that allows conversion of image brightness measured in digital numbers (DN) to physical electromagnetic units of the ground surface. Typically, either surface radiance ($W \cdot m^{-2} \cdot \mu m^{-1} \cdot sr^{-1}$) or reflectance (surface radiance ÷ sun irradiance on surface) is desired, the latter being most intrinsically related to the physical characteristics of the surface. Two general approaches are taken to derive these. The first is simpler but may require more in situ instrumentation. In situ measurements of radiance or reflectance of two or more diffusely reflecting targets is measured in each spectral band of the sensor during flyover. Mean image brightness of the targets in each band is regressed against the in situ measurements, and the resulting relations are used to convert other pixels in the imagery to either physical unit. In the second approach, the sensor is calibrated in the lab to determine the relations between radiance incident to the sensor and image brightness (DN) for each spectral band and exposure setting. The radiance-DN relation is linear for solid-state detectors and log-linear for film. To convert image radiance acquired at a given altitude to ground surface radiance or reflectance, atmospheric effects must be removed. This may been accomplished using the regression procedure above or by modelling of atmospheric transmission using radiative transfer theory. Such models are well developed but require several input parameters describing the atmosphere that can either be measured in situ, acquired in simplified form from a nearby airport (e.g., visibility in km), or assumed for standard conditions of clear-sky imaging.

Calibration of imagery is critical for temporal analysis as the atmosphere and illumination characteristics generally vary between imaging dates. However, absolute calibration using either of the above two approaches has traditionally been expensive and practically difficult to conduct, particularly in isolated areas. An alternative is to relatively calibrate images to each other using some dark and light targets in the imagery that should not change in reflectance from one date to another ("pseudo-invariant" targets) and histogram matching or regression. This approach is useful for comparative analysis but is less precise than absolute calibration if links to surface physical characteristics are to be made.

Correction for spatial non-uniformity in image brightness

There are four primary causes of unwanted spatial variations in image brightness that need to be corrected in medium- to wide-angle imaging. They are: 1) variations in atmospheric scattering and transmission with imaging view angle due to the varying length of atmosphere between the ground and sensor, 2) variations in reflectance caused by variations in the sun angle-view angle geometry throughout an image (the bi-directional reflectance distribution function – BRDF), 3) lens optical effects, and 4) topographic effects. Correction or reduction of varying atmospheric effects requires radiative transfer code where the sensor view angle is known and a variable correction can be applied based on measured or assumed atmospheric properties. This correction is only necessary for any combination of the following: medium- to wide-angle imaging (greater than approximately $\pm$ 20°), altitudes greater than approximately 1000 m, or hazy skies (Edirisinghe 1997). BRDF effects generally cause darker image brightness on the side of the image nearer the sun and a gradual increase in brightness towards the side of the image furthest from the sun. This effect is hard to correct as the brightness variation across the image differs for each land cover type. Empirical methods require multiple view-angle samples of each land cover type. This can be efficiently conducted with video or digital cameras and other sensors that acquire frame images at a high enough rate to view an area from several different angles. Otherwise, field radiometric measurements from various view angles must be taken (expensive for trees over 5 m in height) and integrated into a reflectance-based calibration (as discussed above). Overall, correction for BRDF has been the Achilles heel of remote sensing, although progress is being made. Alternative approaches are to avoid large spatial variations in image brightness by using narrow sensor view angles (less than about 10°) in forest sampling applications, or to actually incorporate BRDF characteristics into the analysis process to characterize given forest types or conditions. The theory and methods of the calibrations and corrections discussed above are well represented in the literature and can be found in detail in many texts (e.g., Asrar 1989). Lens optical effects generally cause a radial decrease in brightness towards the image corners. They are corrected in sensor design and lab calibration (e.g., King 1992, Pellikka 1998). Topographic effects include brighter and more direct illumination of slopes facing the sun and darker more diffuse illumination of slopes facing away from the sun. As aspects of slopes vary continuously, the resulting brightness variations also vary continuously. Corrections require a digital elevation model of similar resolution to the imagery to determine the aspect of each image pixel. Irradiance modelling based on sun zenith and azimuth angles at the time of imaging can be used to determine for each pixel the irradiance that would have resulted if the pixel were lying on flat terrain (e.g., Pellikka 1996,1998). A correction in brightness can then be applied.

In each of the above, as with the variety of geometric processing options described previously, the user must decide, based on knowledge of the spectral reflectance characteristics of the targets to be imaged, the sensitivity range, the number of spectral bands and their corresponding bandwidths, the degree of spectral and radiometric calibration, and the level of correction for image spatial non-uniformity that are most cost-effective. Costs are typically much greater for imaging in regions outside the visible – NIR, for hyperspectral imaging, for imaging in narrow bandwidths, for calibrated imagery (with varying levels of calibration as discussed), and for imagery processed to reduce spatial non-uniformity. Service providers can sometimes aid these decisions but, where possible, several providers should be investigated as each offers (and promotes) different capabilities.

2.3 Information extraction from remotely sensed imagery

Before data analysis is conducted, an appropriate attribute scheme for classification, or variable precision for modelling must be selected. In classification, the attribute scheme must be a set of classes that can be mapped with the desired accuracy. An example standard is 85% average accuracy and 80% minimum accuracy for any class (Anderson *et al.* 1976). The attributes should be at a consistent level of detail, and they should be part of a hierarchical classification system so that aggregation can be accomplished. Large area mapping with relatively large pixels using a few spectral bands of wide bandwidth, is suitable for a few broad classes (e.g., forest / non-forest or deciduous / coniferous / mixed forest). Small land units or entities mapped with small pixels and several narrow spectral bands can usually be defined with greater detail (e.g., species groups, water turbidity classes, and wetland types). The attribute scheme and detail must be designed to match the capabilities of any potential sensor to separate the classes based on spectral or spatial information. Thus *a priori* knowledge of potential sensor capabilities in terms of the characteristics discussed above should be incorporated into project design. Too often class attributes are selected using only management criteria, irrespective of the potential capability of any data acquisition system to accurately provide them. Consequently, much evaluation of remote sensing in forestry has included non-cost-effective and inappropriate sensors, pixel sizes, spectral bands or class attributes. For many application tests, results have often been discouraging and wariness about the technology has developed that has hindered its development within the industry.

In forest modelling, similar arguments can be made to those above. Precision of variables to be modelled through sampling and statistical design must be specified in consideration of the capabilities of possible data acquisition systems. It must also be recognized that remote sensing-based models of forest variables are usually not as precise as models derived from field measurements (e.g., allometric equations) or the field measurements themselves. However, a principal advantage of remote sensing is that data are acquired at all pixels (the data are spatially extensive). With a representative number of sample plots to develop a given model, the remaining image data can be used to map the variable with known precision. This may be an attractive alternative to the sole use of field sampling followed by interpolation between the sample locations using no additional data.

In image analysis, the primary information extraction technique has been visual interpretation of air photographs. An interpreter can see and deduce the meaning of tone (brightness in a local area, including shadow effects), colour, texture (the spatial variation of tone), pattern (the arrangement of tones), shape, and size, while height or elevation can be interpreted and measured in stereo imagery. Combined with knowledge of the area (context) such as expected species associations, relations of elevation, slope and species with drainage and soils, effective interpretations can be made of the various parameters required in many applications. Interpretation requires knowledge of spectral reflectance differences between vegetation types and conditions as well as terrain influences. Additionally, interpretation of false colour combinations (e.g., colour infrared (CIR) imaging with near infrared (NIR), red and green radiation displayed as red, green, and blue, respectively in the image), knowledge of colour representation and mixing is required. The process is subjective and variable within and between interpreters. The goal of digital remote sensing in forestry has been to provide objective, quantitative, more accurate and more precise means for providing the same information that has been provided by air photo interpretation as well as to provide additional information or detail that cannot be obtained reliably through interpretation. The emphasis has been on development of automated or semi-automated techniques that analyze spectral characteristics of individual pixels using statistical techniques (as described in texts such as Jensen 1996, Lillesand and Kiefer 1999). Success in forestry applications has been generally good in site-specific situations but not adequate for generalization over larger areas or over time. Research has therefore concentrated on several aspects of image analysis that provide marked improvement in classification and modelling as summarized later in the Discussion section of this paper.

