

Forest height inventory from airborne Synthetic Aperture Radar

Edward David Wallington
BSc (Hons.), MSc.



Submitted for Doctor of Philosophy

The University of Edinburgh

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Glen Affric, Scottish Highlands, 2004.

"The clearest way into the universe is through a forest wilderness."

John Muir.

Abstract

This study assesses the capabilities of commercially available airborne short wavelength Synthetic Aperture Radar (SAR) Interferometry (InSAR) for retrieving individual tree and forest stand height. Individual tree and stand heights are of importance to the forest industry for a number of reasons. Tree height is a key variable for calculating the amount of wood volume in a tree stem, as well as for predictions of amount of timber for extraction. Forest stand height is an important indicator of standing biomass for management purposes as well as for the assessment of carbon storage. Height is also an important ecological parameter in its own right, and an important input parameter for line-of-site analysis. Remote sensing offers an alternative to destructive measurements for accurate, rapid and cost effective technique without user subjectivity. SAR provides the potential for direct height measurement over large areas, and can operate independently of lighting or weather conditions, which often restricts the use of other remote sensing techniques.

In this study, tree height is estimated by subtracting a ground surface elevation model (a UK Ordnance Survey DEM, OSDEM, or a Digital Terrain Model, DTM, from commercial Intermap Technologies) from a Digital Surface Model, DSM, (from Intermap Technologies) and the results are then compared to field measurements of tree and stand heights. The accuracy of Intermap Technologies STAR-3i InSAR DEM products are initially compared to national elevation data sets. Over various ground types, it was concluded that, within the test areas, over non-vegetated ground the mean difference between the DTM and OSDEM was 1.38m RMSE with a 1.05m Standard Deviation (SD), and this is within Intermap's stated accuracies. Over forested ground the mean difference was 13.51m RMSE (2.21m SD). This vegetation bias was primarily due to limitations of the interpolation procedure used to determine the DTM from the DSM.

Subsequently, the use of two airborne InSAR data sets is assessed for top height retrieval as an operational product, as well as a precursor and supplement to satellite data. Firstly, X-band data from Intermap are used to retrieve homogenous plantation top height over four UK study sites using the difference between the DSM and OSDEM with mean underestimations of 33.48% (6.99m mean difference). When assessed for single species, the DSM-OSDEM procedure gave height underestimations of 18-24% for Sitka spruce and 40% for Scots pine, indicating a dependency on canopy structure. Correcting retrieved height based on linear regression with ground reference data is shown to improve height estimation; as such, applying a generic correction to retrieved heights from all four UK study sites improves overall accuracy to 16.77% (3.12m mean difference). For trees greater than 18m measured height, the accuracy is increased to 12.27% (0.92m mean difference).

Secondly, X-band data are also used to retrieve tree total height over two heterogeneous woodland areas in Belize and the UK. In Glen Affric, UK, height retrieval using the X-band DSM-OSDEM procedure for individual trees produce mean underestimation of 94.87% (6.08m mean difference). In Belize, height retrieval using the X-band DSM-DEM procedure for individual trees produces a mean underestimation of 74.71% (6.85m mean difference). For the Belize test site, height retrieval using JPL Airsar C-band DSM-DEM procedure for individual trees produces retrieved heights with a mean underestimation of 55.97% (4.79m mean difference). The primary cause of error is that layover effects due to SAR geometry may result in the retrieved height from a specific image coordinate not representing the same geographical position as the measured height.

Relationships between radar retrieved height and forest parameters such as stocking density and tree height and radar dependent properties such as slope and edge effects are presented as possible explanations for variations across the collected data. Supporting work using a simple coherent interferometric scattering model is also used to characterise and explain the effects on tree height retrieval due to variations in slope, number density, stand height and forest edges.

The results indicate that top height retrieval over homogenous forest stands is feasible with similar accuracies to those found with other remote sensing techniques and ground survey. Individual tree location assessment does not appear to be a suitable technique for assessing height retrieval in heterogeneous environments, and further investigations are required to determine a more suitable approach. This new data set therefore potentially allows a rapid and timely management tool for use in cost-effective sustainable forest management and related applications.

Declaration

I certify that the work contained in this thesis, including text, figures and tables, is my own, except where specifically stated. The thesis has been composed by myself and has not been previously accepted for a degree or professional qualification.

Signed:

Edward David Wallington

30th September 2005

Acknowledgements

Thank you to the following, without whose help, this thesis would not have been possible:

To Dr. Iain Woodhouse, Dr. Tim Malthus and Juan Suárez for supervising this project, and for all your help, guidance, advice and encouragement during the course of this study.

To colleagues who have been involved with this and other work along the way, without your input and support the work would have been that much harder, so thank you: Izzawati, Dean Turner, Manuela Grippa, Anthony Newton, Chris Place, Chris Hill, Charles Hutchinson, Iain Cameron, Carol Hay, Karin Viergever, Neil Stuart, Duncan Moss, Patrick Meir, Rachel Gaulton, Pete Watt.

To all those at the various organisations who have assisted over the years, especially those at the Forestry Commission and Forest Research: Stewart Snape, Steve Smith, Doug Knox, Joe Hope, Suzanne Martin, Adele Beck and the many others at Silvan House, NRS and field stations. To those at Programme for Belize, including Rudolph Williams, Wilber Sabado and all the rangers and staff at Hillbank. To those at Intermap Technologies for their assistance with data acquisition and queries, including Bryan Mercer, Andy Shepherd, Ivan Maddox, and the pilot I woke up early in the morning in Inverness whilst in the search for corner reflectors.

This work was funded by the Natural Environment Research Council and the UK Forestry Commission, whose support I gratefully acknowledge. Thank you also to the organisations who have supported fieldwork and conference costs: Royal Scottish Geographical Society (RSGS), The Royal Forestry Society, The Remote Sensing and Photogrammetry Society (RSPSoc) and Small Project Grants, The University of Edinburgh.

Lastly, I would like to thank my family, friends and Krista for your support and encouragement over the years. I can finally say it's finished!

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Preface

The research involved in the production of this thesis has been composed by myself. However, I would like to acknowledge the level of teamwork which was involved in all the research projects culminating in this thesis. Specifically, It should be noted that the UK fieldwork was organised, planned, and managed by myself with the fieldwork carried out by myself and a number of field assistants. Subsequent data analysis was performed by myself. I would like to point out that data obtained for the Belize study site were collected during two field seasons which were led and largely funded through grants awarded to myself. During these field seasons and subsequent research, I lead and participated in the fieldwork, the data collection, analyses, and interpretation in conjunction with MSc students Iain Cameron (2004) and Carol Hay (2005). Results of this work are presented in chapter 6. Part of the project research involved comparison of retrieved results to modelled results as presented in chapter 7. The model used for the comparisons was developed by Dr. Izzawati and Dr. Iain Woodhouse at The University of Edinburgh; as part of the project, I was involved in specifying certain elements of the model, for example allometric relationships. I was also involved in specifying which parameters should be assessed using the model, as well as supplying ground data for model runs. I acknowledge Dr. Izzawati for producing the model outputs, and for assistance in interpretations.

List of variables used in thesis

Variable	Definition
H_{100}	The mean height of the 100 trees in 1 hectare (ha^{-1}) with the largest dbh, or the mean height of the 100 tallest trees in 1ha^{-1} .
Hr_{100}	Retrieved top height, the average of the highest 100 retrieved heights/ ha^{-1} .
P_r	Amount of power returned to the sensor from a target.
P_t	The transmitted power.
G	The gain of the transmitting antenna.
σ	The radar cross section.
A	The effective aperture (area) of the antenna.
R	The range between the antenna and the target.
H_t	Total height of an individual tree.
H_r	Retrieved height.
d	The difference between the elevation value obtained from the DTM and the OSDEM.
d_{mean}	The mean difference between the DTM and OSDEM.
n	Sample size.
θ_a	Depression angle.
y	The extent of area affected in metres.
h	Tree height in metres.
θ	Radar viewing angle.
α	The slope angle.
$RMSE$	Root mean square error.
SD	Standard deviation.
SE	Standard error.
$P\text{-value}$	Probability value.
R^2	R-squared.

1 Introduction

“The last thing one discovers in composing a work is what to put first”.

Blaise Pascal (French mathematician, philosopher and physicist, 1623-1662)

1.1 Thesis aims and objectives

The overall aim of this thesis is to assess the use of synthetic aperture radar (SAR) for forest height inventory. Current requirements in inventory necessitate that a reliable, timely, efficient and accurate technique to assess tree height and related parameters. Tree height is especially important with regard to measuring timber volume, for production and management purposes, as well as an important input into biomass and carbon estimations. In particular, the use of airborne X- and C-band SAR interferometry (InSAR) to retrieve height estimations for homogeneous plantation and heterogeneous woodland is presented and discussed in the context of application to four test sites throughout the UK and one test site in Belize. It is envisaged that remote sensing data, including that from SAR, can provide valuable additional information to support, enhance and be integrated with traditional ground-based forest inventory techniques. It is feasible to provide a more detailed assessment of the forest resource than is currently possible using traditional sampling strategies, with similar or higher accuracies. InSAR inventories are achievable over large areas, and can be undertaken frequently, and, as well as being increasingly cost-effective, further adds to the operational potential of remote sensing as a tool for foresters.

The specific aim of this thesis is to demonstrate height retrieval from airborne short wavelength InSAR over homogeneous plantation and heterogeneous woodland by investigating the following:

I. InSAR DEM accuracy validation

Techniques presented in this thesis rely on a high resolution and accurate digital elevation model (DEM) of the ground surface (Digital Terrain Model, DTM). As such, it is necessary to determine the accuracy of an InSAR derived DTM prior to use in forest height retrieval. Validation of the InSAR DTM accuracy is performed by comparison to national elevation data sets over (i) non-vegetated ground and (ii) forested ground.

II. Tree and stand height retrieval

Height retrieval algorithms are discussed and used to retrieve individual tree and stand heights. Retrieval is performed and compared to ground reference measurements over (i) homogenous plantations and (ii) heterogeneous woodland. Both of these woodland types are important in forest inventory; homogenous plantations in the UK are important for timber production and heterogeneous woodlands are important for a number of reasons including conservation, biodiversity, heritage, and landscape. As such it is necessary to assess the potential of InSAR derived products over both forest environments.

III. Examination of reasons for underestimation errors

Any technique which averages height over an area, will always underestimate when compared to top or total height. The use of SAR will always result in an underestimation of tree or stand heights due to the properties of microwave signals at wavelengths used in SAR. Further errors may be introduced by properties of the SAR system geometry and the properties of the target, in this case forest structure. Retrieved height data is used in combination with modelled results to examine possible reasons for underestimation in the context of retrieval over homogeneous and heterogeneous forest environments.

1.2 Rationale

1.2.1 Current issues in forestry inventory

Forest inventory has for a long time been used to gather information about a forest resource, essentially detailing what is where, how much there is of it, and how has it changed, thus aiding informed forest management (Leckie, 1998). Traditional techniques consist of surveyors visiting the field and performing measurements on forest stands. Measurements taken will vary depending on the application for which the data are to be used, and as such, are tailored to requirements. These requirements will vary, so may include qualitative and quantitative measures of parameters relevant to, for example, timber yield estimates, health, conservation, biodiversity or landscape issues. Tree parameters of interest may include height, diameter at breast height (DBH, 1.3m), canopy depth and width, stem straightness, number densities, basal area and species. These variables can then be used as inputs for a number of applications.

If detailed height analysis of a forest resource is required it would be ideal to measure every single tree in a stand, however this is unrealistic due to time and cost constraints (even for a relatively small country the size of the UK), and as such samples of stands are taken. Many sampling strategies exist (McCoy, 2005); with the aim being to obtain a representative sample of a stand/forest, but much reliance is left to the surveyor's judgement and experience. The effect of employing such a technique is the possibility of surveyor bias (McCoy, 2005) in the location of sample plots, resulting in an unrepresentative sample of the forest resource. Further, as all trees in a stand are not measured, there is also an element of bias in the tree measurements.

From both a commercial forestry point of view, as well as inputs into other management decisions such as for biodiversity mapping, landscape assessment and conservation, there is a need for cost-effective, accurate and frequent observations, measurements and subsequent compilation and analysis of the forest resource. Monitoring and information reporting to promote adaptive and sustainable forest management has emerged as an important component in the field of forest management (Hickey *et al.*, 2005). The entire forest inventory production cycle, from planning to map generation, can take several years (Wulder *et al.*, 2005). Such inventories are currently carried out relatively infrequently, for example the UK National Inventory of Woodland and Trees (NIWT) is performed every 15-20 years (Wright, 1998; FC, 2003), as well as only being a sample approach of woodland over 2ha, with sub-samples of forests, woodlands and stands being measured, as discussed. Alongside this, individual forest managers commission surveys as and

when required. This all contributes to an infrequent and dispersed inventory process. The ability to accurately and frequently monitor change, at a variety of scales, is limited. Management decisions are performed on a daily basis, and as such can only be informed if the most up-to-date information is available; this is not, necessarily, currently the case. This has consequences for forest management, as well as knock on effects, such as accurate reporting for national targets such the UK Forestry Standard (FC, 2004), Sustainable Forestry (FC, 2002) and the Kyoto Protocol (UNFCCC, 2005).

Timely assessment of the forest is becoming increasingly important, and as such monitoring of homogenous plantation forests (for timber production) and heterogeneous semi-natural forests (for landscape, conservation and recreation) is required on a more frequent basis than is perhaps currently obtainable. This is even truer due to the apparent move towards continuous cover forestry (CCF; Mason *et al.*, 1999; Pommerening and Murphy, 2004), with the associated, potentially more intensive, assessment requirements. This study assesses height retrieval over homogenous and heterogeneous forests, both in the UK and Belize. The Belize savanna test site (see chapter 3) is of interest in its own right, but also as there are strong characteristic links between the forest structure in the woody savanna, current semi-natural forests in the UK and proposed CCF forest structure.

This study is concerned with height inventory, and as such will focus on individual tree total height and stand top height (defined in section 1.2.3) measurement. Remote sensing is one tool which could be used to estimate tree height, thus supplementing current inventory techniques. The ability to capture large areas of

forest, with a quantified accuracy, providing greater consistency, rigour and objectivity (Mather, 2005), as opposed to an almost unknown and varying accuracy (due partly to individual surveyor interpretation and bias) show promise for forestry applications. The ability to obtain height measurements from remote sensing at an accuracy approaching that of ground based measurements, demonstrates the potential of operational remote sensing to be used in support of traditional inventory.

1.2.2 Remote sensing in forestry

While the potential of remote sensing is enormous, realising that potential has proved difficult (Mather, 2005). Remote sensing technologies (satellite and airborne optical, radar, and laser-based sensors) offer tremendous data acquisition power that has yet to be used to any substantial degree in forest vegetation management (Pitt *et al.*, 1997). Traditionally, remote sensing studies by aerial photography have been used for several decades in the field of forestry (Barrett and Curtis, 1982), and to date, aerial photographs have been the most frequently used source of remote sensing data in forestry (Hall, 2000; Howard, 1991). Extensive ground survey is used in conjunction with visual interpretation of aerial photography to verify and supplement the data to produce a complete forest study or regular inventory. Many organisations use this combined approach, such as the UK Forestry Commission and its subsidiaries, as well as other private forestry companies. However, with the advent of increasingly powerful computers (and their wide spread use), software applications and the rapid emergence of remote sensing technologies, the natural sciences has seen a move away from manual data interpretation techniques, to wide spread adoption of digital remote sensing. The forestry sector has slowly begun to

assess these technologies, and digital remote sensing is now seen as a potential operational solution to forest parameter mapping. Satellite remote sensing is not commonly an integrated component of forest inventory (Wynne *et al.*, 2000) - this is also true for aerial remote sensing, photogrammetry aside. However, it is anticipated that high-resolution satellite imagery may offer an alternative to small-scale aerial photographs for large synoptic views (Pitt *et al.*, 1997).

Remote sensing instruments are capable of providing systematic observations of land cover, repeatedly and consistently (Rosenqvist *et al.*, 2003), and are a valuable tool that can assist forest practitioners because they can be used to map and monitor ecosystems at a variety of scales (Hall, 2000). The techniques discussed in this study have the potential to deliver important new information or improve, simplify and/or speed up the traditional inventory process (van der Sanden, 1997), thus providing cost-effective and useful information about the vertical and horizontal structure of the forest at a range of scales. Another advantage of using digital data is that it is relatively easily imported into Geographical Information Systems (GIS; Longley *et al.*, 2005; Suárez *et al.*, 2003; Skidmore *et al.*, 1997) so as to increase the analysis of the diverse data at a range of scales, and this has been demonstrated by the increased use of GIS-based management systems in forestry. The integrated use of remote sensing, GIS and forest models represent a key piece of infrastructure required for strategic sustainable forest management (Franklin, 2001).

It is suggested that no one system is suitable for all forestry applications. Different scales, data requirements, availability, cost and coverage will effect decisions as to

which remote sensing system is most appropriate. As such, forest management must therefore be inter-disciplinary 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 (King, 2000). It seems likely that it will be the combination of several sensors with different, but complimentary, spatial, spectral and temporal resolutions that will yield accurate and reliable data for terrestrial ecosystem parameters (Donoghue, 2002). The combination of new remote sensing technology and new data analysis techniques with advances in remote sensing science and ecosystem modelling have assured a critical role for remote sensing in mapping, monitoring and managing temperate forest resources (Danson, 2000), and utilising the latest technology can lead to new ways of managing forest-lands, which can increase returns and help reduce environmental impacts and their costs (Means *et al.*, 2001).

The use of remote sensing as a means of data collection, quantification and assessment has been actively pursued for forest management applications at a range of scales from individual trees, stand, forest, and landscape, to national, international and global (Franklin, 2001; Donoghue, 2002). A number of organisations and countries are now using remote sensing to conduct and support forest inventory, such as the US Forestry Service (McRoberts, 2005) and the Swedish National Board of Forestry (Tomppo, 2005; Nilsson *et al.*, 2005). The UK Forestry Commission is now beginning to consider the use of remote sensing to support national inventories. Remote sensing has the ability to map and measure a range of key forest inventory parameters; this study focuses on tree height retrieval.

1.2.3 Tree height – a well known term, but what does it mean?

The term 'tree height' is often referred to in many publications and everyday usage. However, the actual height of an individual tree or a stand can be defined in many ways (see Appendix A; West, 2004; Edwards, 1998; Philip, 1994; Hamilton, 1998; Helms, 1998). Definitions of tree height will also depend on whether it is referencing the land-use, stand, sub-stand or individual trees. Most definitions of tree height, in particular for stands, have been developed for homogeneous temperate forest plantation stands, and as such may not be useful when applied to a heterogeneous stand such as in CCF or tropical forest environments. Further, the notion of a stand may not be relevant in many applications of this nature. There is a need for consistent use of terminology when discussing 'tree height'; this is not only pertinent to forestry discussions, but also when comparing heights retrieved from remote sensing. A misrepresentation of a sensor's ability to accurately estimate tree height can occur if compared to ground data where a different tree height is being referenced. A requirement for explicit definitions or statements of which height is being discussed is essential when comparing different techniques of height retrieval – there are a number of height definitions and terminologies which can be used (See Appendix A). This study shall define individual tree height as 'total height' – that of the vertical distance from ground level to the highest point (tip) on the tree. Stand height is defined as 'top height' or H_{100} – the mean height of the 100 trees in 1 hectare (ha) with the largest dbh, or the mean height of the 100 tallest trees in 1ha (Phillip, 1994). Remote sensing techniques measure height as opposed to diameter, and so the latter definition of top height is used in this study.

1.2.4 Why tree height is important

The height of an individual tree is important in forestry for a number of reasons. In timber resource management, tree height (or stem length) is a critical variable when calculating the amount of wood in the tree (West, 2004) – height is combined using allometric relationships with, for example, DBH, crown width, basal area and stem taper to produce estimates of timber volume (Franklin, 2001). These estimates can then be scaled up to stand and forest areas to produce predictions of timber yield. Regular estimations are required to accurately predict, and manage, the forest crop to maximise yield over time. The volume of a tree is also an important indicator of standing biomass (Patenaude *et al.*, 2004) which can also be converted into estimates of carbon storage, which can be used as inputs into national and global climate change prediction models, particularly when coupled with regular measurements to assess carbon volume change over time. Top height is an important parameter in production forestry (West, 2004) that can also be used in studies looking at forest stand structure, bio-fuel estimations or carbon sequestration. Likewise, top height is used to estimate structural parameters within the stand such as dominance and diameter distribution, and site characteristics such as site productive capacity. Height is also an important ecological parameter in its own right (Latto *et al.*, 1996), and an important input parameter for line-of-site analysis (Longley *et al.*, 1999).

1.2.5 SAR as a potential tool

There are a multitude of existing sensors and techniques which have been researched in forestry, including optical, LiDAR and RADAR (see chapter 2). Each system has been applied to a number of forest applications with various degrees of success. This

study is directed at height retrieval, and as such each of the systems mentioned above have been used for height estimation and are briefly discussed in chapter 2. Of note is the difference between height estimation with optical systems, which use a correlation of signal reflectance with height, and the technique of direct height measurement from LiDAR and RADAR.

Synthetic Aperture Radar (SAR) operates in the microwave region of the electromagnetic spectrum, with wavelengths in the order of centimetres (cm) to metres (m). SAR has advantages over other systems. Firstly, as an active sensor, SAR emits its own signal, and is therefore independent of lighting conditions (and hence illumination direction), being able to operate day or night, thus increasing data acquisition time. Secondly, the wavelengths used are several orders of magnitude larger than atmospheric particles, and as such are virtually unaffected by atmospheric conditions, including clouds (Danson, 2000). This results in the ability to operate when optical systems cannot – particularly in areas of frequent cloud cover, such as the UK and tropical regions. The longer wavelengths also allow penetration into vegetation canopies (Balzter, 2001), the degree of penetration dependent on a number of factors including the particular wavelength used. A number of SAR techniques exist, which range from commercially available Interferometry (InSAR), to research-only techniques such as Polarimetry (PolSAR) and Polarimetric Interferometry (PolInSAR). These are briefly described and compared for height retrieval in chapter 2.

Initial research efforts in this study were focused on airborne L-band (~23.5cm) PolInSAR data for forest classification and height indicators (see Appendix B; Wallington *et al.*, 2002; Wallington *et al.*, 2003; Wallington *et al.*, 2004a). Results of this study did not provide evidence of increased ability, and the impetus of the study was redirected to commercially available (potentially operational) data sets. The use of airborne Interferometric Synthetic Aperture Radar (InSAR) data, as a precursor, and supplement, to future satellite based sensors for forest height retrieval is presented. Data sets used include X-band (~3cm) data sets in the UK and Belize, supported with C-band (~5.5cm) data in Belize. Results are discussed in the context of the development of a cost-effective method for the estimation of top height in homogenous forest stands and tree total height in heterogeneous forest environments.

1.3 Thesis structure

This chapter has given an overview of current issues in operational forestry, and outlined the impetus for InSAR use for forest height inventory. Chapter 2 reviews the use of different remote sensing systems for generation of digital elevation models (DEMs) and height retrieval. This chapter then focuses on characteristics of SAR which affect height retrieval, before comparing different SAR techniques. Chapter 3 gives details of the study sites, data and methods used in this study for height retrieval and assessment. Chapter 4 presents results of comparisons of InSAR derived DEM's and national datasets prior to use in height retrieval. Chapters 5 and 6 present results of height retrieval over homogeneous and heterogeneous forest environments respectively. Chapter 7 investigates potential reasons for height underestimation by comparing retrieved results to modelled results. Finally, chapter

8 concludes with a summary of the key findings, and the implications for operational InSAR forest height inventory.

2 Principles and techniques related to forest height inventory

“See first, think later, then test. But always see first. Otherwise you will only see what you were expecting. Most scientists forget that.”

Douglas Adams (British comic writer, 1952-2001)

2.1 Introduction

The height of a tree (total height) is defined as the distance from the ground to the highest point. To be able to measure height, it is therefore a requirement to know the location of the ground, and the location of the top of the tree. The aim of this chapter is to give an overview of techniques for height retrieval. This is achieved by (i) giving an overview of methods for digital elevation model (DEM) generation of the ground surface (Li *et al.*, 2005) followed by (ii) an overview of methods of tree height estimation. The remainder of the chapter focuses on the use of various SAR techniques for height retrieval. An indication of achievable accuracies for tree height retrieval is given, and these are compared for the differing techniques.

2.2 Methods of DEM generation

2.2.1 Surveying

Traditional surveying techniques (e.g. Uren and Price, 1994; Bannister *et al.*, 1992) are used to determine the coordinates (x, y, z) of a series of points through the measurement of angles and distances, which originate from a point with known

coordinates. Interpolation between these points enables the creation of a digital surface which is representative of the ground surface with trees and buildings removed commonly referred to as a bald-Earth digital terrain model (DTM). Accuracy of the DTM produced is a combination of the accuracy of the surveying and the number and density of points surveyed. Accuracies in surveying are very high (in the order of cm), but the ultimate accuracy of the DTM at representing the ground is the skill of the surveyor selecting representative ground points. As such, the technique is open to subjectivity. The technique is very labour intensive, time consuming, covers a small area at a time and is hence extremely costly. The use of GPS in surveying has helped to speed up point data collection, but at the detriment of accuracy (in the order of cm-m). The combination of GPS and traditional surveying is commonly used. This technique frees the surveyor from having to start from a fixed known point, as the use of differential GPS allows an accurate known point to be created within the area of interest. High accuracy is achievable as long as the GPS coordinates are measured over a long enough period to reduce errors in the known point.

2.2.2 Cartographic digitisation

Digital extraction from existing topographic data is another common method of DTM creation. This involves the digitisation of contour maps, whereby contour lines are followed and individual point coordinates are recorded. Interpolation between points then allows generation of a DTM. This technique is very time consuming, with only small areas being mapped at once, and is therefore expensive. The accuracy of the final product is primarily driven by the accuracy and scale of the

original map being digitised, and the accuracy of the user in digitising along contour lines.

2.2.3 Stereographic methods

Stereo aerial photogrammetry

Height can be measured from two overlapping aerial photographs by using the principle of parallax differences (Paine and Kiser, 2003). This uses the relative displacement (parallax) of a point in the two images (base and top), in combination with viewing geometry to estimate height (Lillesand *et al.*, 2004). This method has the need for photographs to overlap by a minimum of 60% so as to produce the parallax. Due to their nature, and to maintain a reasonable resolution, aerial photographs have to be taken from fairly low level, and as such their extent is very limited, thus resulting in high costs. Digital photography has gone some way to reducing costs by automating much of the processing, and automated DEM creation is now an operationally established procedure.

SAR stereography

A similar principle to stereo photography, that of stereography (or stereoscopy or radargrammetry; Leberl, 1998), can be applied to SAR images, providing they have a sufficiently large baseline (Toutin and Gray, 2000), and forms a stereo model for measurement (Li, *et al.*, 2005). Since distortion in the SAR image is in proportion to the topography relative to the flight path, the difference in distortion (which is equivalent to optical parallax but is not based on angular differences) between images provides information on relative height. As with optical stereography, the

method requires image features with high visibility (contrast) and so works best over areas of varied topography.

2.2.4 LiDAR

The use of Lidar (Light Detection and Ranging) for DEM production is now an established technique, and becoming an important tool in operational remote sensing, surveying and mapping (Ackermann, 1996, cited in Li *et al.*, 2005). The last return from the laser signal is normally representative of the ground surface. Where the ground is not clearly visible, interpolation is necessary to fill the gaps. One limitation to the use of lidar for DEM production is the current cost of the data collection (thus limiting coverage), and the large data files produced.

2.2.5 SAR Interferometry

SAR Interferometry (InSAR) combines images recorded either by two antennas at different locations (single-pass) or the same antenna at different times (repeat-pass) (Madsen and Zebker; 1998; Woodhouse, 2005). The phase-difference information between the SAR images is used to precisely measure changes in the range, on the sub-wavelength scale, for corresponding points in an image pair (Toutin and Gray, 2000). These phase differences are represented as a phase difference image, commonly referred to as an interferogram. Unwrapping of the phase differences (conversion of stepped phase changes into a continuous surface) allows an estimate of the differential range changes across an image, and hence an estimation of elevation.

Repeat-pass InSAR is based on the acquisition of images from the same instrument but at different times, and as a consequence suffers from temporal decorrelation (and hence error) over any area that moves in a random fashion during the interval of the two passes. Changes in soil moisture or roughness, or the motion of vegetation in the wind can all result in a degradation of performance. The amount of information lost is related to a number of parameters, including the time interval, the weather conditions, the structure and density of the vegetation, as well as instrument characteristics such as wavelength and polarisation. Repeat-pass InSAR is the most common source of satellite based data since required baselines for satellite systems are usually tens to hundreds of metres (Toutin and Gray, 2000). Although there has been some success with the ERS tandem pair data with a 24 hr interval, much longer time periods between acquisitions can result in a loss of coherence resulting in no DEM data available for areas with significant vegetation cover. Single-pass InSAR has the ability to overcome temporal decorrelation issues. One example is the Shuttle Radar Topography Mission (SRTM; JPL, 2005), which was able to fly two antennas simultaneously at either end of a long boom. Other current single-pass systems are based on airborne platforms such as the NASA Jet Propulsion Laboratories (JPL) AIRSAR (NASA, 2004) and Intermap Technologies STAR-3i (Intermap, 2005). It should be noted that DEMs generated from SAR are based on returns from the first object the signal comes into contact with, and as such, there may be a vegetation bias in the DEMs (dependent on wavelength). Penetration into canopy is also a factor to be taken into account. Dependent on the wavelength (Table 2.1) used, penetration into the canopy can vary (related to wavelength interaction with a target of a similar size). Figure 2.1 gives a graphical representation on the penetration depth of

differing SAR wavelength. The vegetation bias can be used as an advantage for estimating tree height (Woodhouse, 2005; see section 2.3).

Table 2.1 Typical SAR wavelengths.

Radar Band	Frequency (GHz)	Wavelength (cm)	Typically (cm)
X	8.0 - 12.5	2.4 - 3.8	3
C	4.8 - 8.0	3.8 - 7.5	5.6
L	4.8 - 8.0	15.0 - 30.0	23.5
P	0.3 - 1.0	30.0 - 100.0	75

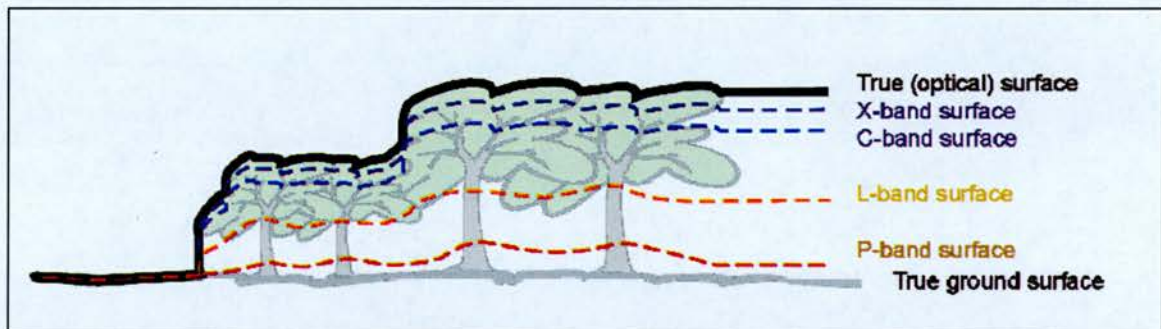


Figure 2.1 Relative penetration of SAR wavelengths. Note that even X-band would be expected to have some capability to penetrate the top of the canopy. (Wallington and Woodhouse, 2005)

2.3 Methods of tree height estimation

2.3.1 Ground based

Ground based measurements of tree height have long been the mainstay of forestry through the use of direct, geometric and trigonometric techniques (Philip, 1994), using clinometers and hypsometers (Helms, 1998), and more recently electronic hypsometers such as the Vertex (Hagloff, 2005). Traditional surveying techniques and instruments can also be used to estimate tree height, although this is less common. These methods are suitable for measuring individual trees or small groups

of trees, but become unduly expensive where a large number of trees are involved (Hamilton, 1998). Error sources, other than human induced (such as measuring to an incorrect tree tip), include failure to correctly measure horizontal distances to the tree, not accounting for wind sway or tree lean, and non-linearity of the relationship between tree height and the angle of sight affecting the ability to correctly identify the highest point, therefore increasing potential errors (Philip, 1994). Added to this is surveyor subjectivity, particularly at specific times, e.g. the end of the day, or unfavourable weather conditions. An overall accuracy of 10% is expected to be achieved from ground survey techniques (Barron, 2001; Meir, 2005). See table 2.2.

2.3.2 Aerial photogrammetry

Ground survey is generally supported by aerial photogrammetry. The best method is to measure height by parallax differences (Paine and Kiser, 2003). This uses the relative displacement (parallax) of an object in two images, in combination with viewing geometry to estimate elevation. Assuming that ground is visible as well as the tree tops, it is possible to use the relative parallax to estimate the difference in height between the top and the ground, and hence determine tree height. Such techniques are commonly used for height estimation, structure assessment and subsequent forest management (e.g. Lachowski *et al.*, 2000; Stone, 1998; Fensham *et al.*, 2002; Fujita *et al.*, 2003). Limitations of aerial photogrammetry are a reliance on overlap between images and to be of high enough resolution to distinguish individual trees. This requires a low flying height, resulting in limited coverage, resulting in high costs. There is also a need for skilled photo-interpreters, and there is often a need for individual interpreters to establish corrections based on regression with

ground data for each type and scale of photography used (Paine and Kiser, 2003). For example, Itaya *et al.* (2004) found an overall height accuracy of 3.83m RMSE (18.5%) for trees of 15-35m.