3.0 Sensors

For the practical purpose of this paper, the wide diversity of airborne remote sensors will be divided into: aerial photography, solid-state optical sensors, radar, and lasers/lidar. Solid-state optical sensors are further divided into those that are used for frame imaging in a manner analogous to photography, and those that generate one line of imagery at a time (line scanning). Example applications are listed briefly for each sensor type. The paper is not intended as a comprehensive treatment of applications' information needs and suitable imaging configurations. Other papers have been published on these aspects. For example, Gillis and Leckie (1993, 1996), provide significant detail on the processes of air photo-based mapping for inventory and inventory update across Canada. Leckie (1990, 1994) and Leckie and Gillis (1995) provide reviews of various forest applications of remote sensing.

3.1 Aerial photographic systems

Aerial photography is a flexible-imaging medium that includes a variety of formats (image dimensions), film types, and possible imaging scales. Of the available formats, 23cm film has been the most cost-effective remote sensing data type for regional mapping applications such as inventory. It provides larger area coverage, higher spatial resolution and better stereo rendition than most digital sensors. Black and white visible spectrum panchromatic film has been preferred for its low cost but black and white panchromatic visible-NIR, colour, and CIR films are becoming more prevalent as information needs become more detailed and complex, necessitating improved information extraction from the imagery. Each province has experimented with and adopted different film types for their respective sets of applications (Leckie and Gillis (1995) provide details). Photography has advanced at a similar pace as digital sensors, although in different ways. Significant advancements have been made in provision of: 1) a wider range of film sensitivities and exposure latitude, 2) improved spatial resolution up to 90 line-pairs/mm (about twice as good as digital sensors), 3) introduction of 35mm CIR film that can be developed using the common E-6 process, 4) a wider range of camera exposure control options, 5) capability for use of a variety of lens focal lengths, thus providing a wide range of possible coverages and scales, 6) reduced lens distortions (as low as 2–3 microns at the image edge), 7) accurate image motion compensation in camera mounts that eliminates image smear during exposure, 8) gyro-stabilized mounts, 9) computer control of camera operations, and 10) integration with GPS for positioning of images (Personal communication, R.J. Hall, Natural Resources Canada, Canadian Forest Service, Northern Forestry Research Centre, Edmonton, Alberta, March, 1999.).

Large format photography has primarily been used for inventory applications (Gillis and Leckie 1993, Leckie and Gillis 1995) at scales of between 1:10 000 and 1:20 000. Common attributes that are assigned to delineated stands include species composition, density (usually as crown closure), stand height, an estimate of age based on stand height, structure and site characteristics, and site quality from the given composition, structure and terrain characteristics (Leckie, 1994). Inventories differ in other attributes, and are evolving as the nature of forest use and management information needs evolve. In inventory update, large area imaging of harvest and other major disturbances is required. Gillis and Leckie (1996) provide a detailed analysis of such procedures. Two such disturbance applications that have been documented but not yet adopted operationally are regeneration assessment for areas larger than about 2000 ha (Goba *et al.* 1982) and broad forest damage mapping (e.g., Murtha 1972, Hall *et al.* 1998). Major pest attacks can be evaluated using a combination of aerial photography and sketch mapping so that adjustments can be made to annual allowable cut estimates for lost volume. In both damage and inventory update for other purposes, fast production of information may be critical. Airborne data acquisition using photography has proven to be very capable in such situations.

Small format photography typically with 70 mm cameras (usually with a film size of about 57 × 57 mm) or 35 mm cameras (36 × 24 mm film size) is acquired in stereo using a single camera and forward overlap from aircraft translation, or using two cameras at either end of a transverse or longitudinal boom (Hall, 1984, Spencer and Hall 1988, Pitt *et al.* 1997). For mapping, it requires a shorter focal length lens to provide coverage similar to large format photography and, consequently, image distortions are generally higher unless a corrected lens is used. This, in combination with its lower spatial resolution of about 50 line-pairs/mm (Pitt *et al.* 1997) and lack of widespread knowledge of its potential (Spencer and Hall 1988), has hindered its application in mapping. An exception is in southern Ontario where Kodak 2443 CIR 70mm photography (e.g., Fig. 1), acquired at 1:10 000 scale and scanned to 4096 × 4096 pixels of 57 cm ground dimension, is currently being used for inventory purposes {(Klimes *et al.* 1997)}. Also, Leckie (1994) states that small format photography can be acquired at even a smaller scale than that used for inventory and then enlarged to

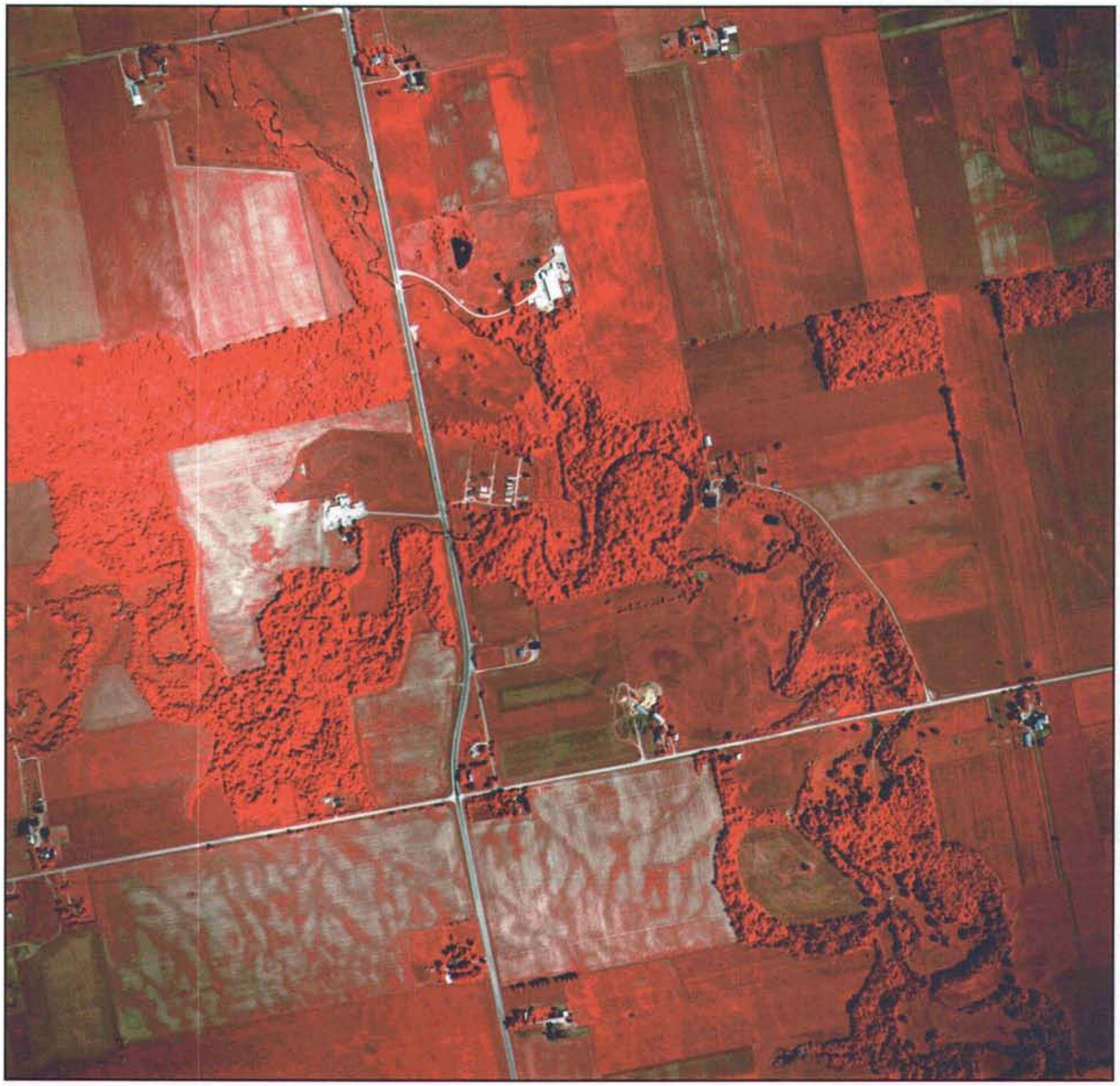

Fig. 1. 70mm colour infrared photograph for forest inventory (1:10 000 original scale, scanned to 4096 × 4096 pixels, each being about 57 cm on the ground). Courtesy of the Ontario Ministry of Natural Resources, Geomatics and Data Acquisition Section, Peterborough, ON.

inventory scale with resolution of 5–10 m for delineation and interpretation of many disturbance types.