2.3.3 Optical systems

Optical remote sensing satellite systems, such as Landsat and Spot, have been used for a number of years for forestry applications (Wulder, 1998). New remote sensing systems, such as hyperspectral and Ikonos, are increasingly being used (e.g. Thenkabail *et al.*, 2004). Tree height retrieval is achieved by correlating spectral response to tree height. The general trend is for a decreasing (less bright) spectral response as tree height increases (Franklin *et al.*, 2003). As trees age and grow taller, the amount of foliage increases, thereby covering the brighter understorey and soils of the forest floor; overall stand spectral response is further decreased by the shadows cast by the taller trees (Franklin *et al.*, 2003). Sensitivity to tree height becomes limited once canopy closure has occurred, at for example around 7-13m (Puhr and Donoghue, 2000; Watt *et al.*, 2004). Studies of optical tree height retrieval have varied in success, for example Donoghue *et al.* (2004) found an overall RMSE of 1.5m, with a range of 0.9-2.3m (R^2 of 0.85-0.001) when using Landsat ETM+ and Spot 4 HRVIR. Similarly, Watt *et al.* (2004) had a height estimation RMSE of between 0.26-1.09m (R^2 of 0.86-0.30) when using Landsat ETM+ and IKONOS. Franklin, *et al.* (2003) used Landsat-5 TM data to predict forest height with R^2 values ranging from 0.41-0.72. Optical remote sensing systems, whilst providing relatively inexpensive data, are limited by the dependency on light to record measurements, and hence are limited to day light cloud-free operation. A further limitation is the

regular presence of cloud cover obscuring the target area. This is an issue for remote sensing in areas of regular cloud cover such as the UK and tropical regions.

2.3.4 LiDAR

Lidar (Light Detection and Ranging; Aronoff and Petrie, 2005) currently operates from an airborne platform, and is still at a predominately research stage for vegetation mapping purposes, although the technique has been utilised for other purposes to date. A pulse is transmitted from the antenna, and the return time for the pulse recorded (Aronoff and Petrie, 2005; Suárez *et al.*, 2005b). The returned signal is characterised by several peak returns. These are related to multiple returns from the vegetation. Under ideal conditions, the first return (i.e. shortest return time) will be from within the top of the canopy (may not be actual top), several returns from within the canopy (related to structure) and a last return (i.e. latest return time) from the ground surface. The first returns are filtered and interpolated so as to construct a canopy DEM, and the last returns are similarly filtered and interpolated into a ground DEM. Estimated tree height can be retrieved by deducting the ground DEM from the canopy DEM. Estimations are expected to always underestimate actual height due to penetration of the signal into the canopy. LiDAR derived heights have been shown to have tree height underestimations in the region of 7% (Suárez and Wallington, 2005; Suárez *et al.*, 2005b), 13% (Lefsky *et al.*, 2002), 15% (Næsset and Bjerknes, 2001), 6% (Næsset, 2002), 7.1% (Patenaude *et al.*, 2004), 7.6-17.6% (Næsset and Økland, 2002), 22% (Zimble *et al.*, 2003), ~17-30% (Nilsson, 1996) and McCombs *et al.* (2003) found mean underestimations of 0.15m (~0.9%) and 0.38m (~2.2%) depending on stand density. The technique relies on adequate signal penetration to

the ground to create an accurate ground DEM; interpolation of this DEM where insufficient ground points have been measured may lead to ground elevation errors, which in turn lead to height estimation errors.

2.3.5 SAR

Synthetic Aperture Radar (SAR; Henderson and Lewis, 1998; Woodhouse, 2005) has the advantage of being able to operate independently of lighting conditions and weather (Henderson and Lewis, 1998; Woodhouse, 2005), and as such is seen as having the potential to overcome some of the limitations in applying optical data under UK conditions (i.e. cloud cover). SAR data, utilising backscatter intensity or interferometric coherence, has been used for a number of forestry applications (e.g. Leckie, 1998; Smith and Askne, 2001) and most recently for height retrieval, volume estimation and biomass estimation through correlation with known biomass values (e.g. Luckman *et al.*, 1997; Baker and Luckman, 1999; Luckman *et al.*, 2000; Gaveau, 2002; Castel *et al.*, 2002a; Castel *et al.*, 2002b; Santoro *et al.* 2002; Austin *et al.*, 2003; Gaveau *et al.*, 2003; Pulliainen *et al.*, 2003; Wallington *et al.*, 2004; Treuhaft and Siqueira, 2004; Dobson *et al.*, 1992; Le Toan *et al.*, 1992; Smith and Ulander, 2000; Ulander *et al.*, 2000). These studies and others have also utilised the polarisation of the signal through the technique of polarimetric SAR (PolSAR; Evans *et al.*, 1988; Boerner *et al.*, 1998; Woodhouse, in press) to aid the interpretations of backscatter (Leckie and Ranson, 1998). SAR also has the ability to measure heights directly through the use of interferometry (InSAR), and the more advanced technique of polarimetric Interferometry (PolInSAR). Studies have also investigated the use of multi-baseline interferometry and multi-frequency interferometry. Although not

discussed here, techniques such as SAR stereography and tomography have been pursued for height retrieval (e.g. Reigber and Moreira, 2000; Reigber *et al.*, 2000; Toutin and Amaral, 2000). The ability to measure height over a large area has great potential for forest height inventories and associated applications, such as using allometric equations to estimate timber volume and biomass.

2.3.5.1 Interferometry

SAR interferometry (InSAR; Henderson and Lewis, 1998; Woodhouse, 2005) can be used to estimate the height of objects, in this study the height of trees. As mentioned previously, DEMs produced from InSAR over forests have an element of vegetation bias, and this bias can be used to estimate tree height. The vertical location of the InSAR retrieved height is determined by a combination of the relative scattering contributions of elements in a range cell, such as the ground, canopy, branches etc. The combination of these scattering terms will result in the height being retrieved at a 'scattering phase centre' (SPC), which will usually lie between the canopy and the ground (Woodhouse, 2005). Different SAR wavelengths will produce different vertical locations of the SPC, with longer wavelengths being nearer the ground, and shorter wavelengths being nearer the top of the canopy. As such, height underestimation will always occur due to penetration of the signal into the canopy, even at short wavelengths (figure 2.1). The use of interferometry to create DEMs of the ground surface has been discussed (section 2.2). Short-wavelength (X- or C-band) InSAR can be used to create a Digital Surface Model (DSM) of the canopy, and in combination with existing ground elevation data (e.g. national elevation data sets) can be used to estimate height. Longer wavelengths such as P-band and VHF

(Ulander and Froilind, 1998) have wavelengths long enough so as to reach the ground and so provide topographic information from the ground surface. When InSAR is applied using two different frequencies (and so different penetration into the canopy) it is possible to infer a vegetation canopy height through comparison of the two DEMs (Dutra *et al.* 2002).

The use of InSAR for height retrieval has had varying degrees of success. For example using C-band ERS-1/2 repeat-pass InSAR, Hyyppa and Engdahl (2000) found standard errors of 5.1m (R^2 of 0.58); similar poor results were found by Santoro *et al.* (2003 and 2005), with errors of 7-11m, Ulander *et al.* (1995) found errors of around 50%, and Dammert and Askne (1998) found errors of up to 60%. Yong *et al.* (2003) used L- and C-band data from the SIR-C/X-SAR mission, and concluded that for 3 plots C-band underestimated by 7.92m (63%) – 21.79m (100%), and for L-band 9.61m (86%) – 19.44m (90%). Hagberg *et al.* (1995) found height could be estimated to within 6-50% when using ERS-1 C-band InSAR. Similarly, Hoekman and Verekamp (2001) found mean errors of 13.17m when using airborne C-band InSAR. One major limitation of repeat-pass systems, particularly satellite borne systems with long revisit times, is the degrading effect of temporal decorrelation. InSAR requires high correlation between images to effectively produce DEMs; if targets in an image move (even in the order of a wavelength) between image acquisitions, correlation can drop significantly, and introduce errors. Such a situation can regularly occur in a forest - a gust of wind moving the location of branches and the canopy, for example. As such, the use of single-pass systems

have also been assessed for tree height retrieval, as the two images are captured instantaneously, thus effectively eliminating temporal decorrelation.

Currently, single-pass systems are limited to airborne platforms, although the Shuttle Radar Topography Mission (SRTM; JPL, 2005) is one exception where a single-pass spaceborne system was used to produce a near-global DEM. The following gives an overview of height retrievals using single-pass systems. Aulinger *et al.*, (2005) subtracted an airborne P-band ground surface from an X-band canopy surface, and retrieved heights with an underestimation of approximately 40% for 35m high trees. Santos *et al.* (2004) also used airborne X-band minus P-band and found that through regression analysis, an R^2 of 0.87 was possible. Similarly, Dutra *et al.* (2002) found underestimations in the order of 1.1m (4.5%) – 7.32m (31%). Using C-band JPL TOPSAR InSAR, Kobayashi *et al.* (2000) concluded that tree heights could be estimated to within 1m (10%). SRTM X-SAR data has been assessed in combination with national elevation datasets and was found to have a vegetation bias in the DSM (Weydahl *et al.*, 2003), as expected. Walker *et al.* (2004) used SRTM to retrieve height to within 6.13m ($R^2 = 0.15$), and other studies have demonstrated height retrieval with errors of up to 50% (Kellndorfer *et al.*, 2004a and 2004b) and 33.1% (Brown and Sarabandi, 2003). Although a RMSE of 1.8m was achievable after adjustment for outlying stands (Kellndorfer *et al.*, 2004a and 2004b). Single-pass InSAR systems have demonstrated an increased ability to estimate tree height when compared to repeat-pass systems. The ability to calibrate data based on a sample of ground reference data is one way to improve estimations, and heralds use on larger

scales. A number of factors are also present which can affect the height retrieval from InSAR; these are discussed in the context of this study in Chapter 7.

2.3.5.2 *PolInSAR*

Polarimetric SAR Interferometry (PolInSAR; Cloude and Papathanassiou, 1998; Papathanassiou and Cloude, 2001; Cloude and Papathanassiou, 2003) uses a single frequency InSAR, but exploits the polarimetric information (Zebker and Van Zyl, 1991) in the signal to differentiate between canopy and ground responses, and thus has the capability to retrieve tree height, as well as detailed ground DEM's (Cloude *et al.*, 2002; Woodhouse, 2005;). L-band is the most common wavelength used for PolInSAR, as penetration to the ground is possible, but there is still a significant contribution from the canopy. Examples of PolInSAR use for height estimation, for comparison to other techniques, include the study by Cloude *et al.* (2001), where height estimation correlations gave an R^2 of 0.88 (Woodhouse *et al.*, 2002); Sarabandi *et al.* (1999) found underestimations in the order of 15%; Mette *et al.* (2004) found that in 3 out of 4 study sites, the retrieved height was an overestimate of around 5%, and in 1 site an underestimate of 10%. Papathanassiou *et al.* (2003) concluded that over 3 test stands a height estimation accuracy of 5-10% was achieved. Gabriel *et al.* (1999) found that for trees of max height 25m, the retrieved height was 9m (a 64% underestimation). Treuhaft and Cloude (1999) found that for a 20m vegetation layer, height retrieval accuracy may be within 2-8m (10-40%). Li *et al.* (2004) used dual frequency (C- and L-band) PolInSAR to retrieve height, and found underestimations in the order of 2-5m (approx 12-30% underestimation). Significantly better results have been found by Cloude and Corr (2003) who retrieved heights over Scots pine trees with underestimations of 2.5%. PolInSAR for

tree height retrieval still remains a topic of ongoing research, and are additionally limited by the current lack of a suitable commercial system.

Technique	Accuracy	Reference
Ground Survey	10%	Barron, 2001; Meir, 2005
Aerial photogrammetry	3.83 m (18.5%)	Itaya <i>et al.</i> , 2004
Optical		
<i>Landsat ETM+ and SPOT 4 HRVIR</i>	0.9-2.3 m	Donoghue <i>et al.</i> , 2004
<i>Landsat ETM+ and KONOS</i>	0.26-1.09 m (R^2 0.86-0.30)	Watt <i>et al.</i> , 2004
<i>Landsat-5 TM</i>	0.41-0.72 R^2	Franklin <i>et al.</i> , 2003
LiDAR		
	7%	Suárez and Wallington, 2005
	13%	Lefsky <i>et al.</i> , 2002
	15%	Næsset and Bjercknes, 2001
	6%	Næsset, 2002
	7.1%	Patenaude <i>et al.</i> , 2004
	7.6-17.6%	Næsset and Økland, 2002
	22%	Zimble <i>et al.</i> , 2003
	~17-30%	Nilsson, 1996
	0.15 m (~0.9%)	McCombs <i>et al.</i> , 2003
	0.38 m (~2.2%)	McCombs <i>et al.</i> , 2003
InSAR		
<i>C-band ERS-1/2 repeat-pass</i>	5.1m (R^2 0.58)	Hyypa and Engdahl, 2000
<i>C-band ERS-1/2 repeat-pass</i>	7-11 m	Santoro <i>et al.</i> , 2003 and 2005
<i>C-band ERS-1/2 repeat-pass</i>	50%	Ulander <i>et al.</i> , 1995
<i>C-band ERS-1/2 repeat-pass</i>	60%	Dammert and Askne, 1998
<i>SIR-C/X-SAR C-band repeat-pass</i>	7.92m (63%) – 21.79 m (100%)	Yong <i>et al.</i> , 2003
<i>SIR-C/X-SAR L-band repeat-pass</i>	9.61m (86%) – 19.44 m (90%)	Yong <i>et al.</i> , 2003
<i>ERS-1 C-band repeat-pass</i>	6-50%	Hagberg <i>et al.</i> , 1995
<i>Airborne C-band repeat-pass</i>	13.71 m	Hoekman and Varekamp, 2001
<i>Airborne X-band – P-band</i>	40%	Aulinge <i>et al.</i> , 2005
<i>Airborne X-band – P-band</i>	R^2 0.87	Santos <i>et al.</i> , 2004
<i>Airborne X-band – P-band</i>	1.1 m (4.5%) – 7.32 m (31%)	Dutra <i>et al.</i> , 2002
<i>Airborne C-band</i>	1 m (10%)	Kobayashi <i>et al.</i> , 2000
<i>SRTM X-band</i>	6.13m (R^2 0.15)	Walker <i>et al.</i> , 2004
<i>SRTM X-band</i>	50%	Kellndorfer <i>et al.</i> , 2004a; 2004b
<i>SRTM X-band</i>	33.1%	Brown and Sarabandi, 2003
PolInSAR		
<i>Airborne L-band</i>	R^2 0.88	Cloude <i>et al.</i> , 2001; Woodhouse <i>et al.</i> , 2002
<i>Airborne L-band</i>	15%	Sarabandi <i>et al.</i> , 1999
<i>Airborne L-band</i>	5% - 10%	Mette <i>et al.</i> , 2004
<i>Airborne L-band</i>	5% - 10%	Papathanassiou <i>et al.</i> , 2003
<i>Airborne L-band</i>	64%	Gabriel <i>et al.</i> , 1999
<i>Airborne L-band</i>	2-8 m (10-40%)	Treuhaft and Cloude, 1999
<i>Dual frequency C- and L-band</i>	2-5 m (12-30%)	Li <i>et al.</i> , 2004

Table 2.2 Summary of tree height estimation per technique. Accuracy is stated as a percentage where possible, where not stated, absolute values are given.

2.4 Summary of theory and principles of SAR

Synthetic Aperture Radar (SAR) operates as a side looking active microwave sensor, and as such there are a number of key differences to other remote sensing systems. In addition to the discussion on the use of SAR in this chapter, the following sections summarise the fundamentals of SAR, and give an understanding of the principles underlying the methods utilised and referred to in this study.

2.4.1 Geometry

Figure 2.2 shows a schematic of the geometry looking along the flight line (into page; the azimuth direction) of a single sensor. The depression angle is measured from the instruments local horizontal to the line of sight (the range direction), the look angle is the angle from nadir direction to the line of sight, and the incidence angle is measured from the line of sight and the normal of a reference surface (Woodhouse, 2005; Lewis *et al.*, 1998; Oliver and Quegan, 1998; Bamler and Harl, 1998).

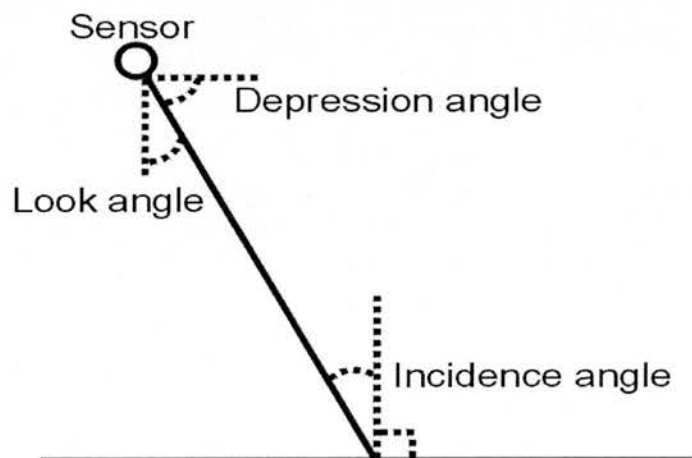


Figure 2.2 Schematic summary of SAR geometry.

2.4.2 Range measurement

SAR is a ranging device, which measures the travel time for a signal between the sensor and the target (Madsen and Zebker, 1998). The actual range measured by the SAR sensor is called the *slant range*, and is the direct distance to the target along the line of sight. During image construction, the slant range is translated to the *ground range*, which is the horizontal distance between nadir and the target (or scatterer) (Woodhouse, 2005; Bamler and Hartl, 1998).

2.4.3 Backscatter

Backscatter is the proportional amount of signal (power) returned directly to the sensor from the target. The amount of power, P_r , is returned to the sensor is defined by the radar equation (Raney, 1998; Woodhouse, 2005; Kingsley and Quegan, 1002):

$$P_r = \frac{P_t G \sigma A}{(4\pi)^2 R^4} \quad (2.1)$$

Where, P_t is the transmitted power, G is the gain of the transmitting antenna, σ is the radar cross section, A is effective aperture (area) of the antenna, and R is the range between the antenna and the target.