Small format photography has been best proven in applications of large-scale sampling. They can be categorized as: 1) regeneration assessment for density, stocking, and survival of non-obstructed seedlings for interpretation and measurement (e.g., Goba *et al.* 1982, Hall 1984, Spencer and Hall 1988, Hall and Aldred 1992), 2) vegetation management measures of height, crown diameter, crown volume and per cent cover of crop and non-crop vegetation (Pitt *et al.* (1997) provides a review and system design for this purpose), and 3) species distribution and volume estimates (Zsilinsky and Palabekiroglu 1975, Nielsen *et al.* 1979, Spencer and Hall 1988). Additional potential sampling applications include ecological habitat classification (Befort 1986), modelling of forest leaf area index, crown closure and basal area (Pellikka *et al.*, 2000), and damage assessment (Murtha 1972, Goba *et al.* 1982, McCarthy and Witler 1982, Hall *et al.* 1993, Spencer 1998). Fig. 2 shows an example 1:900 Kodak 2448 70 mm photograph used in a project to assess jack pine budworm damage.

Multispectral photography systems employing more than one camera, each with a different spectral bandpass filter, have been tested in a variety of applications. However, they have not been adopted operationally in forestry as the cost is relatively high and the non-linear response of film to incident radiation does not permit straightforward and consistent quantitative spectral analysis. In addition, the relatively low sensitivity of film necessitates that the spectral bandwidths be wide to obtain adequate exposures. Consequently, the spectral information content of aerial photography is considerably lower than most

Fig. 2. 70 mm colour photograph for forest sampling (1:900 original scale). Courtesy of the Canadian Forest Service, Northern Forestry Research Centre, Edmonton, AB.

multispectral solid-state digital sensors. Photography is therefore best used for its prime advantages of large area stereo coverage and good tone/texture rendition.

3.2 Solid-state optical sensors

Solid-state optical sensors incorporate a detector of specific composition that is sensitive to radiation in either the visible-NIR, mid-IR, or the thermal IR portions of the spectrum. Energy incident to the detector surface is processed into an electronic signal and digitized to a given quantization level. Typical current quantization levels of low cost detectors are eight (256 DN) or 10 bits (1024 DN), but 12-bit (4096 DN) and higher are becoming more common. The detector compound is composed of a discrete set of photosites where photons are absorbed. The photosites can be arranged linearly in a single row (line-scanning sensors) or in a two-dimensional array (frame sensors). Formats vary from a few photosites (for opto-mechanical scanners described below) to up to 10 000 (for pushbroom line scanners to several million for frame sensors as described below). Larger formats of over 6000 pixels across the swath are capable of matching large format aerial photography in terms of coverage per image through the use of wide-angle lenses, but they are still very expensive. The primary advantages of solid-state sensors over photography are capability for real-time image viewing, exposure optimization and target coverage verification in-flight, more consistent sensor response, and high sensitivity in the visible-NIR range permitting narrowband spectral filters to be used. Research in forestry using these sensors has generally been for information extraction of the same variables that have been obtained using photographic techniques, but with goals to improve the accuracy, precision, objectivity, consistency, automation, and cost of the data. In many applications, these goals have been achieved, or are close to achievement.

In the following discussion of sensors, frame sensors are considered separately from line-scanning sensors due to specific advantages and limitations of each. Hyperspectral sensors are considered under each section as designs have been developed that use both frame and line imaging.

Frame sensors

Frame sensors are considered first as they represent the most marginal technological change from photography. Both the geometric format and operation are very similar. These sensors can be categorized in two groups: video and digital cameras. King (1995) gives an extensive review of video and digital cameras in airborne remote sensing including system designs and applications.

Video cameras conform to standard television scanning specifications and are thus constrained in terms of resolution, scanning format, and other electronics. Their detectors are typically composed of silicon arrays of up to super VGA format (1024×768 photosites). The image is either re-formatted to an analog signal for recording on videotape or digitized with a frame grabber for computer storage. Both formats may be viewed and interpreted for a variety of forest and environmental characteristics (e.g., forest damage, stream erosion, verification of larger scale sampling image location, etc.). The continuous movement of the imagery (30 frames per second – from tape and in current computer displays) provides additional interpretation power in some cases over a series of still overlapping images. Recent video cameras have been developed for high definition television standards of about 1500×1000 pixels. In contrast to video cameras, digital cameras convert the image signal to digital within the camera. Images are usually stored on a disk housed in the camera body or within a computer. The prime advantage of digital cameras over video cameras is that they are not confined to television standards and thus a variety of image formats, computer control, and processing functions are available. However, both technologies are merging, as most new cameras are purely digital but can also produce a standard video output.

Multispectral imagery can be obtained with frame cameras in a variety of ways. The simplest is to use a colour or colour IR camera and separately output the three colour channels corresponding to three spectral bands. In these cameras, filtering of incident radiation is achieved using either: 1) spectral dispersion optics (dichroic mirrors or prisms) that divide the spectrum into three bands, each being transmitted to one of three detectors, or 2) a composite filter placed over a single detector that transmits one of the three spectral bands to each photosite. In the latter, since each photosite receives radiation in only one of the spectral bands, the remaining two bands must be derived from interpolation of their values in neighbouring pixels. In this format, digital images with large numbers of pixels can be stored using a file that is one-third the size of files using the three-detector technique. However, the spatial resolution is reduced due to the need for interpolation of two-thirds of the data. A limitation of both camera types described above is that they are generally produced for consumer or photo-journalism use so they are designed to emulate photography (hence the common term "digital photography") and the filters in each spectral band typically have wide bandwidths of about 100nm. Consequently, as with photography, they are not well suited to quantitative spectral analysis but are better utilized in visual interpretation or quantitative analysis of image spatial information.

Fig. 3. Kodak DCS420CIR image with 25cm pixels of the boreal forest. Image from author's research data.

Fig. 3 shows an example image of mixed boreal forest species at the edge of a mine tailings deposit that was produced using the second technique described above. A Kodak DCS420 CIR camera was used with 1524 × 1012 × 12-bit pixels in green, red and near IR. The ground pixel size was 25cm.

Several other types of multispectral sensors using custom narrowband (approx. 10nm) filtering of video or digital cameras have also been developed. The most common use multiple cameras (two to twelve), each with a separate narrowband interference filter placed in front of, or behind the lens (e.g., Vlcek and King 1984, Nixon *et al.* 1985, Benkelman and Behrendt 1992, Butler and Otten 1994, Mao *et al.* 1994, personal communication, C.M.U. Neale, Dept. of Biological and Irrigation Engineering, Utah State University, Logan UT, March, 1999). To avoid the high costs of several cameras and synchronization electronics, some systems use a single camera with an attached high speed filter wheel (four to eight spectral bands) (Niedrauer and Paul 1985, Verreault and Gagnon 1993, King 1995), or a single camera with an attached tuneable filter that changes transmission wavelength in response to a computer-controlled input pulse (e.g., Mao and Heitschmidt (1998) can essentially achieve hyperspectral imaging with up to 31 bands). These two single camera designs suffer from a small amount of aircraft advance between spectral bands. They are thus limited in terms of the amount of overlap present between successive images (bands) and the accuracy with which band alignment can be performed. Fig. 4 shows an example of the Ontario boreal forest in eight spectral bands acquired with the 1300 × 1000 × 8-bit filter wheel digital camera sensor developed by the author (King 1995). The ground pixel size is 80 cm.

Most developers and users of airborne video and digital camera sensors have been in the United States and Europe. Applications have centred more on agriculture, rangeland, and water than on forestry. The small size of the detector in these cameras hinders application in mapping, so most work has been in sampling for detailed analysis. In forestry, the USDA Forest Service (USFS) is probably the most significant user of video and digital camera imagery. It started with colour and colour IR video cameras (Munson *et al.* 1988, Myrhe *et al.* 1992 Myrhe 1995), and later commissioned Kodak to convert its DCS420 colour digital camera to colour infrared (Bobbe and Zigadlo 1995). Kodak has since developed the DCS460 CIR digital camera with over 3000 × 2000 pixels and 12-bit quantization. The USFS has used the DCS cameras in pest damage mapping as a more accurate alternative to sketch mapping (Omer 1997, Bobbe 1997). Other example studies of forest damage using video or digital cameras include: 1) Lusch and Sappio (1987) in mapping gypsy moth defoliation for the State of Michigan, 2) Yuan *et al.* (1991) who developed a sugar maple decline index based on spectral and textural image measures, 3) {Jacobs and Eggen-McIntosh (1993)} for hurricane damage assessment over a large area by systematic sampling, 4) Franklin *et al.* (1995) in classification of western spruce budworm damage, 5) Carter *et al.* (1998) in detection of southern pine beetle damage, and 6) Lévesque and King (1999) and Olthof and King (2000) who developed models for structural and spectral damage assessment of boreal forest species from acid mine contaminant loading and wind stress. In provision of information for inventory applications, Biging *et al.* (1995) used spatial analytical techniques to delineate tree crowns and measure crown size and cover per cent. Slaymaker *et al.* (1995) used two scales of video imagery (1 m and 6 cm pixels) to provide 42 classes of species groupings for classification of New England forests using Landsat. In regeneration assessment and vegetation management, Verreault *et al.* (1993), using 17cm pixels, were able to accurately count conifers more than ten years old while Haddow *et al.* (2000) using 2.5 cm pixels found that accurate counts could be made of unobstructed two-year-old seedlings. Haddow *et al.* also conducted modelling of leaf area index (LAI) and per cent cover under various densities of competing vegetation.

Line-scanning sensors

Line-scanning sensors are either opto-mechanical or "pushbroom." In the former, a scanning mirror traverses the terrain and reflects radiation onto single or multiple detectors (each detector being equivalent to a single photosite in a frame sensor but larger in size). Images are generated one line at a time synchronized to the aircraft advance. The latter utilizes a linear array (single row) of photosites that generates one line of imagery at a time, the whole line being exposed at once. This differs from opto-mechanical sensors, which only sense radiation from a small area visible to the mirror at any instant in time (termed the "instantaneous field of view" – IFOV). The primary limitation of both designs with respect to frame sensors is that they require good attitude instrumentation as rotations of the aircraft between image lines produce poor pixel-to-pixel geometry. A significant advantage of line-scanning over frame sensors is that, if flown parallel to the principal plane of the sun, there are no BRDF problems in that direction (where they are most significant).

Although opto-mechanical sensors represented most of the line scanners available in the 1960s to 1980s, they have been largely replaced by pushbroom sensors except in a few cases of specialized design such as the AVIRIS hyperspectral sensor (e.g., Porter and Enmark 1987, Simmonds and Green 1996) and the Landsat Thematic Mapper. They will not be discussed further as their high cost does not permit operationalization in forestry, except perhaps from space for broad applications. In Canada, the best-known pushbroom linear array sensor is the MEIS II (Multispectral Electro-optical Imaging Sensor) (McColl *et al.* 1983). It consists of up to eight linear arrays, each of 1728 photosites across the swath. A custom-designed spectral filter is placed in front of each lens to provide multispectral imagery.

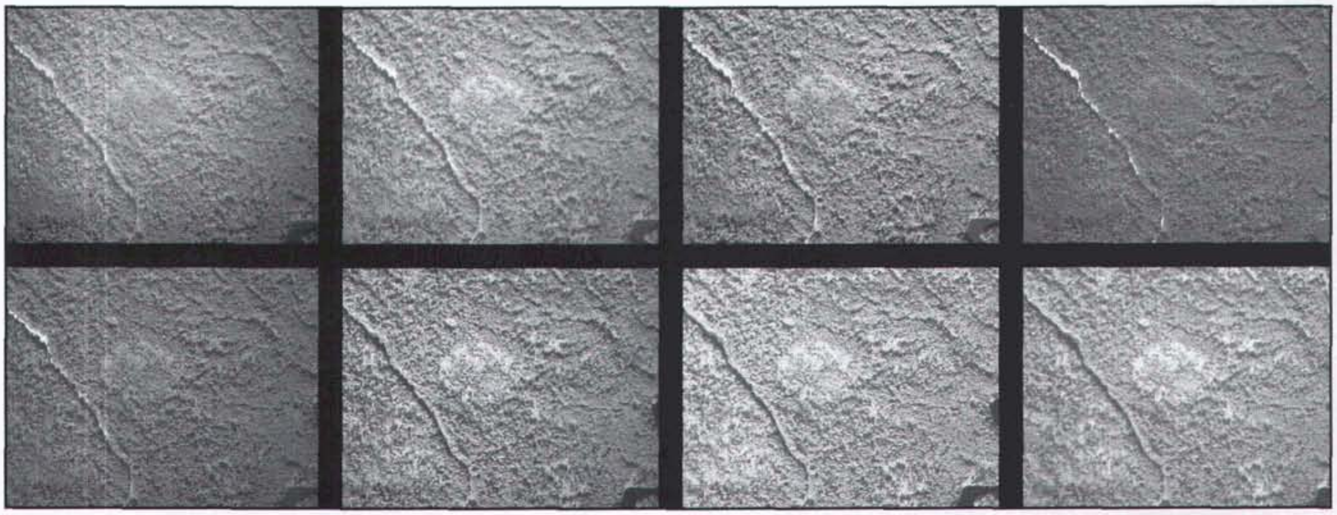

Fig. 4. Eight spectral bands acquired with a multispectral digital camera sensor. The format is 1300 × 1000 pixels with ground dimension of about 80 cm. The spectral bands are as follows reading left to right starting in the top row: blue (430–470 nm), green (545–555 nm), orange (595–605 nm), red (665–675 nm), red edge (695–705 nm), red edge (725–735 nm), near IR (795–805 nm), near IR (895–905 nm). Images from author's research data.

The design also included capability for stereo imaging by pointing two of the eight arrays obliquely (Gibson 1984). The MEIS II was applied in Canadian forestry research from 1982 to about 1994 when it was commercialized and used primarily overseas. It was found to be effective in several forestry applications because of its capabilities for imaging with small pixel sizes (30 cm – 2 m), well-positioned narrow spectral bands, and in stereo with good aircraft attitude correction and positioning. The Canadian Forest Service hosted an international forum on technical aspects of the MEIS II sensor and its use in forestry applications (Leckie and Gillis 1993). Other studies include Ahern *et al.* (1985), Kneppeck and Ahern (1989) and Leckie *et al.* (1992), each demonstrating success in discerning several conifer defoliation classes. Kneppeck and Ahern (1987) and Brand *et al.* (1991) found counting of five-year and older conifer seedlings to be as accurate as from air photos of scales of 1:2000 to 1:10 000, and much easier in digital format on the screen than from hardcopy photos. Edwards (1992) found that stocking of conifers over 1m in height was well estimated using texture measures. St. Onge and Cavayas (1995,1997) predicted crown diameter, stem density, tree height and crown closure from MEIS II imagery of a variety of pixel sizes. The successor to the MEIS II, the MEIS FM (Forestry and Mapping) (Neville 1993) was to be developed as a replacement of photography in mapping and modelling. It included a 6000 photosite linear array that could acquire images with pixel sizes as small as 25cm over the same swath as standard inventory photography. A prototype panchromatic black and white sensor was constructed but never fully evaluated as the program was cancelled in 1995.