The amount of backscatter (power) returned to the antenna is influenced by a number of factors other than those listed above. There are also effects at the target, in terms of scattering mechanisms associated with the target surface type, which will vary the amount of energy reflected back towards the target (Woodhouse, 2005). A smooth target will result in specular reflection, where all the energy is reflected away from the sensor, and as the surface becomes rougher (relative to the wavelength used)

more energy will be reflected towards the sensor. Further properties of the target itself, such as size and shape, orientation, moisture content (dielectric constant; Raney, 1998), and absorption by the target, all effect the amount of energy returned.

2.4.4 Signal interaction with vegetation

There are a number of ways which the SAR signal can interact with the target, in this case vegetation, and in particular forest. For different wavelengths (see figure 2.1 and table 2.1) there will be different interactions with the vegetation, i.e. interaction will occur with a target (scatterer) of a similar dimension to the wavelength. Shorter wavelengths, e.g. X- and C-band, will interact with the canopy and smaller scatterers, whereas longer wavelengths, e.g. L- and P-band, will interact with larger scatters such as branches and trunks. VHF wavelengths will only interact with the trunks and ground. There are a number of differing scattering mechanisms with regard to signal interaction (Raney, 1998; Lucas *et al.*, 2004; Woodhouse, 2005): over open ground, there will be direct scattering, whereas over vegetation (figure 2.3) there will be attenuated direct scattering from the ground (a), direct canopy scattering (b), 'double-bounce' trunk-ground interactions (c) and volume scattering from the canopy (d).

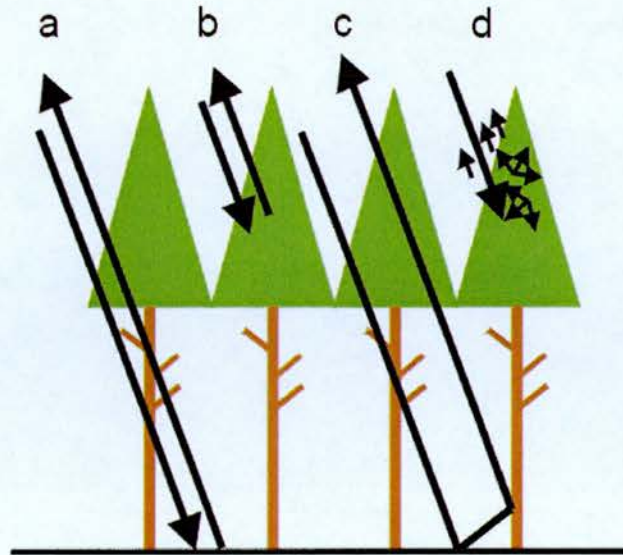


Figure 2.3 Signal interaction with vegetation

2.4.5 Interferometry

SAR Interferometry (InSAR; Madsen and Zebker, 1998; Bamler and Hartl, 1998) makes use of the phase properties of the signal to measure path length, and more accurately, the difference in path length (phase) between two offset antennas (in time or space) to a target (Woodhouse, 2005). Phase differences between the two SAR images are created into a 'differences image' or interferogram (figure 2.4), which represents the difference in phase across the image (Rosen *et al.*, 2000). At this stage the phase differences are contained in 'fringes', representing a change of 2π radians (360°), therefore the change 'steps' across the image as is termed wrapped phase, as each fringe wraps over to the next. The technique of phase unwrapping is used to calculate the differential range changes across the image, and therefore allows assessment of change in elevation over the image (Bamler and Hartl, 1998; Loffeld and Kramer, 1994). This elevation change can be transformed in conjunction with a reference surface to provide actual elevation in a defined projection. The resultant

output from the InSAR processing chain is therefore a SAR intensity image and a digital elevation model (DEM; figure 2.4).

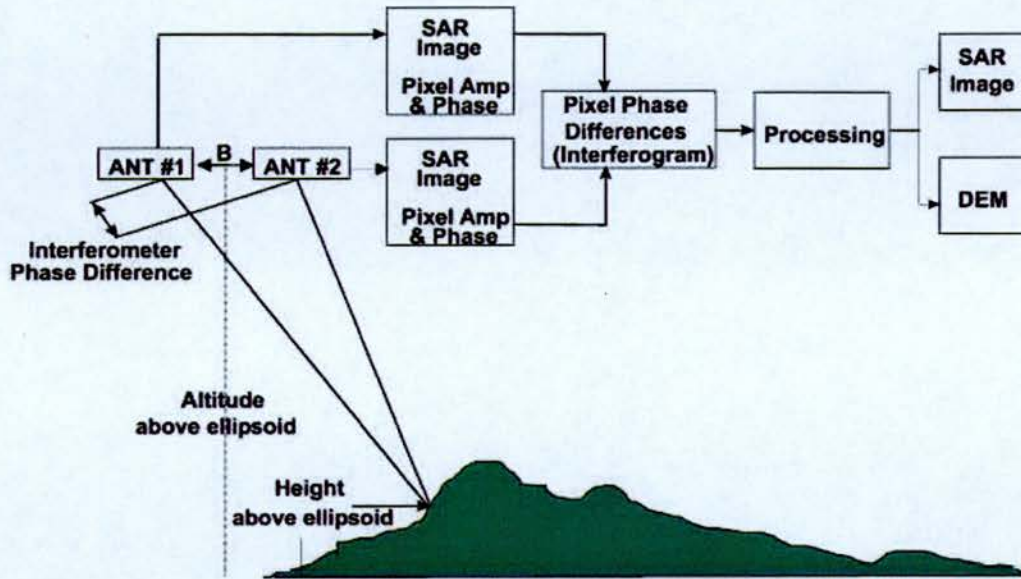


Figure 2.4 InSAR processing chain (after Intermap, 2005)

2.4.5.1 Scattering phase centre

The vertical location of the InSAR retrieved height is determined by the relative contribution of scatterers in the target area (range cell; figure 2.5), such as the upper canopy (a), lower canopy (b), branches and trunk (c) and the ground (d). The combination of scatter contributions will return a retrieved height at a point called the 'scattering phase centre' (SPC; Woodhouse, 2005; Sarabandi, 1996; black dot in figure 2.5). As discussed in section 2.4.4., different wavelengths will return a different SPC due to the varying contributions of different size scatterers. For example, X-band would return a SPC near the top of the canopy, whereas P-band would result in a SPC near the ground. The interpolation of SPC creates a DEM which would vary in height relative to the vegetation height, as indicated by the

surfaces in figure 2.1. If an X-band canopy surface is derived, subtracting a ground surface allows estimation of vegetation height.

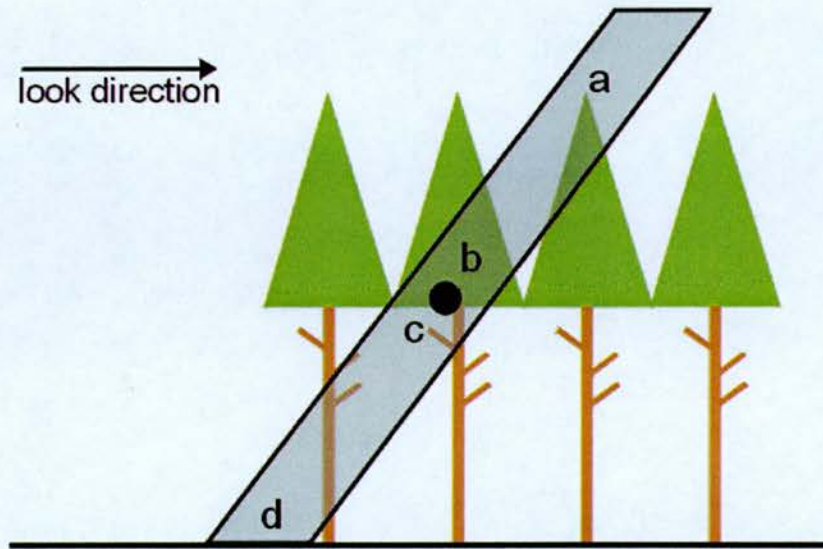


Figure 2.5 Schematic of scatters contributing to the scattering phase centre (SPC)

2.4.6 Polarimetry

SAR polarimetry (PolSAR; Boerner *et al.*, 1998; Evans *et al.*, 1998) utilises the orientation of the signal wave as a further parameter for interpretation (Zebker and Van Zyl, 1991). Waves can be described as horizontally (H) or vertically (V) polarised, and in some cases can be described as a combination of both (Cordey, 1996). SAR sensors are designed to operate with a number of polarisation combinations, and as such are said to be HH (horizontal transmit, horizontal receive), VV, HV, or VH. Interpretation of the returned signal polarisation, knowing the transmitted polarisation, allows inference of the properties of the target (Praks *et al.*, 2001). The technique of PolSAR has therefore been used to aid classification of land cover types, or differentiation of returns from a forest canopy or the ground (e.g. Rignot *et al.*, 1994).

2.4.7 PolInSAR

Polarimetric SAR Interferometry (PolInSAR; Yunjin and Van Zyl, 2000; Cloude and Papathanassiou, 1998 and 2003) combines polarimetry and interferometry into one technique, which allows a single wavelength to be used to estimate height. This is achieved by using the polarisation of different parts of the wave to determine whether it is located near/in the canopy or the ground, thus allowing an estimate of vegetation height to be made (Treuhaft and Cloude, 1999; Zhang *et al.*, 2002).

2.5 Conclusion

This chapter has given an overview of the techniques available for DEM generation and tree height retrieval, with a brief discussion of accuracies achievable. DEMs can be produced in a number of ways, with varying accuracies and related costs; generally, as accuracy increases so does the cost. This is primarily due to the fact that higher accuracy methods (e.g. surveying) are labour intensive, and require detailed field work to gather ground elevation information for interpolation into a DEM. Techniques such as Lidar and InSAR provide elevations at a similar accuracy to many other systems, over large areas rapidly, and remove much of the subjectivity of human interpreters. As such these techniques are seen as promising for forestry applications and associated uses of DEM data. Tree height retrieval also lends itself towards Lidar and SAR techniques. Again, large areas are mapped rapidly, and to an accuracy approaching, if not similar to, those achievable from more traditional methods. Furthermore, remote sensing provides a significantly more usable data set for management purposes, by mapping of continuous land areas, as opposed to sampling strategies currently employed by field teams.

The cost involved in data collection is also one which needs to be addressed. The technique chosen will ultimately be decided by the forest manager, and will be a combination of application, accuracy requirement, data availability and cost. For example, ground survey costs approximately £5/ha (Knox, 2005); for comparison optical data (e.g. Landsat and Spot) may cost as little as £0.01/ha (Donoghue *et al.*, 2004), airborne Lidar is around £5/ha (~£500/km² at 4 returns m²; Suárez, 2004), and commercially available airborne InSAR data is around £0.50/ha (~£50/km², purchase of larger areas is cheaper per ha; GetMapping, 2005). It should be noted that fly-on-request may result in higher costs. Imagery from satellites provides much larger area coverage, and although apparently more costly per scene, is more cost-effective, and will work out cheaper per hectare. With regards to SAR data availability for civilian use, this is currently limited to that of a handful of previous missions, such as SeaSat-1, ERS-1, JERS-1, SRTM and most recently ENVISAT. Currently, airborne data is provided to the research community by NASA's Jet Propulsion Lab (JPL) using the AIRSAR system, the German Space Agency (DLR) E-SAR system, the Danish EMISAR (which has recently lost its dedicated aircraft from the Danish military), the French RAMSES system, the Astrium Micro-SAR, the Dutch Pharus, and the Japanese Pi-SAR. Commercial airborne data is currently collected by Intermap Technologies using their STAR-3i system. Intermap also possess a multi-frequency research aircraft, TopoSAR, following their acquisition of Aerosensing. Current satellite systems include ERS-2, Envisat and Radarsat-1. Future satellite SAR systems include the proposed Radarsat-2 (2006 launch), and Radarsat-3 (launch approx 2008) which would allow a tandem mission and hence InSAR measurements on a global scale. TerraSAR-X is proposed for launch in 2006, TerraSAR-L is also

proposed. TanDEM-X is also proposed for 2008, which will allow InSAR measurements in conjunction with the TerraSAR-X antenna. The proposed COSMO-SkyMed consists of 4 X-band satellites with the first due for deployment in 2005. ALOS-PALSAR is an L-band sensor and is due for launch in 2005. Finally, SAR-Lupe, a constellation of 5 small X-band SAR satellites, is proposed with first deployment in 2005, with all 5 being up by 2007. There is also likely to be increased interest in the use of unmanned aerial vehicle (UAV) based SAR systems such as the Astrium QUASAR. The result of this is that even though data is currently limited, a large array of systems will soon be available in the coming years, and this will see an increase in data availability, and increased uptake of the data will see reduced prices.

This study shall focus on the use of airborne single-pass X-band InSAR. There a number of reasons for this. Firstly, SAR has the ability to operate when many other systems cannot, for example at night and in cloud conditions. Secondly, direct height retrieval is potentially possible, and is not limited by canopy closure, tree height or signal saturation as in correlation methods. Also, InSAR is available commercially, and products are used operationally for many applications, and as such is a potential operational forestry tool for height inventory.

3 Study sites, data descriptions and methodology

"The way to do fieldwork is never to come up for air until it is all over".

Margaret Mead (American anthropologist, 1901-1978)

3.1 Introduction, aim and objectives

The specific aim of this chapter is to give an overview of the study sites, data and methodology used in this study. The objectives to meet the aim are (i) to introduce the study sites in the UK and Belize, (ii) to introduce the SAR and supporting datasets, (iii) to describe the method used for ground height comparison, and (iv) to describe the methods used for tree height retrieval and comparison over homogeneous and heterogeneous forests.

3.2 Study Sites

Four study sites were selected in the UK: Coed Y Brenin in North Wales, Kielder in Northumberland, North England, Glen Affric in the Scottish Highlands and Aberfoyle in the South West of Scotland (figure 3.1). Sections 3.2.1 to 3.2.4 describe the location and characteristics of these study sites, with elevation information provide in table 3.1. There was also a test site in the Rio Bravo Conservation Management Area (RBCMA) in North Belize, Central America (figure 3.6). The RBCMA is described in section 3.2.5, with elevation information in table 3.1. In total, 64 plantation forest stands were considered in the UK study sites, and consisted of a number of species including Sitka spruce (*Picea sitchensis*), Norway

spruce (*Picea abies*), Japanese larch (*Larix kaempferi*), Western hemlock (*Tsuga heterophylla*) and Scots pine (*Pinus sylvestris*). A 1km transect was studied in the RBCMA, containing a number of species, however only Caribbean pine (*Pinus caribbea*) is considered in this study.

Table 3.1 Summary of study site elevation statistics.

Study site		Coed y Brenin	Kielder	Glen Affric	Aberfoyle	RBCMA
Elevation	Min	0	0	98	13	8
	Max	732	511	931	255	18
	Mean	280	281	388	94	14
	SD	129	69	156	64	3

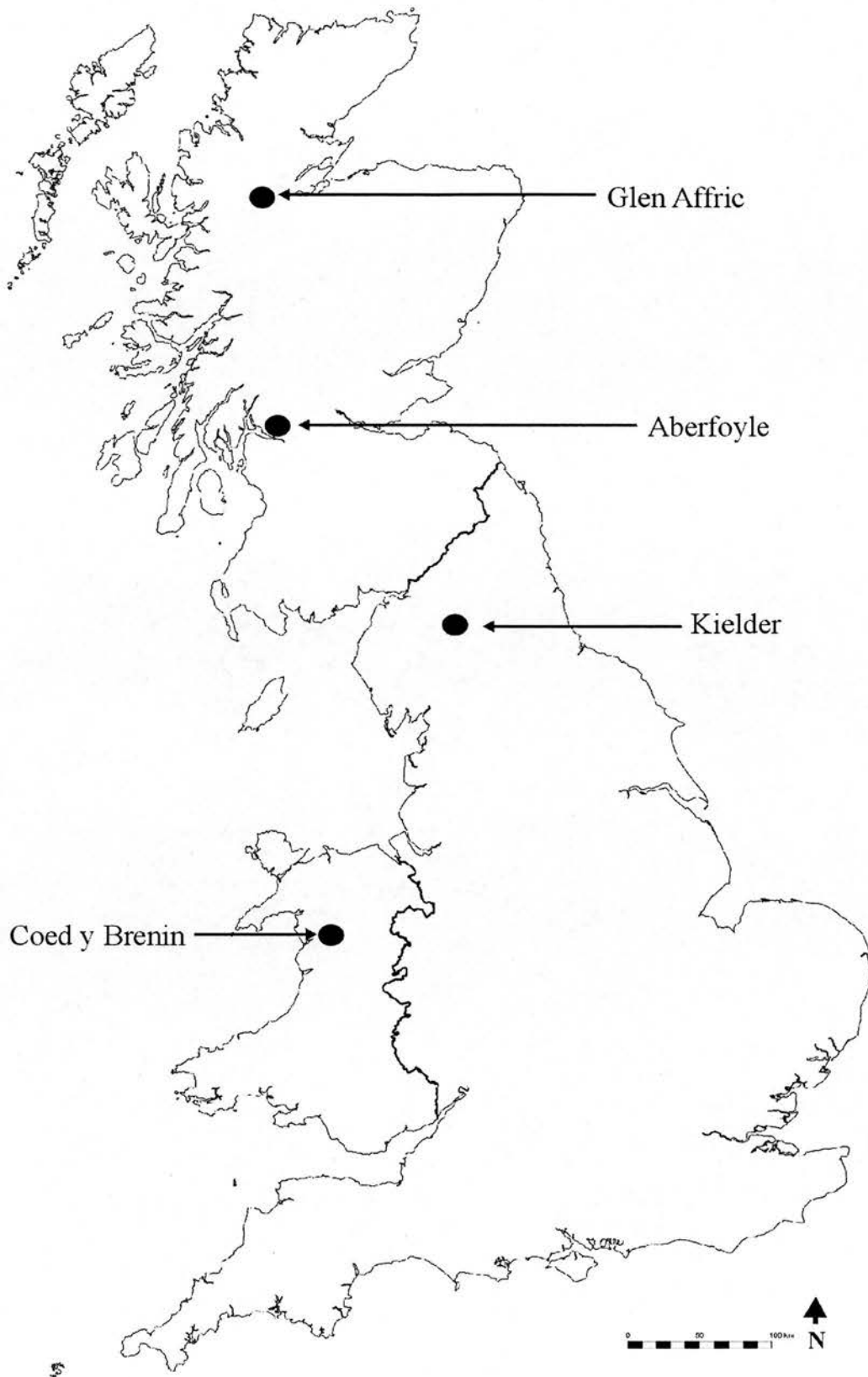


Figure 3.1 Locations of UK study sites. Base map is Crown Copyright Ordnance Survey.