Airborne hyperspectral sensors using pushbroom techniques typically consist of a two-dimensional frame detector (e.g., a video format array) as described above but with a line slit opening to acquire one line of imagery at a time and dispersion optics that spread the spectral radiation of the line over one dimension of the detector. Each row (or group of rows) of photosites on the detector becomes a spectral band. The dispersion optics are typically diffraction gratings (e.g., the Compact Airborne Spectrographic Imager, *casi* sensor (Babey and Anger 1989, the RDACS/H2 sensor (Mao *et al.* 1994)) and/or prisms (e.g., the AISA sensor (Okkonen *et al.*1994)). This design was pioneered in Canada in the early 1980s, the *casi* being probably the most commonly sold and used airborne hyperspectral sensor worldwide. The *casi* can acquire data in many spectral bands (up to 288) with reduced spatial resolution, or in several bands with full spatial resolution (>50 cm pixels). It has seen consistent design improvements in the past ten years in terms of image quality characteristics, radiometric calibration and geometric calibration (e.g., Anger *et al.* 1994, Anger *et al.* 1996). The spectral band positions and response are well known through rigorous radiometric calibration. For mapping, on-board inertial navigation and GPS systems allow for precise measurement of aircraft attitude and image position. Fig. 5 presents an example colour composite image of three spectral bands acquired as part of a ten-band *casi* image set. The ground pixel size is about 60 cm. The image is a mosaic that has been orthorectified to UTM coordinates. On the left is a species map generated from the imagery. Another hyperspectral design that has gained some prominence for its very low cost utilizes a single filter that has linearly variable spectral band transmission across one dimension (Sun and Anderson 1994, Mao *et al.* 1997). One frame at a time is acquired, with the spectral bands dispersed across the columns of the image. The aircraft velocity and data acquisition rates are synchronized so that images are acquired at an interval equal to the forward translation of the aircraft. The columns representing a given spectral band can be extracted from several images along a flight line and placed side-by-side to form a strip of imagery in that band. New hyperspectral sensors are being developed at a rapid pace. Since 1990, there have been more than twenty worldwide, although most are not yet suitable for practical forestry implementation. Besides imaging in the visible-near infrared, some hyperspectral sensors are sensitive in the mid-infrared (approx.

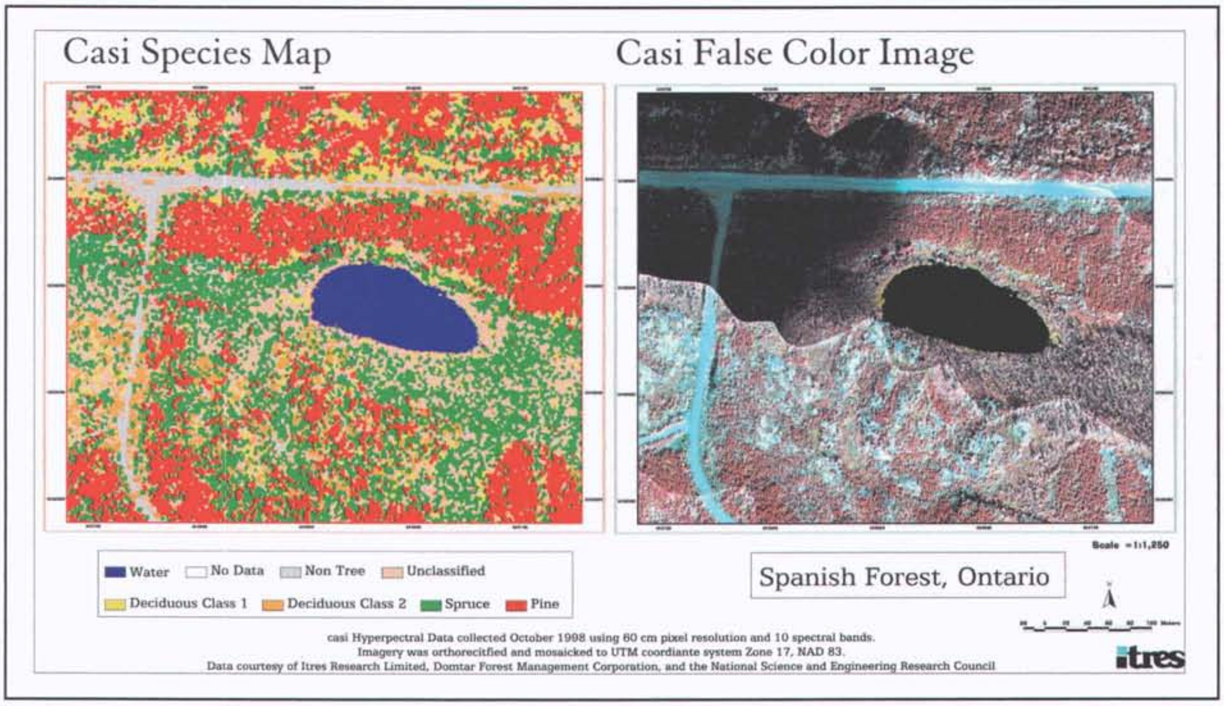

Fig. 5. *Casi* image and associated forest species map. Techniques for data classification within cloud shadows (e.g., upper left of image) have been developed to provide greater flexibility in timing of data acquisition. Image courtesy of Itres Inc., Calgary, AB.

1.3–2.5 µm). In this region of the spectrum water in vegetation absorbs radiation significantly, thus providing potential applications in forest damage/health, composition, and structure. Two Canadian examples of such sensors are the Short-Wave Infrared Full Spectrum Imager, SFSI (Neville *et al.* 1995) and the Short-wave infrared *casi* (Itres Inc. 1999).

In Canada, after the commercial deployment of the MEIS II overseas, and with the increased prominence of hyperspectral imaging, the *casi* became the most commonly applied line imaging sensor in forestry applications. It has proven to be useful in applied research when its precise spectral information and many bands reveal characteristics about the target that cannot be obtained with simple filtering of photography, video, or digital cameras. Operationally, however, it has typically been used as a multispectral scanner similar to the MEIS II (i.e., with full spatial resolution and several spectral bands). The Canadian Forest Service held a similar workshop to that for the MEIS II cited above, but in this case with emphasis on analysis of high resolution imagery for forest composition, health, structure and other applications (Hill and Leckie 1999). A significant number of applications using the *casi* can be found in the proceedings, as well as applications of aerial photography and digital cameras. For example, Brown and Fletcher (1999) were able to derive stocking estimates close to those obtained by ground surveys on backlog "not sufficiently regenerated" sites where seedlings were not obstructed by deciduous competition. The methods were proven to be more cost-effective than field surveys. Magnussen and Boudewyn (1999) predicted total stem volume to within 10% in a thinning and fertilization trial using spectral and spatial measures. In other studies, Gong *et al.* (1995) found vegetation indices of near IR and red channels to be highly correlated with the leaf area index of coniferous stands. Wulder *et al.* (1998) combined spectral and textural image information to model LAI in mixed and deciduous forests.

3.3 Radar

Radar sensors transmit long-wave radiation from an antenna to the ground where it interacts with surface and subsurface features. The reflected signal exhibits modified strength, polarization, and phase that are characteristic of the surface. Radar system parameters critical to project design are spectral band, polarization, and imaging geometry. Two spectral bands have generally been used in radar remote sensing, C-band (5.2–7.7 cm), and L-band (19–77 cm), although several others have been evaluated infrequently. Shorter wavelengths provide higher resolution but the signal reflects mostly from the upper surface of the canopy. Longer wavelengths provide poorer resolution but the signal penetrates the canopy more, providing information on vegetation structure. The radar signal may be transmitted and received with either vertical (V) or horizontal (H) polarization. In all, four possible configurations may be used: HH, VV, HV, and VH. Generally like-polarization provides the strongest signal return and a wider image brightness range, while cross-polarization shows the effects of multiple scattering from leaf and twig surfaces and edges (Leckie 1990). Classification of land cover types and conditions can been aided by using more than one of these polarization configurations, multiple spectral bands, and/or analysis of the phase changes in the signal. The geometry of radar imaging differs from most optical imaging because it is conducted obliquely; the signal is emitted at a specific range of incidence angles to the terrain. It arrives first at points closest to the imaging platform, and then successively later at points further away, forming a line of imagery perpendicular to the platform flight direc-

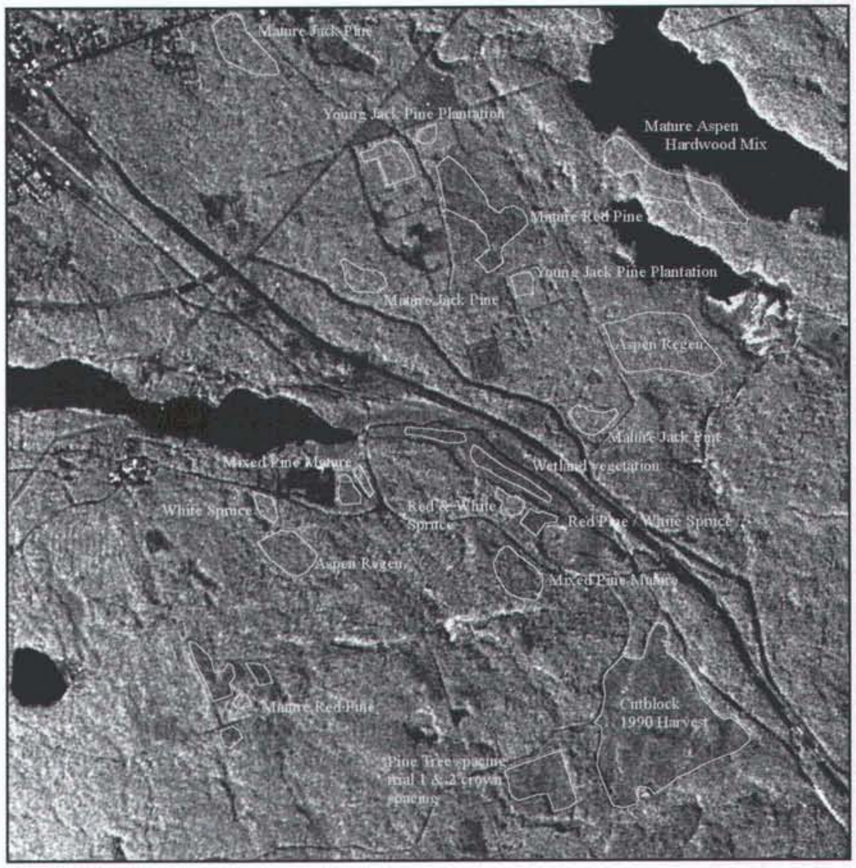

Fig. 6. Example C-band radar image of mixed forest near Petawawa, Ontario. Ground pixel size is 5 m. Species and growth stages produce some variations in image brightness (backscatter) and pattern. Courtesy of the Canadian Forest Service.

tion. As the platform moves forward, successive lines of imagery are created to form a strip. In terrain of moderate to high relief, parts of the signal may be compressed into smaller sections by slopes facing towards the sensor (foreshortening), or, in extreme cases, reversed in geographic representation in the image, i.e., the tops are closer to the sensor in the image than the bottoms (layover). High and steep hills may also block some of the signal from reaching the ground behind and a "shadow" may occur with no image data. Although many of the geometric corrections for these imaging defects have been developed, analysis cannot be conducted where no data are received due to shadow or layover. In terms of image brightness, slopes facing the sensor will generally be brighter than flat terrain or slopes facing away from the sensor. Sharp angles facing the sensor such as vertical surfaces building walls or trees on a flat surface may cause direct reflection of the signal back to the antenna, resulting in a very high bright image signal.

The primary terrain surface characteristics that affect radar reflection are dielectric constant, roughness, and geometry. The dielectric constant of a material describes how well it responds electro-magnetically to an incident radar pulse. Water is most critical in this regard as its dielectric constant is twenty times or more greater than most other surface materials. This results in a strong return where water is present in soils or vegetation. In terms of surface roughness, a smooth surface will reflect the radar signal away from the sensor and the feature will be dark in the image. Consequently, smooth open water, with its high dielectric constant, appears black in radar imagery. A rough surface will reflect more of the signal back creating a brighter image. These interpretations must, however, be tempered by knowledge of radar band interactions with the surface. For example, a sandy surface will be bright in short wavelength imagery and darker in long wavelength imagery, because of differences in resolution of the surface roughness of the two bands.

Another aspect of radar sensing that is critical to determining its potential usefulness is noise caused by multiple interactions of the radar waves and varying degrees of constructive and destructive interference. This results in a different noise level being added to each pixel, termed "speckle." Image filtering or averaging of multiple images of the same terrain is generally conducted to reduce such speckle. However, the resulting imagery has never achieved the signal-to-noise ratios present in optical imagery and thus development of applications has been hindered.

The primary advantage of radar is that the signal can penetrate clouds and darkness. Thus forestry applications in tropical regions and ice/geology applications in northern regions have been the most rapid to develop operationally. In Canada, practical forestry applications of radar have not yet been as well proven as those for optical sensors. The radar signal responds to the size, shape, orientation, distribution and quantity of vegetation elements (Leckie 1998, Pitt *et al.* 1997) but included in the signal are the effects of moisture, topography, speckle, and other system effects. As a consequence of this complexity and of the inherent noise levels, airborne radar cannot generally provide enough information content for detailed forestry applications to warrant the cost (Leckie 1994). However, research continues and potential has been demonstrated in species discrimination, regeneration assessment, and forest clearing

(Leckie 1990, 1998). For example, in species discrimination red and white pines provide low backscatter, while jack pine and spruces provide high backscatter. Ahern *et al.* (1996) found that multi-seasonal and/or multi-polarized C-band radar has potential for distinguishing these conifer groups and poplar dominated hardwoods. However, there was little success in estimation of forest structural parameters using these data. Longer wavelengths are generally preferable for forest structure modelling (Ahern *et al.* 1995), but such sensors are not commonly available. In mapping of major forest disturbances radar has been more successful (e.g., clear-cuts (Banner and Ahern 1995), particularly when blanketed by wet snow (Leckie *et al.* 1998), and burns (Landry *et al.* 1995).

Fig. 6 shows an example C-band radar image of mixed forests near Petawawa, Ontario.