3.2.1 Coed y Brenin

Coed y Brenin forest is situated in Coed y Mynydd Forest District in North Wales (N52:49:12 W3:53:27 lat/long; figure 3.2), north of the small town of Dolgellau. Coed y Brenin is a predominantly Sitka spruce dominated plantation forest (e.g. figure 3.3 bottom), with typical soils composed of brown earths, surface water gleys and intergrade ironpan. 23 stands were assessed in this study, consisting of Sitka spruce, Japanese larch, Scots pine, Douglas fir, Norway Spruce and Western Hemlock.

3.2.2 Kielder

Kielder forest is situated in Kielder Forest District in Northumberland, North England (N55:11:44 W2:32:11 lat/long; figure 3.3), to the north west of Newcastle-upon-Tyne. Kielder is a predominantly Sitka spruce dominated plantation forest (e.g. figure 3.3 bottom), with typical soils composed of brown earths, clay and surface water gley. 11 stands were assessed in this study, and consisted of Sitka spruce.

3.2.3 Glen Affric

Glen Affric is situated in Fort Augustus Forest District in the Scottish Highlands (N57:17:00 W4:54:49 lat/long; figure 3.4), to the west of the small village of Cannich, west of Inverness. Glen Affric is a National Nature Reserve (NNR), and contains some of the largest abundances of semi-natural Scots pine in the UK. Large areas of Glen Affric are managed plantation (e.g. figure 3.3 bottom), but large tracts are also set aside as 'natural' areas (e.g. figure 3.4 bottom). These areas are

primarily situated along the sides of Loch Affric (further west than study site) and Loch Beinn á Mheadhoin (figure 3.4), with typical soils composed of peaty gley and peaty podzol. 25 plantation stands were assessed in this study, consisting of Scots pine and Lodgepole pine. One stand of semi-natural Scots pine was also chosen as a representative example of ancient semi-natural woodland. Site characteristics (e.g. upward and downward slopes both present) and height composition (e.g. range of small and large trees) allow for assessing of affect on retrieved height. This particular stand has also been previously studied by Woodhouse *et al.* (2002) for tree height retrieval using L-band PolInSAR techniques.

3.2.4 Aberfoyle

Aberfoyle forest is situated in Cowal and Trossachs Forest District, within the Loch Lomond & The Trossachs National Park in south west Scotland (N56:10:00 W:4:22:00 lat/long; figure 3.5), to the west of the small town of Aberfoyle. Aberfoyle is a predominantly Sitka spruce dominated plantation forest (e.g. figure 3.3 botom), with typical soils composed of brown earths, clay, ironpan, podzols and surface water gley. 5 stands were assessed in this study, and consisted of Sitka spruce. Aberfoyle is also of interest due to the number of stands undergoing transformation to continuous cover forestry (CCF), and is the study area for a number of other remote sensing in forestry related projects (e.g. Wallington and Suárez, 2005; Gaulton *et al.*, 2005).

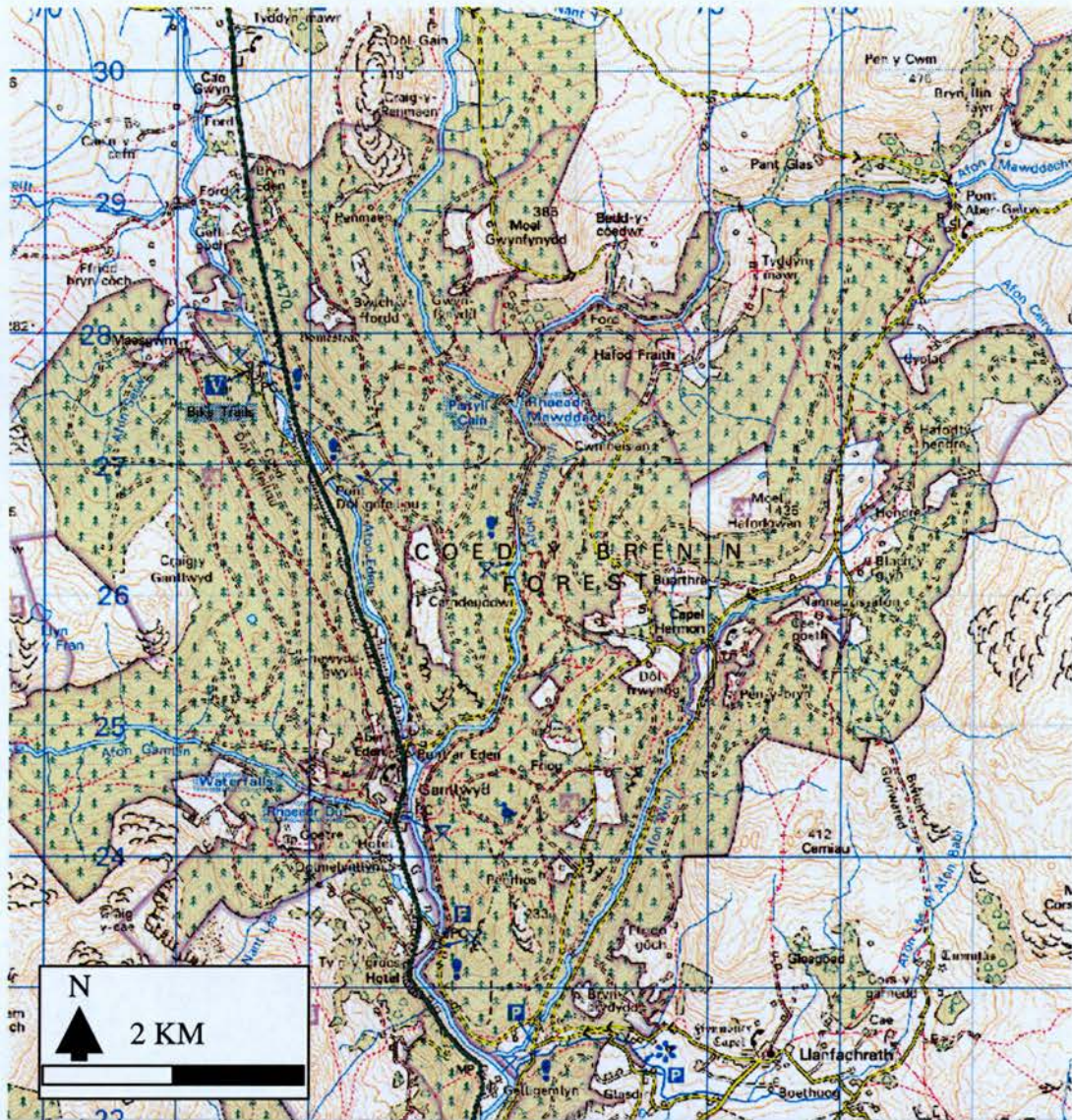


Figure 3.2 Detail of Coed y Brenin study site. Note outline shape of forest, as this will be seen in images throughout this thesis. Crown Copyright Ordnance Survey. An EDINA Digimap/JISC supplied service.

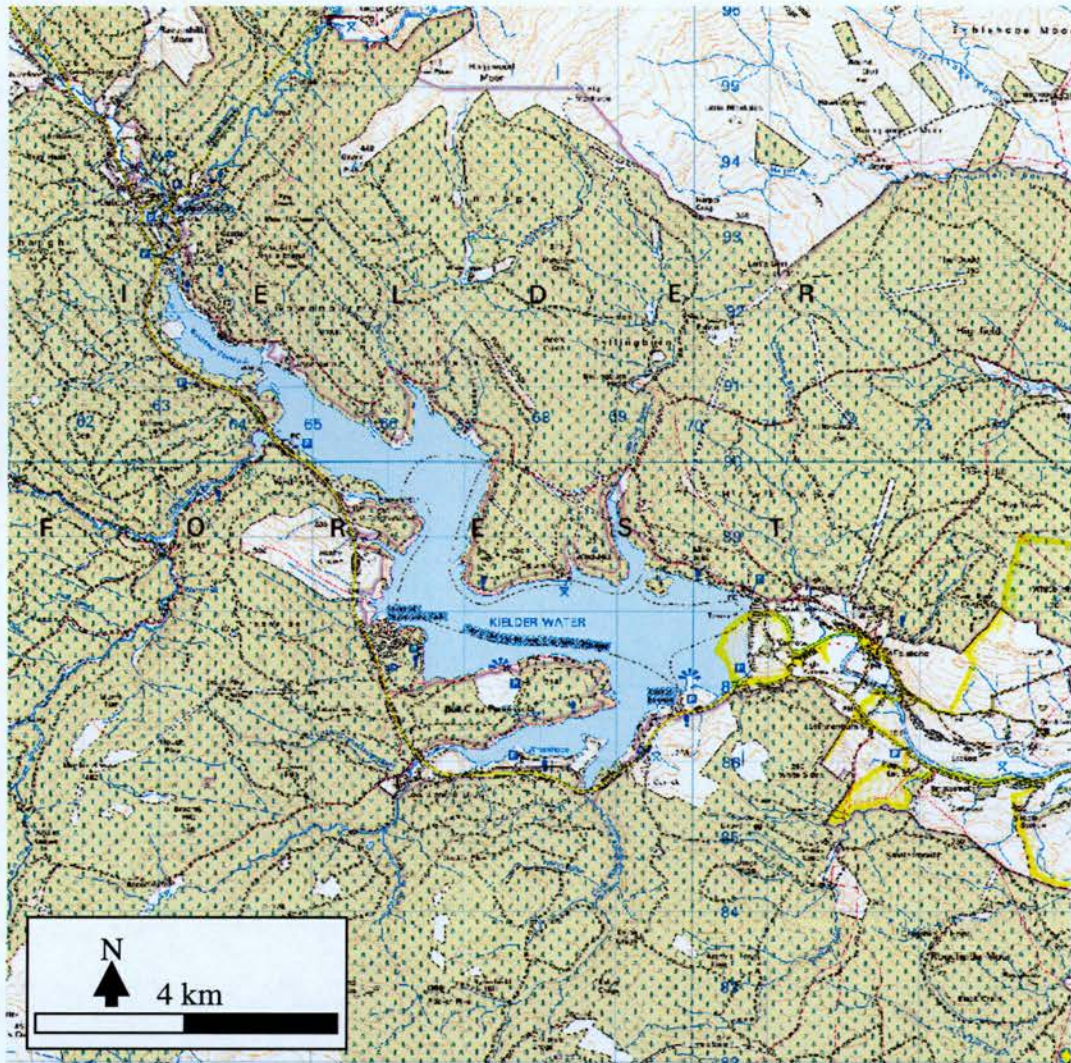


Figure 3.3 Detail of Kielder study site (top) and photos of typical plantation stands (bottom). Map is Crown Copyright Ordnance Survey. An EDINA Digimap/JISC supplied service.



Figure 3.4 Detail of Glen Affric study site (top) and photos of typical semi-natural Scots pine stand (bottom). Map is Crown Copyright Ordnance Survey. An EDINA Digimap/JISC supplied service.

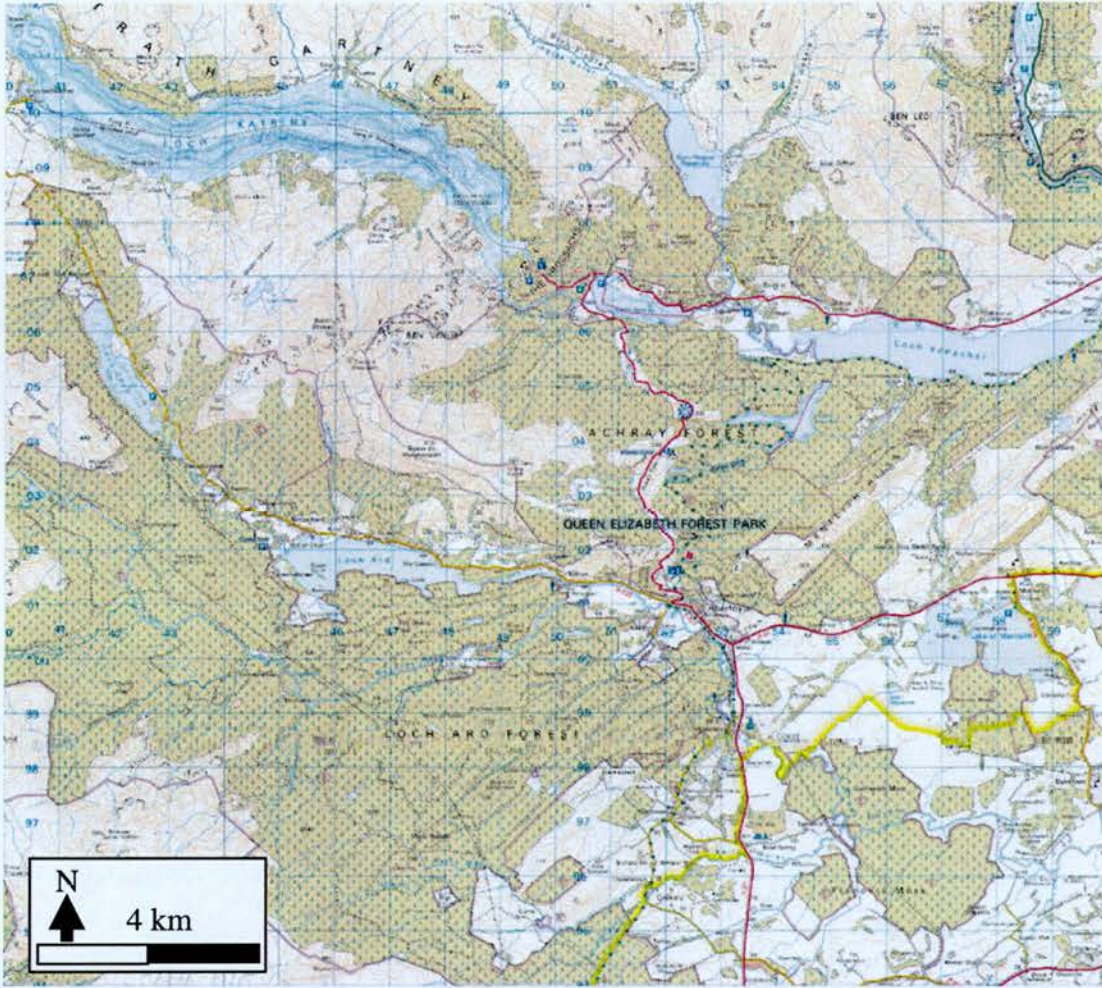


Figure 3.5 Detail of Aberfoyle study site. Crown Copyright Ordnance Survey. An EDINA Digimap/JISC supplied service.

3.2.5 Rio Bravo Conservation Management Area

The Rio Bravo Conservation Management Area (RBCMA) is situated in north west Belize ($17^{\circ} 36'N$, $88^{\circ} 39'W$; figure 3.6), to the northwest of Belize City. The RBCMA has been owned and managed by the non-profit organisation, Programme for Belize (PFB) since 1989 (PFB, 2005). The area, which constitutes approximately 4% of Belize's land cover, contains a wide range of vegetation types including savannas, tropical forests and wetlands (Wallington *et al.*, 2005). The particular study site under investigation in this study consists of the Rancho Dolores savanna to the southeast of the Hillbank research station. This area is characteristic of woody

savanna, and is composed of a range of vegetation types, including grassland, scrub grassland, palmetto (*Acoelorrhaphes wrightii*) and pine ridges dominated by Caribbean pine (*Pinus caribaea*), but also including Olive oak (*Quercus oleoides*). This study concentrates on height retrieval of the Caribbean pine only. The Caribbean pine resembles the Scots pine found in Glen Affric, and has a characteristically similar structure with a heterogeneous mixture of mature trees with open crowns interspersed with younger trees (figure 3.6 bottom); therefore these two study sites are complimentary for studying height retrieval in heterogeneous environments. The national elevation data for Belize is at a too low resolution for this study, and an intensive field survey had to be undertaken (section 3.4.3).