3.4 Laser remote sensing

Lasers have been used to provide horizontal transects of height of vegetation and terrain for over twenty years Leckie (1994). With GPS position and attitude measurement, absolute height can be determined. It can then be used in geo-referencing or ortho-rectification of airborne imagery. Vegetation profiles can be used to estimate forest and tree structure. In operation, a laser (typically near infrared) is emitted with a given pulse rate and a field of view on the ground in the range of a few centimetres to several metres for sensing of trees or the forest canopy, respectively (Leckie 1990). The return time of the laser determines the distance to the surface. Lidar sensors are laser systems capable of measuring multiple returns from within the canopy and thus provide vertical structure information to a resolution of 15–70 cm (Leckie 1990). Currently, some laser systems are coupled with a video camera that can acquire imagery synchronized and boresighted with the laser. Positions of laser pulses can be determined and plotted graphically or on the video image {(Tickle *et al.* 1998)}. A technological advance over transect profiling is laser or lidar scanning. Laser pulses are scanned across a swath in a manner similar to the opto-mechanical imaging scanners described previously. Interpolation between pulses across a swath and between swaths produces a three-dimensional canopy surface model. Resolution is typically larger than 1m in order to cover a swath suitable for canopy modelling. Swath width can be as large as about 8km, but for forestry applications angular sensing through the canopy will produce different returns and confound forest structure analysis (Leckie 1994).

The most common application of laser remote sensing is tree height measurement. Accuracy in relation to photogrammetrically or field-measured height is between 1–2 m (Nelson *et al.* 1984, Aldred and Bonnor 1985, Naesset 1997a) although Jacobs *et al.* (1993) achieved accuracies of about 5 cm in very low altitude laser profiling with video image reference. Tickle *et al.* (1998) compared their laser height estimates to those of field personnel and found that the laser height precision was better than that of the subjective field techniques. Laser height accuracy is, however, limited because the laser rarely hits the tops of trees, particularly for conical coniferous species, and thus an underestimated average tree height is obtained for a stand (Leckie 1990). Techniques to account for this bias, though, are being developed that will improve height accuracy (e.g., Magnussen and Boudewyn (1998) using a geometric model of the upper canopy surface combined with a probability model for estimating where the laser will hit tree crowns; Tickle *et al.* (1998) using only the highest laser "hits" observed in their synchronized video images). Other applications of lasers include counts of rising and falling profile components for tree count/density estimation (Leckie 1990) and analysis of the width or shape of the laser profile components in discrimination of hardwoods, conifers and regenerating vegetation (Schreier *et al.* 1985), in detection of the presence of understory vegetation (Leckie 1994), and in measurement of per cent cover (Tickle *et al.* 1998). Volume estimation was conducted by Naesset (1997b) and Lefsky *et al.* (1997). The latter also derived accurate estimates of biomass, dbh and basal area using scanning lidar. It should be noted however, that estimation of such forest structural variables requires prior knowledge of species composition and proportions (Leckie 1994).

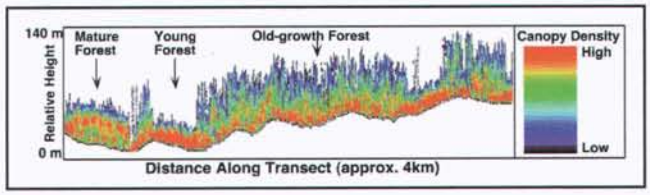

Fig. 7. Colour-coded lidar returns show vertical canopy density within several forest types along a transect in Oregon. Courtesy of M.A. Lefsky, personal communication.

Fig. 7 shows an example of lidar results along a transect in several forest types in Oregon. The canopy density is colour-coded according to the timing and strength of the lidar returns from within the canopy.

4.0 Discussion

In airborne remote sensing, visual interpretation of air photos and pixel-based statistical classification of image spectral data are considered to be "traditional" approaches to mapping and modelling of forest types and conditions. Their primary limitations will be discussed here accompanied by a summary of new directions in sensors and image analysis.

4.1 Limitations of the current aerial photography approach

Air photo interpretation of forest attributes is often combined with stereo measurement of such parameters as tree height and crown diameter. Both of these tasks require significant training to become proficient. Visual interpretation has suffered from the principal criticisms that it is subjective, too inaccurate, and that it is based on a spatial unit, the forest stand, that is too aggregated for today's highly detailed forest characterization requirements. Much variability within stands is not accounted for. Accuracies of species proportions can be in the range of ±25%, 70–85% of the time (Leckie and Gillis 1995). Also, the concept of forest stands is based more on management principles and does not always represent ecological status and process. Interpretation has been shown to improve with the use of multiple spectral bands in high-resolution imaging with digital sensors, mostly as a result of the added capability for image contrast and colour manipulation. However, computer monitors of formats up to about 1600 × 1200 pixels cannot provide full resolution display of images acquired by large digital sensors or scanned photos. Interpretation is thus hindered by viewing of small areas or by low-resolution overviews (Leckie 1994). Measurement of height remains a major limitation of stereo imaging as typical operational height errors of about 2m may produce 10–15% error in volume estimates. Height estimates can be improved using the same stereo techniques with a larger scale of imagery, acquired at the same time, or subsequent to, the inventory images. However, the most promising technology to provide more accurate and consistent height estimates is laser remote sensing, particularly scanning lidar as described above. An additional consideration is cost; aerial photography is relatively inexpensive to acquire and interpret, but costs are high for transfer of the information to digital GIS databases, typically being about 23% of total map production costs (Leckie and Gillis 1995). Digital sensors coupled with automated analysis techniques may be able to match or improve upon current costs of the photographic interpretation/database compilation process by eliminating the digitization or information transfer steps (Leckie 1994).

4.2 Limitations of current spectral analysis

Statistical analysis of spectral data derived from individual pixels cannot adequately distinguish features of interest in many forestry applications. For example, in forest classification, it is well known that acceptable accuracy of classification of coniferous species cannot be achieved using spectral data alone. The principal limitations are: 1) the current forest at a site is a result of complex interactions between vegetation, soils, climate, drainage, and topography – spectral data imaged mostly from the upper canopy surface cannot model the complete variability of the forest, 2) spectral information is but one of many image information types, the others being primarily spatial in nature, 3) parametric statistical techniques have requirements of data normality and independence that can often not be met (particularly for non-spectral data), 4) the approach is mostly data-driven, knowledge of the site and conditions is not well integrated, and 5) use of a set of pixel samples of arbitrary size in a raster image grid is artificial and does not represent the objects of the forest, i.e., trees. During the past fifteen years, research has therefore concentrated on improvement of spectral information analysis and development of alternative approaches that integrate image spatial information, other types of geographic information, non-parametric classification techniques, contextual knowledge and expertise, and object-based data representation. The following discussion provides a brief overview of these fields of study. Each is well developed and much literature is available that cannot be fully integrated into this paper.

4.3 Alternatives to traditional image analysis techniques

Advanced spectral analysis

The development of narrow band multispectral and hyperspectral sensors has improved discrimination capabilities of subtle spectral reflectance features that are linked to species, physiology, health or structure characteristics. In addition, new techniques for analysis of these data have emerged. Three primary techniques are: 1) mixture modelling, 2) spectral curve matching, and 3) spectral curve modelling. Mixture modelling consists of identification of pixel(s) within a scene that represent pure examples (end members) of each object or class that are not mixed with other classes. For an unknown pixel, linear (or sometimes non-linear) analysis is carried out to determine the proportional combination of the end member spectra that best match the pixel's spectra. In this sense, sub-pixel classification is conducted as each pixel can be assigned a proportion of all constituent classes. Spectral curve matching uses measures of goodness of fit (e.g., cross-correlograms) of a spectral reflectance curve derived for a given pixel with reference curves previously acquired using a spectro-radiometer or other means. Such reference curves may be acquired from extensive databases that have been assembled by agencies such as the US Geologic Survey. Spectral curve modelling involves fitting a mathematical model to all or a portion of a pixel's reflectance curve. For example, the red edge of reflectance between approximately 670 nm and 800 nm, where vegetation reflectance increases substantially, is commonly modelled using Gaussian parameters or its derivatives, and can be used to model forest structure and physiological health characteristics. Each of the above techniques is particularly well suited to hyperspectral imaging but they can also be applied less precisely to multispectral data with as few as three or four bands.