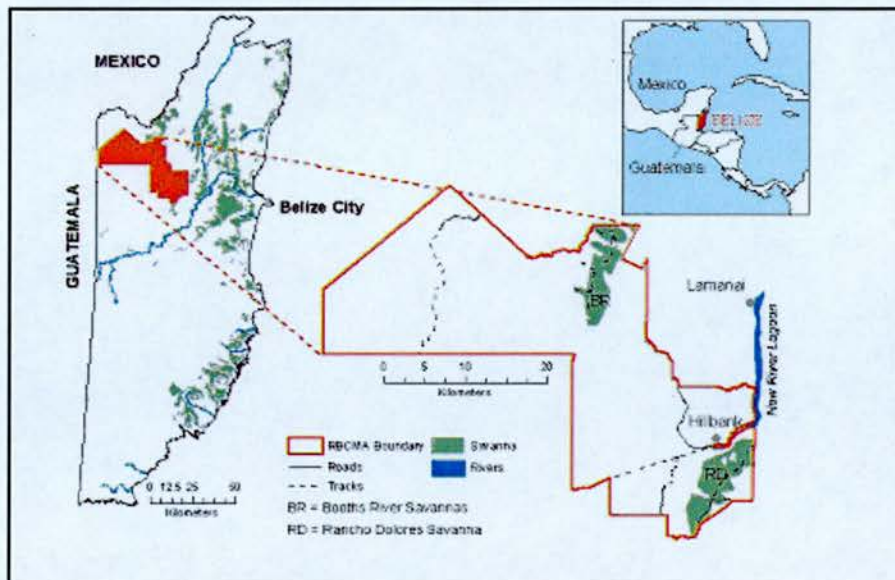


Figure 3.6 Location of RBCMA, Belize (top) and photos of pine ridge. (Map: Cameron, 2004, cited in Wallington *et al.*, 2005; used with permission).

3.3 InSAR Data Sets

This study utilises interferometric SAR data from two single-pass airborne systems: Intermap Technologies STAR-3i is used in the UK (section 3.3.1). In Belize, data from a pre-upgrade of the current STAR-3i sensor is used (section 3.3.2), as well as data from JPL AIRSAR (section 3.3.3).

3.3.1 Intermap STAR-3i

Intermap Technologies (Intermap, 2005) is a Canadian based company which commercially operates the STAR-3i sensor onboard a Learjet platform (figure 3.7; table 3.2). The STAR-3i sensor is a single-pass SAR interferometer which operates at X-band (3cm) wavelength (Li and Baker, 2003; Mercer, 2004a). Intermap recently completed NEXTmap Britain (MacKay, 2002; Coleman and Mercer, 2002), a mapping campaign funded jointly with Norwich Union Insurance, which provided complete elevation data coverage of the UK at high resolution (table 3.2). England, Wales and southern Scotland were flown during January-May 2002, with the rest of Scotland and the islands flown in October 2003 (Bonham, 2004). Three InSAR data sets were supplied by Intermap Technologies (Intermap, 2005), namely an ORRI, DSM and DTM. The products were all geo-referenced to OSGB36 prior to delivery.



Figure 3.7 Intermap STAR-3i sensor mounted on Learjet platform.

Table 3.2 Intermap STAR-3i X-band sensor and data characteristics.

Intermap X-band characteristics	
Platform	Learjet 36A
Sensor	STAR-3i
Wavelength	X-band, ~3cm, 9.5Ghz
Polarisation	HH
Flying Height	8500m
Speed	700km/hr
Baseline	0.9m
Depression angle	35°-55°, centred on 45°.
Acquisition Date	01-05/2002 and 10/2003
ORRI posting	1.25m
DSM/DTM posting	5m
Horizontal RMSE	2m
Vertical RMSE	0.5-1m (95%: 1-2m)
Projection	OSGB36
Datum	OSGM91 (Geoid model)

3.3.1.1 ORRI

The Orthorectified Radar Image (ORRI) is a grey scale intensity image, which shows the amount of backscatter received from the target (figure 3.8). A sub-set of the ORRI is shown in figure 3.9. The shadow evident in the image is radar shadow in areas that are not within the line of sight of the instrument – radar shadow results in little or no return signal, and hence are areas void of data. Brighter areas, primarily at the front edge of stands facing the sensor, with high intensity backscatter, are predominantly attributed to double-bounce returns due to interactions with the ground and tree stems at the edge of the stand. Other bright returns are due to a steep slopes facing the sensor resulting in a high backscatter. The ORRI has a pixel size of 1.25m and an estimated horizontal RMSE of 2m (under test conditions in which corner reflectors were deployed in flat, unobstructed areas) (Intermap, 2004).

3.3.1.2 DSM

The Digital Surface Model (DSM) is produced from the first return of the signal, this represents the first surface the signal came into contact with, be it the ground or vegetation canopy. The DSM (Figure 3.10) has a pixel size of 5m and a vertical RMSE of between 0.5 – 1.0m (95% = 1.0 - 2.0m) dependent on flying height. The DSM corresponds to the first response from the terrain. For X-band microwaves, this equates to the “near top” of the canopy. These accuracies are quoted for moderately sloped (<20°), unobstructed terrain (Intermap, 2004).

3.3.1.3 DTM

The Digital Terrain Model (DTM) is an interpolated surface produced from the DSM (Wang *et al.*, 2001), and as such is a ‘bald Earth’ ground surface model.

Interpolation is used to infill areas where the bare ground cannot be seen, for example in built up and vegetated areas. The DTM (Figure 3.11) has a pixel size of 5m and a RMSE of between 0.7 – 1.0m (95% = 1.5 - 2.0m) dependent on flying height. These accuracies are quoted for moderately sloped ($<20^\circ$), unobstructed terrain (Intermap, 2004).

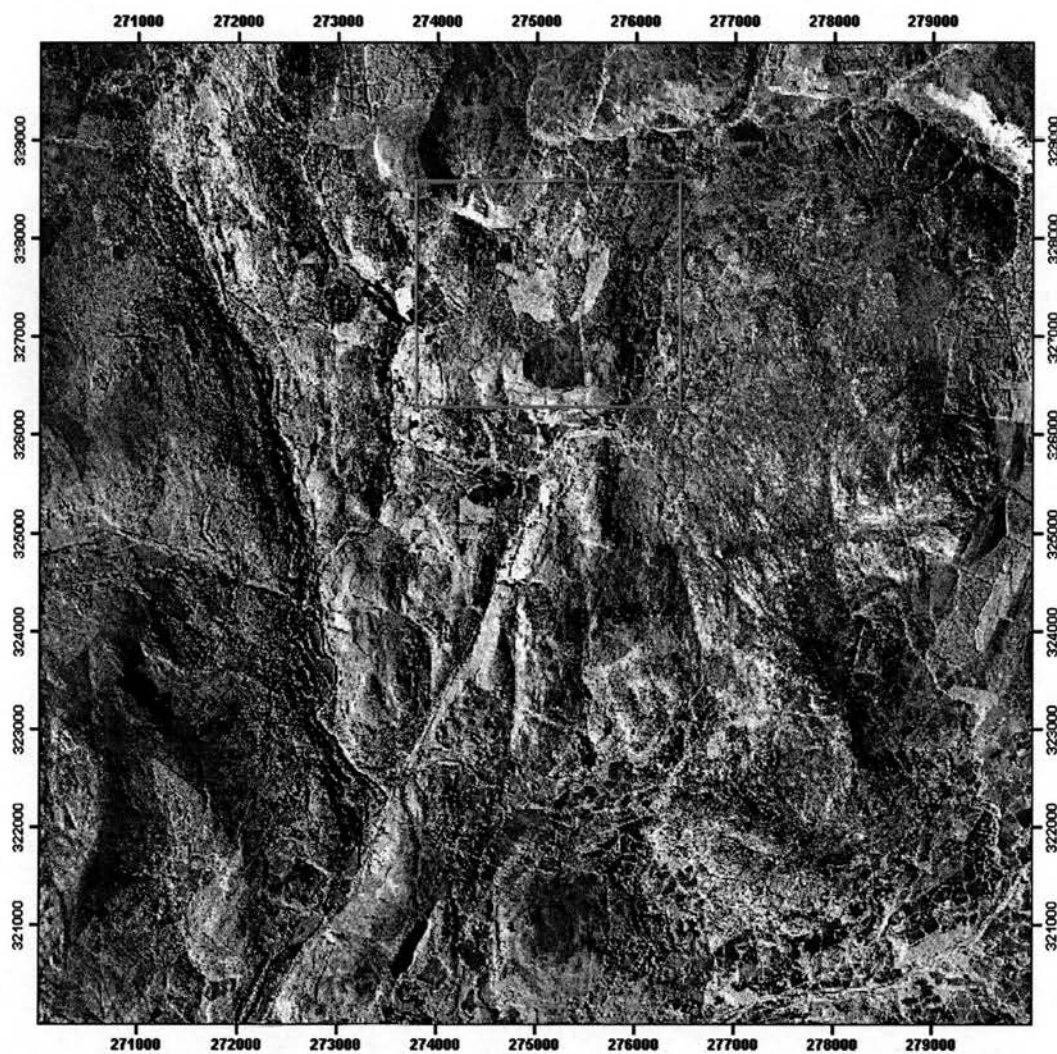


Figure 3.8 Orthorectified Radar Image (ORRI), Coed y Brenin. Dark areas represent low backscatter, bright areas represent high backscatter. Red box indicates area of sub-sample in figure 3.9. Coordinates are Ordnance Survey National Grid coordinates.



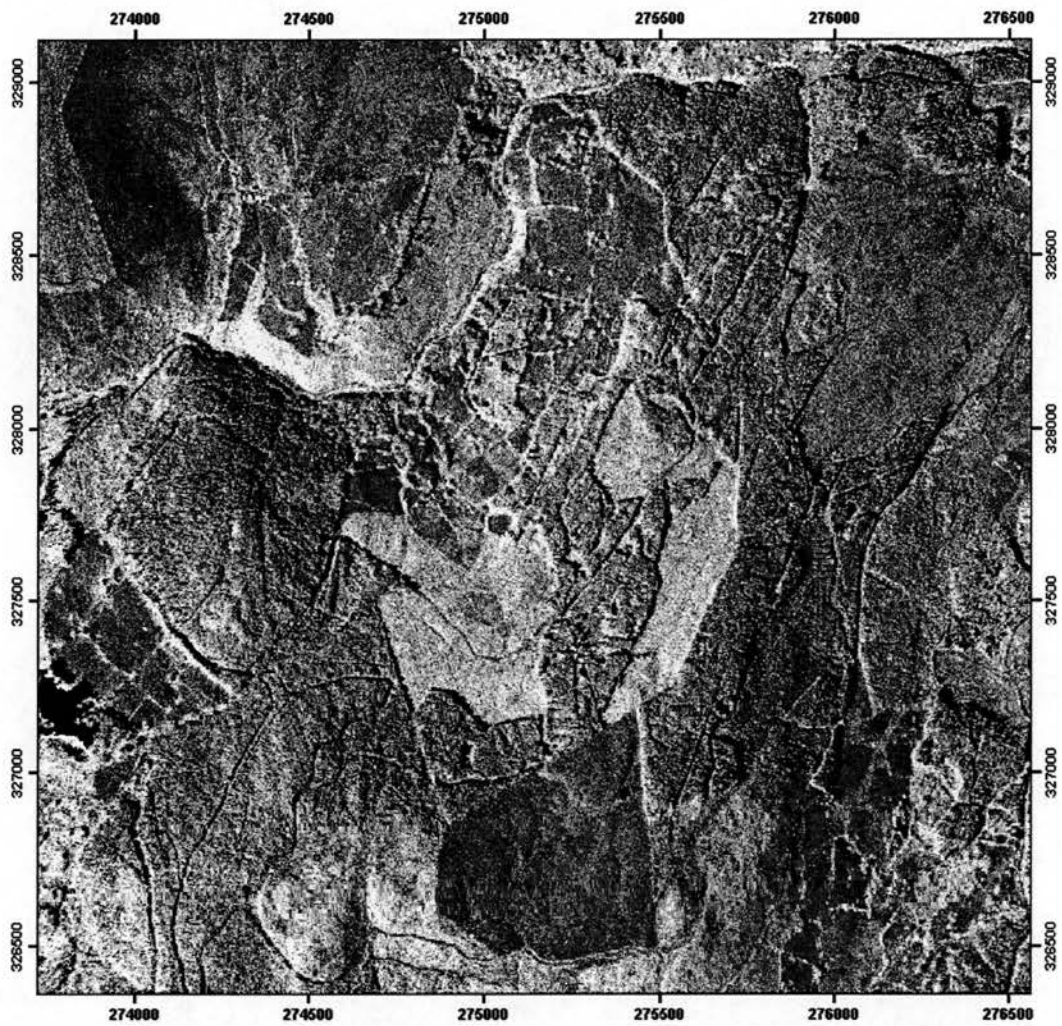


Figure 3.9 ORRI sub-sample, Coed y Brenin. Refer to figure 3.8 for area of sub-sample. Coordinates are Ordnance Survey National Grid coordinates.

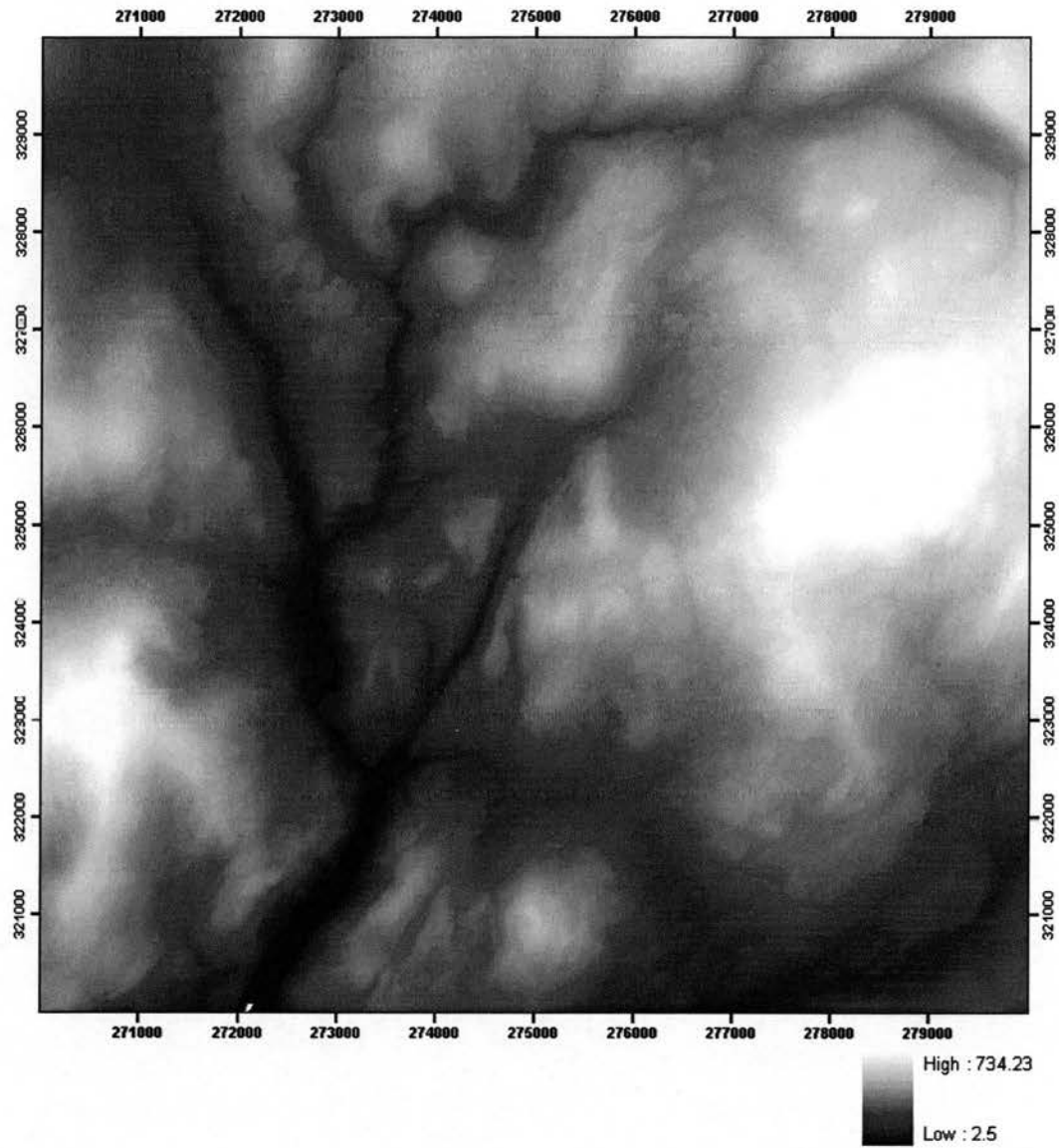


Figure 3.10 Digital Surface Model (DSM), Coed y Brenin. Coordinates are Ordnance Survey National Grid coordinates.