Spatial information analysis

Image spatial information consists primarily of image texture, and image structure. The former represents the spatial variation of tones while the latter represents the proportions, and perhaps arrangement or pattern, of radiometric features such as shadows, directly or diffusely illuminated portions of tree crowns, and illuminated understory/background. Contrary to advanced spectral analysis as presented above, costly sensors and processing are not required for high quality spatial analysis. Photography, with its inherent high resolution, digital cameras and video cameras, provide highly detailed spatial information at relatively low cost. Techniques for quantitative extraction of spatial image information have been proven at least as significant as spectral information in mapping of vegetation classes and modelling of health and structure. Spatial information can be analyzed at a variety of scales including within individual trees, characterizing foliage and crown structure, or over the forest canopy characterizing stem density, crown size, gap size distribution and forest productivity.

Forest structure modelling has proven to be one of the most successful applications of image spatial analysis. Forest structure parameters such as leaf area index, gap distribution, canopy closure, stem density, and basal area have all been modelled effectively using various quantitative measures of texture or spatial dependence. Detailed description of such measures is beyond the scope of this paper; examples can be found in (Yuan *et al.* 1991; Edwards 1992; Roach and Fung 1994; St. Onge and Cavayas 1995, 1997; Olthof and King 1997; Wulder and Boots 1998; Lévesque and King 1999; Pellikka *et al.* 2000). In classification, the combination of image spatial and spectral information may improve accuracy. However, image texture is often not normally distributed so non-parametric classifiers that incorporate spatial information have been developed. For example, the context classifier of Gong and Howarth (1992) incorporates the frequency of grey levels in a sample area around a given pixel to aid in its class assignment. Others have integrated measures of spatial autocorrelation between pixels into the classifier as adjacent pixels have a high probability of being the same class. In radiometric structure modelling, the proportions of the canopy and background that are sunlit, diffusely lit, or in shadow have been determined by techniques such as histogram analysis (e.g., Seed and King 1997, Pellikka *et al.* 2000) or mixture modelling (e.g., Peddle *et al.* 1999) and related to canopy structure. Zheng *et al.* (1995) developed techniques that use morphological filters to distinguish species by crown shape measures.

Integration of other types of geographic information

Forest species, structure, and condition are a response to site conditions among other factors. Integration of such information into classification or modelling can improve accuracy significantly. The most common data type that is integrated with image information is the digital elevation model (DEM). The parameters of elevation, slope and aspect are strongly linked to vegetation cover type, abundance and diversity. Peddle (1993) and Peddle *et al.* (1994) provide good comparisons of land cover classification using various combinations of spectral, textural and DEM derivatives. Other types of information that may improve forest mapping and modelling include soils, drainage, and climate data. Many of these variables are, however, not normally distributed, some are ordinal, some are bounded (e.g., slope is typically not greater than 90°), and some are non-Cartesian (e.g., aspect). Thus, as with spatial image variables, non-parametric analysis techniques are required.

Alternative, non-parametric classification techniques

Standard classifiers that require data normality, randomness, and independence are not robust enough for the variety of image and terrain data types discussed above. In recent years many alternative classifiers that incorporate image, geographic, and other expert contextual knowledge of vegetation-site relations have been proposed and evaluated. The most common of these are fuzzy, neural network, belief, and rule-based classifiers. A complete discussion is beyond the scope of this paper but a summary statement on each is given as follows: Fuzzy data representation considers each pixel to be a member to some degree (0–1) of all classes (e.g., Foody 1996). It is similar to mixture modelling as membership scores in each class are essentially equivalent to mixture proportions. Neural networks provide a means to iteratively derive mathematical functions that relate known image (ratio data) and terrain data (ratio, ordinal, or nominal) to numbered classes (nominal data) of interest (e.g., Kanellopoulos and Wilkinson 1997). Belief classifiers determine degrees (support, plausibility, etc.) to which given data contribute to the outcome of each class (Peddle 1993, Peddle *et al.* 1994). Rule-based classifiers generally consist of "if-then-else" conditions. If certain data values, modelling results, or contextual knowledge exist, then the resulting class is known, else the pixel is a member of another class. Studies that have evaluated these advanced classifiers generally show improvements in cover type accuracy over conventional classification, although Skidmore *et al.* (1997) and King *et al.* (1999) provide examples where lower accuracies were achieved.

Each of the above techniques can be implemented using combinations of acquired data and expert knowledge, however rule-based classifiers have most often been associated with the term "expert systems." Encoding of complex forest-site-process relations from expert knowledge is difficult and such systems can only be applied under a regional set of forest conditions. However, if used within their design context, they can be very powerful and accurate. An example in the Canadian forestry context is the SEIDAM project (Bhogal *et al.* 1996).

Data representation: from stand to tree-level information

One of the primary advances that has been made in analysis of high-resolution airborne imagery in forestry has been in data processing to identify individual trees and delineate their crowns. Until the early 1990s, image data were analyzed only on a per pixel basis, with pixels aggregated after classification for determination of tree species and structure. However, delineation of tree crowns before classification or modelling provides capability for much more realistic image analysis that is linked more practically to forest management. The tree becomes the object that is located, classified and measured as opposed to individual pixels. Manual delineation of crowns using stereo viewing (e.g., Meyer *et al.* 1996) is accurate but tedious, so much effort has been placed on development of automated tree apex detection and crown delineation. Apex detection is usually accomplished with a high-pass filter that identifies local maximum brightness. Verreault (1999) used counts of these to determine stem density in high-resolution multispectral video and also to assign individual crowns to health classes. Walsworth and King (1999) used presence/absence of tree apexes in scanned forest inventory photography to determine growth and mortality due to environmental stress at a mine site over a thirty-year period. Crown delineation is generally conducted following apex detection. It can permit accurate and automated measurement of crown size and classification of tree species or other attributes using the spectral and spatial characteristics of the pixels within the delineated crowns. Gougeon (1995) provided much of the earlier work in crown delineation; other algorithms have been produced more recently (e.g., Culvenor *et al.* 1999; Pollock 1999, Walsworth and King 1999, Warner *et al.* 1999). These algorithms have been proven in coniferous plantations and in delineating whole deciduous crowns in open canopies. Where crowns overlap or there is a more complex vertical structure, current algorithms tend to identify clusters of varying numbers of trees. However, modelling of such critical parameters as canopy closure, stem density or crown diameter, and mapping of species composition using these techniques is constantly improving and should be realistic for practical application within a few years.

5.0 Summary

This paper has reviewed critical spectral and geometric imaging characteristics of remote sensing, the variety of airborne sensors available, sample forestry applications using these sensors, and current developments in data analysis techniques. Advances are being made rapidly in provision of more detailed, accurate and consistent information than can be obtained by air photo interpretation and, in some cases, by field sampling. Digital airborne remote sensing can provide: 1) ecologically important structural parameters (e.g., LAI, gap distribution) that cannot be obtained from visual interpretation of air photos, 2) improved accuracy and detail of inventory parameters that are typically derived from visual photo interpretation (e.g., species composition, canopy closure), and 3) parameters that require costly field work to obtain (e.g., in regeneration assessment).

The most common criticism of remote sensing in the past twenty years has been that it has not progressed from research domains to operational status for real information needs. This criticism is no longer valid. The remote sensing industry has expanded greatly and is collaborating with both the forest industry and government agencies in pilot projects under operational conditions. The basic requirement in these projects is that the necessary information be obtained cost-effectively. Hence, we are entering an era where user needs are driving remote sensing R&D and operational integration of remote sensing into various forestry applications will be commonplace.

This paper has cited many scientific references in an attempt to preserve objectivity. In practice, though, one would want to know how to proceed in integration of remote sensing into given applications. Provision of a list of service providers here would be only partial and biased. Instead, the reader can determine potential remote sensing service providers by consulting the following Canada Centre for Remote Sensing website.

Home page:

http://www.ccrs.nrcan.gc.ca/ccrs

Geomatics company listing as of 02/2000: http://www.ccrs.nrcan.gc.ca/ccrs/comvnts/comp/rscompe.html.

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