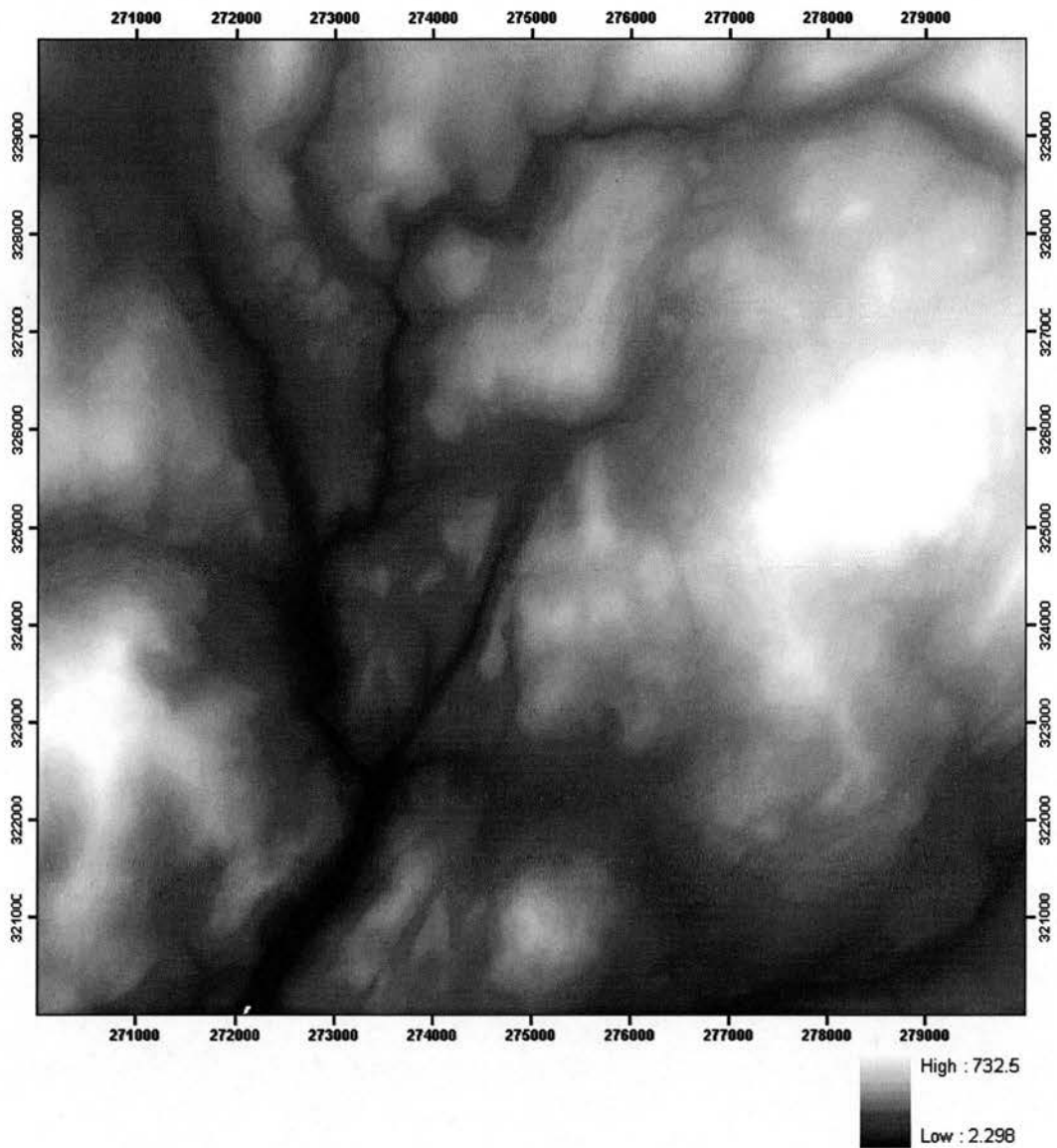


Figure 3.11 Digital Terrain Model (DTM), Coed y Brenin. Coordinates are Ordnance Survey National Grid coordinates.

3.3.2 Intermap STAR-3i – pre-upgrade

Products from the pre-upgraded STAR-3i sensor were used in Belize (upgrade occurred in 2001). This data was captured during the dry season in March-April 1999, and is the only time to date that Intermap has flown data collection in Belize. The data is essentially the same as described above, the only difference being the

ORRI resolution, and the horizontal and vertical accuracies, which are slightly reduced than the current sensor (table 3.3). An ORRI and a DSM were supplied, geo-referenced to WGS84 prior to delivery.

Table 3.3 Pre-upgrade Intermap STAR-3i X-band sensor and data characteristics.

Pre-upgrade Intermap X-band characteristics	
Platform	Learjet 36A
Sensor	STAR-3i
Wavelength	X-band, ~3cm, 9.5Ghz
Polarisation	HH
Flying Height	9144m
Speed	700km/hr
Baseline	0.9m
Depression angle	35°-55°, centred on 45°.
Acquisition Date	26/03/1999–05/04/1999
ORRI posting	2.5m
DSM/DTM posting	5m
Horizontal RMSE	2.5m
Vertical RMSE	3m
Projection	UTM/WGS84
Datum	EGM96(geoidal)

3.3.3 JPL AIRSAR

The Jet Propulsion Laboratories (JPL; NASA JPL, 2005) operates the TOPSAR sensor onboard a DC-8 platform as a research sensor (figure 3.12; table 3.4). The TOPSAR sensor is a single-pass SAR interferometer which operates at C-band (5.7cm) wavelength. Two InSAR data sets were supplied by JPL, namely an ORRI and a DSM, which were geo-referenced to WGS84 prior to delivery. The JPL AIRSAR also operates at L- and P-band frequencies, but these data sets are not interferometric, and so are not considered in this study.



Figure 3.12 JPL AIRSAR

Table 3.4 JPL AIRSAR C-band sensor and data characteristics.

AIRSAR C-band characteristics	
Platform	NASA DC-8
Sensor	TOPSAR
Wavelength	C-band, ~5.7cm, 5.3Ghz
Polarisation	VV
Flying Height	8182m
Speed	700km/hr
Baseline	1.93m
Depression angle	0-70°, typically 40°.
Acquisition Date	07/03/2004
ORRI posting	5m
DSM/DTM posting	5m
Horizontal RMSE	1m
Vertical RMSE	1-5m
Projection	UTM/WGS84
Datum	EGM96(geoidal)

3.4 Supporting reference material

3.4.1 Ordnance Survey DEM

The Ordnance Survey (OS) 1:10,000 Profile 10m Digital Elevation Model (OSDEM; figure 3.13) was used as a ground reference surface (OS, 2001). The product was supplied geo-referenced to OSGB36 through the EDINA Digimap service (Edina, 2005). The OSDEM has a pixel size of 10m (re-sampled to 5m to match DSM; this was purely to ease comparison and not an attempt to improve resolution). This DEM is assumed to be a representation of the true ground surface for the purposes of this

study. The OSDEM has an overall quoted accuracy of +/- 5m (OS, 2001) but is expected to be significantly better over small areas (see chapter 4).

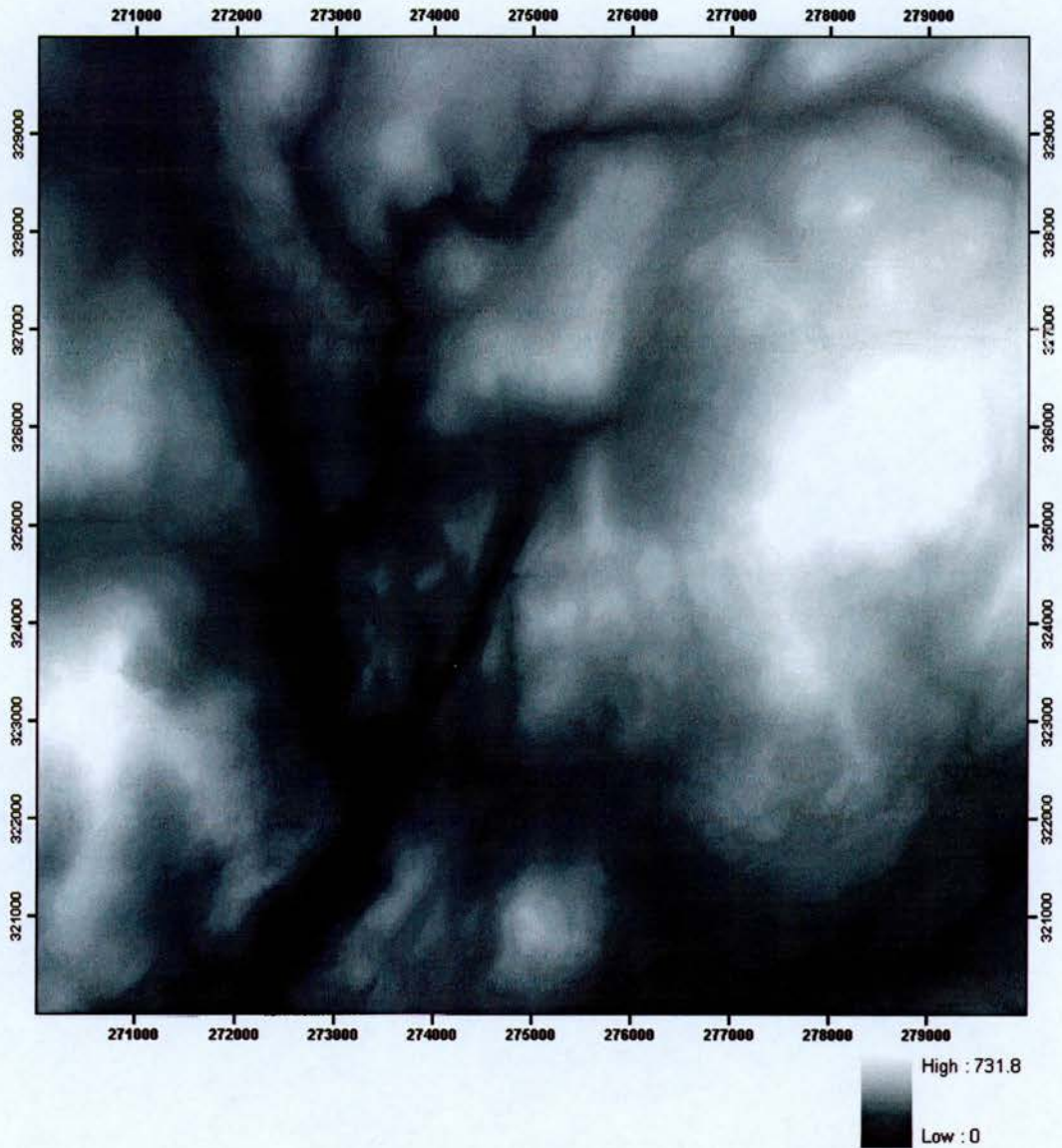


Figure 3.13 Ordnance Survey DEM (OSDEM), Coed y Brenin. Coordinates are Ordnance Survey National Grid coordinates.

3.4.2 Forestry Commission Sub-Compartment Database

The Forestry Commission Sub-Compartment Database (SCDB) was supplied by Forest Research (figure 3.14). This contains stand boundaries geo-referenced to OSGB36, and associated information about each compartment, such as species, planting year and compartment area, amongst others. Stand boundaries were used for visual assessment purposes (chapters 4, 5, and 6), as well as for locating stands for fieldwork and associated height retrieval.

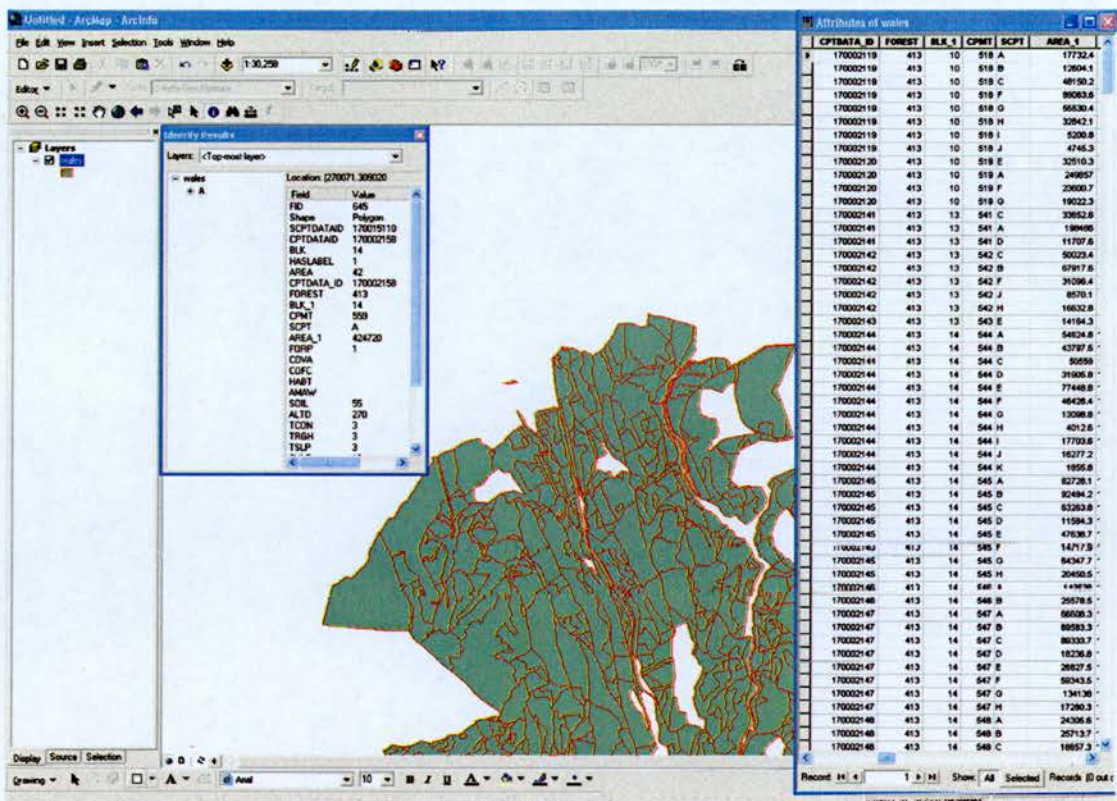


Figure 3.14 Example of Forestry Commission SCDB, Coed y Brenin.

3.4.3 Field data collection

Field data was collected in homogenous stands in the UK (section 3.4.3.1), and within heterogeneous stands within the UK (section 3.4.3.2) and Belize (section 3.4.3.3).

3.4.3.1 UK stand top height

Traditional forest inventory techniques (Philip, 1994; Husch *et al.*, 2003; Hamilton, 1998; Hart, 1998; Methley, J., 2001a; Methley, J., 2001b; West, 2004) were used to establish the top height of the 64 sample stands (see Appendix A). A single 50m x 50m plot was located within each stand, and individual tree total heights (see Appendix A) were measured using a Haglof Vertex digital hypsometer (Haglof, 2005), these heights were then used to estimate the top height of the stand (see section 3.5.2). Other stand parameters of interest were also measured including, diameter at breast height (DBH) and height to first live whorl (indicative of the height to the base of the crown); and density was inferred by counting the number of trees per plot and multiplying up to a hectare (ha^{-1}). A summary of the measured stand statistics is shown in table 3.5. The 50m x 50m plots were located in a stand by means of a handheld GPS. Precise coordinates of the plot were not required, as locating a plot within the relevant stand was all that was required. As such, a handheld WAAS enabled GPS was used to fix the location of the plot. It was found that the handheld GPS could acquire a satellite fix under a forest canopy, whereas a survey grade GPS receiver could not. Locating a plot within a stand without precise plot coordinates can be justified. Enough details of the plot were recorded to be able to find the plot again if required (corner coordinates, size of plot, and bearing of plot

sides). The technique of plot based sampling replicated that carried out in a traditional forest inventory (e.g. Philip, 1994). There was also no intention to retrieve InSAR tree heights at the exact location of the plot, as the plot may have been located in an area of radar edge effect (see chapter 7). All that was required was a measure of the stand top height for comparison to radar retrieved top height. Further, some stand data for Coed y Brenin which was supplied by the Forestry Commission (Snape, 2003) only contained the stand top height information, and no plot locations. Extra ground data for Kielder was supplied by Danny Donoghue and Pete Watt (Durham University; Donoghue and Watt, 2004) in the form of individual tree measurements for a number of plots; these were converted to stand top height using the same methodology described in section 3.5.2. Similar data was provided for Kielder and Aberfoyle by Juan Suárez (Forest Research; Suárez, 2004), and again top height was estimate using the method described in section 3.5.2.

Table 3.5 Summary of measured stands.

Site	Compartment number	Species*	Age (Years)	Density (stems/ha ⁻¹)	Measured top height (m)
Coed y Brenin	586L	JL	53	1270	29.00
Coed y Brenin	641H	SP	75	90	43.00
Coed y Brenin	641A	DF	75	97	46.00
Coed y Brenin	544C	SS	54	133	32.00
Coed y Brenin	640F	JL	61	118	32.00
Coed y Brenin	586M	SS	65	900	23.00
Coed y Brenin	589F	SP	55	813	17.00
Coed y Brenin	637A	NS	36	764	24.00
Coed y Brenin	640E	SS	51	213	32.00
Coed y Brenin	558A	mix	49	1050	24.00
Coed y Brenin	637K	NS	43	800	22.00
Coed y Brenin	593B	NS	55	750	24.00
Coed y Brenin	621F	WH	39	925	28.00
Coed y Brenin	586H	SS	53	1510	29.00
Coed y Brenin	593G	SS	55	1100	20.00
Coed y Brenin	621B	SS	39	1670	26.00
Coed y Brenin	622A	SS	17	2034	9.00
Coed y Brenin	593E	SS	70	108	34.00
Coed y Brenin	600C	SS	37	1050	22.00
Coed y Brenin	601I	SS	39	1530	26.00
Coed y Brenin	623C	NS	49	942	26.00

Coed y Brenin	629C	SS	49	538	31.00
Coed y Brenin	545H	JL	53	115	27.00
Kielder	3405D	SS	34	2052	21.35
Kielder	3406F	SS	34	2064	20.33
Kielder	1026A	SS	60	1168	28.15
Kielder	3626A	SS	61	1816	24.96
Kielder	3603E	SS	49	2060	21.67
Kielder	3617A	SS	33	1900	18.93
Kielder	3642A	SS	57	1468	28.80
Kielder	3412A	SS	50	2736	20.83
Kielder	1024C	SS	60	952	32.82
Kielder	3452A	SS	11	2575	6.30
Kielder	3636G	SS	8	2575	4.23
Glen Affric	2306D	SP	42	1280	17.07
Glen Affric	2306D	SP	42	2176	16.32
Glen Affric	2322B	LP	41	2048	18.38
Glen Affric	2322B	LP	41	2048	18.52
Glen Affric	2324A	SP	153	384	25.23
Glen Affric	2321C	SP	41	1632	16.08
Glen Affric	2321B	LP	41	2368	17.20
Glen Affric	2321A	SP	41	2752	17.63
Glen Affric	2310E	SP	45	1024	18.82
Glen Affric	2312B	SP	42	1952	18.72
Glen Affric	2313B	SP	41	2304	19.78
Glen Affric	2105C	LP	41	2048	17.28
Glen Affric	2105A	LP	41	1472	17.82
Glen Affric	2106A	LP	32	1792	19.67
Glen Affric	2103A	SP	36	1408	19.75
Glen Affric	2324C	SP	39	2176	15.02
Glen Affric	2324C	SP	39	1856	12.75
Glen Affric	2323E	SP	38	1592	10.67
Glen Affric	2323D	LP	42	792	15.60
Glen Affric	2322B	LP	41	2720	17.68
Glen Affric	2322A	SP	42	1984	16.50
Glen Affric	2322A	SP	42	2368	15.87
Glen Affric	2313B	SP	41	2176	16.60
Glen Affric	2320A	SP	41	2080	17.42
Glen Affric	2322A	SP	42	1984	14.07
Aberfoyle	2219A	SS	34	580	27.18
Aberfoyle	2219B	SS	32	1028	22.61
Aberfoyle	2184E	SS	33	1256	21.68
Aberfoyle	2251H	SS	34	516	22.02

* SS = Sitka spruce, LP = Lodgepole pine, SP = Scots pine, JL = Japanese larch, NS = Norway spruce, WH = Western hemlock, DF = Douglas Fir, Mix = mixture.

3.4.3.2 *Glen Affric heterogeneous stand tree heights*

One sample stand was chosen in Glen Affric to represent a semi-natural heterogeneous stand. A traditional ground survey (e.g. Philip, 2004 and Smith, 1986) was performed using a Trimble 5600 total station to measure 395 trees within

the test stand. The survey was tied into GPS coordinates which were measured using a Trimble 4000 survey grade GPS receiver. Measurements of each individual tree consisted of the x, y, z location of the tree stem, the total height of the tree (see appendix A), dbh, height to first live whorl, and canopy width.

3.4.3.3 Belize heterogeneous transect tree heights

Data collection in Belize consisted of two field seasons. The aims were to firstly create a high resolution DEM of the ground surface, as the national elevation data is at a too low resolution for this study; and secondly to measure tree parameters for comparison with radar image data.

The first field season was carried out in June – July 2004 and consisted of a closed loop traverse. A series of 5 survey stations were established in the field using a Trimble 4000 survey grade GPS receiver, and a traverse between the stations was performed with a total station. All points were observed for six hours to ensure a high degree of accuracy (± 0.1 m). An online GPS differential correction service, AUSPOS (Geoscience Australia, 2005), was used to correct the observed readings into precise ITRF latitude and longitude coordinates. These were then projected into WGS84/UTM coordinates so as to be in the same reference frame as the radar data. A point of detail survey was then performed to measure ground points characteristic and representative of the ground surface. Interpolation of the ground DEM points was performed using Ordinary Kriging with first order trend removal. This method was used following successful comparison of techniques by Cameron (2004). An

indication of the vegetation height of the Caribbean pine ridge was ascertained through a number of 10 m x 10 m plots.

During the second field season (April – May, 2005), work was carried out within a 60m wide, 1000m long transect orientated in the AIRSAR look direction (310°). The orientation was chosen so as to assess the influence of layover on the retrieved heights in future studies. This results in the AIRSAR layover being along the transect, and the STAR-3i layover being across the transect. A linear ground survey network was established using a combination of survey grade GPS and total station instrumentation. Two end point survey stations were created and observed by GPS to accurately determine their location; two additional nodes were also measured for each station to aid network orientation. All points were observed for six hours to ensure a high degree of accuracy. An online GPS differential correction service, AUSPOS (Geoscience Australia, 2005), was used to correct the observed readings into precise ITRF latitude and longitude coordinates. These were then projected into WGS84/UTM coordinates to be in the same reference frame as the radar data. 10 survey stations were established between the two end stations of known coordinates, and a linear transect survey was performed. Horizontal misclosure through the survey network was 0.22m and 0.61 vertical (Hay, 2005). A point of detail (POD) survey was then performed in a 60m wide transect from each of the survey stations to collect x, y, z locations of each of the trees, total height, dbh, first live whorl, and canopy width. The canopy width was only taken for a subset of 40% of the trees due to time constraints in the field. A number of tree species were measured, only results of 563 individual Caribbean pine trees are discussed in this study. To supplement the

x, y, z tree locations, further ground points were collected to ensure a high density of points which could subsequently be used for DEM interpolation. Correction of surveyed point coordinates was performed using Trimble Geomatics Office (TGO) software. Interpolation of the ground DEM points was performed using Ordinary Kriging with first order trend removal. This method was used following successful comparison of techniques by Cameron (2004).

3.4.3.4 Uncertainty of tree height measurements

Measurement of individual tree total height is prone to a number of uncertainties and potential errors. These can be due to user or instrument error (e.g. Methley, J., 2001b; Hamilton, 1998; Philip, 1994). User errors include measuring to the incorrect tree tip, incorrectly identifying a lower branch as the leader, not taking account of a leaning tree or not taking account of excessive tree movement due to strong winds. The effect of these can lead to under- or over-estimation of the height of the tree. Plot based sampling is also reliant on the plot being an assumed representative sample of the stand being measured; this can be achieved by choosing a plot location away from stand edges, where different growing conditions may introduce edge effects, and hence different size and shape of trees than those within the stand. Further errors may also be introduced if the instrument being used is not calibrated correctly. In the case of the Vertex hypsometer, calibration involves the instrument not being used until the internal and external temperature is equal and ensuring that the distance measurement is calibrated regularly based on a known distance.

Traditional field survey techniques are generally expected to achieve accuracies of around 10% (Barron, 2001; Meir, 2005) incorporating both user and instrument error as described above. Given this, the measured individual total heights may be $\pm 10\%$, and this will have an impact on the estimated top height which is calculated from the measured total heights (section 3.5.2). For example, a stand in Glen Affric may have a measured top height of 16.32 m. When applying the $\pm 10\%$ error estimate to the individual tree heights, potential top height measurements are within the range of 14.69 (-10% underestimation) to 17.95 m (+10% overestimation).

3.4.4 Aerial photographs

Aerial photographs were supplied by the Forestry Commission, and were supplied geo-referenced to OSGB36. These were originally supplied to the FC by Bluesky (Bluesky, 2006) in conjunction with GetMapping (GetMapping, 2005) and have a resolution of 0.25 m. The photographs covered all of the Coed y Brenin study area, and subsets of the Kielder study area. An example of the aerial photographs are shown in figure 3.15. The aerial photographs were used to ascertain land cover types for DEM comparison (chapter 4) and for a visual analysis of stand height (chapter 5).

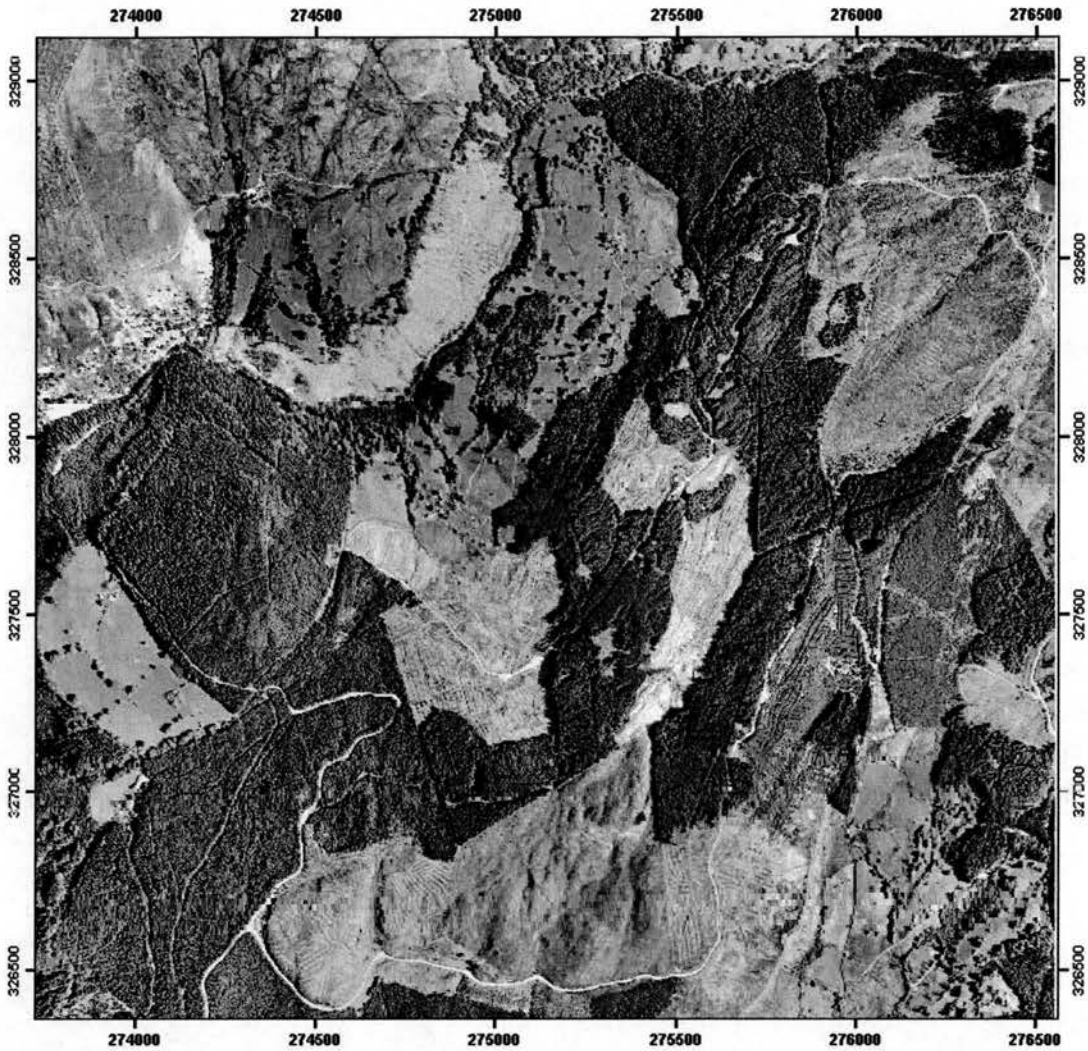


Figure 3.15 Example of aerial photograph used in this study, Coed y Brenin. Coordinates are Ordnance Survey National Grid coordinates.

3.5 Height comparison methodology

3.5.1 DEM comparison procedure

The analysis was performed over six ground cover types (bare, soil, grass, moorland, clearfell, forested), and where available these were duplicated in Coed y Brenin and Kielder. Areas of apparent homogeneous land cover type were chosen through visual analysis of aerial photographs. Reference areas were assigned a size as large as possible within each of the chosen areas, without overlapping a neighbouring land cover type; this resulted in some areas of interest being up to 300 m x 300 m, whilst

others were only 30m x 30m. Pixel values from within the selected areas of interest were extracted from the DTM and OSDEM, and a subtraction procedure performed to retrieve the height difference between the two ground surface datasets (Figure 3.16). To obtain a consistent result, the OSDEM was subtracted from the Star-3i DTM throughout a number of plots (on different cover types), therefore a positive difference value would imply the DTM gives a higher elevation than the OSDEM. For this study, the OSDEM was used as the reference data set, and as such was assumed to represent the true ground elevation. The assessment of the DTM also provided a degree of validation of the OSDEM, whereby differences between the two data sets over open ground would indicate that one or both of the datasets are not a true representation of the ground surface. The assessment carried out in this study is assuming the OSDEM is a true representation, however it may be the case that DTM is a better representation, and that differences are due to the OSDEM. Ideally, further field validation of the OSDEM could have been performed (e.g. by differential GPS check points), and further validation information would have been useful.

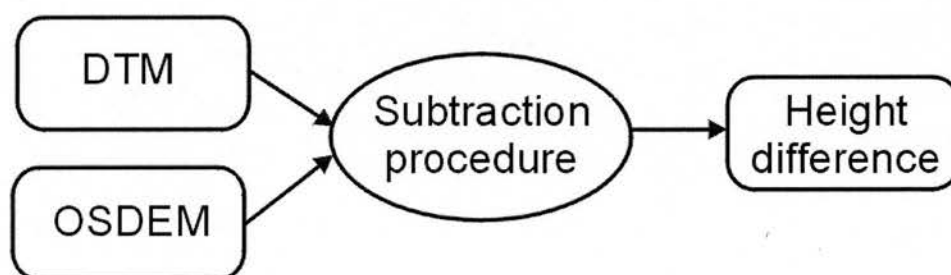


Figure 3.16 Ground surface DEM comparison procedure.

The Root Mean Square Error (RMSE) was used to assess the accuracy of the DTM compared to the OSDEM. RMSE is expressed as:

$$\text{RMSE} = \sqrt{\frac{\sum (d)^2}{n}} \quad (3.1)$$

Where d is the difference between the elevation value obtained from the DTM and the OSDEM (DTM-OSDEM; figure 3.16), and n is the number of points sampled.

The standard deviation (SD) is also used to show the amount of variation (or similarity) within the values, the smaller the SD, the smaller the range in values. SD is defined as:

$$\text{SD} = \sqrt{\frac{\sum (d - d_{\text{mean}})^2}{n}} \quad (3.2)$$

Where d_{mean} is the mean difference between the DTM and OSDEM.

P-values derived from regression analysis are used to provide a measure of the significance of the regression, in which the statistical relationship between two data sets is tested. For example, in this study, P-values provide an indication of the strength of the relationship between the DTM and OSDEM. The strength of relationship highlights the similarities between the OSDEM and DTM by assessing how well the DTM predicts the OSDEM. Significance testing was carried out at the 95% confidence level. As such, P-values less than 0.05 imply a significant relationship, and those below 0.01 indicate a highly significant relationship. For this assessment the hypotheses used were as follows:

H_0 = DTM is not a significant predictor of OSDEM.

H_1 = DTM is a significant predictor of OSDEM.

3.5.2 Homogenous height retrieval procedure

Tree height and stand height can be described in a number of ways. In this study, stand height is expressed as the traditional Top Height (H_{100}) measurement, which is defined as either the average height of the 100 trees/ha with largest diameter at breast height (DBH), or the average height of the 100 tallest trees/ha (Philip, 1994), the latter definition was used in this study:

$$H_{100} = \sum_0^{100} \frac{H_t}{N} \quad (3.3)$$

where H_t is total height and N is the sample size. Similarly, the retrieved top height (H_{r100}) is defined as the average of the highest 100 retrieved heights/ha:

$$H_{r100} = \sum_0^{100} \frac{H_r}{N} \quad (3.4)$$

where H_{r100} is the retrieved top height. Top height is the average of the total heights of the specified number of trees; total height is defined as:

$$\text{Height}_{\text{Tree}} = \text{Height}_{\text{Canopy}} - \text{Height}_{\text{Ground}} \quad (3.5)$$

The specific realisation of equation 3.5 used to retrieve tree height using SAR in this study was achieved by subtracting the DTM or the OSDEM from the DSM (figure 3.17), as defined by:

$$H_{\text{Tree}} = H_{\text{DSM}} - H_{\text{OSDEM}} \quad (3.6)$$

In each of the chosen stands, height values from the DSM, DTM and OSDEM were retrieved from a 50 x 50 m plot; smaller plots were used if the stand was too small to

accommodate a 50 x 50 m. Plots were located away from stand edges (to minimise any edge effects), and in apparent homogenous (locally uniform) areas, without radar shadow, which were evaluated from qualitative assessment of the aerial photographs and radar intensity image. Equation 3.6 was implemented to retrieve the height per pixel within the plot, and equation 3.4 was used to estimate the retrieved top height, H_{r100} . This top height was then compared to the measured top height per plot, H_{100} .

P-values were again used to assess the statistical relationship between the two data sets, providing an indication of the strength of the relationship between the retrieved height and the measured height. The strength of relationship highlights the similarities between the data sets by assessing how well the retrieved heights predict the measured heights. Significance testing was carried out at the 95% confidence level. As such, P-values less than 0.05 imply a significant relationship, and those below 0.01 indicate a highly significant relationship. For this assessment the hypotheses used were as follows:

H_0 = Retrieved height is not a significant predictor of measured height.

H_1 = Retrieved height is a significant predictor of measured height.

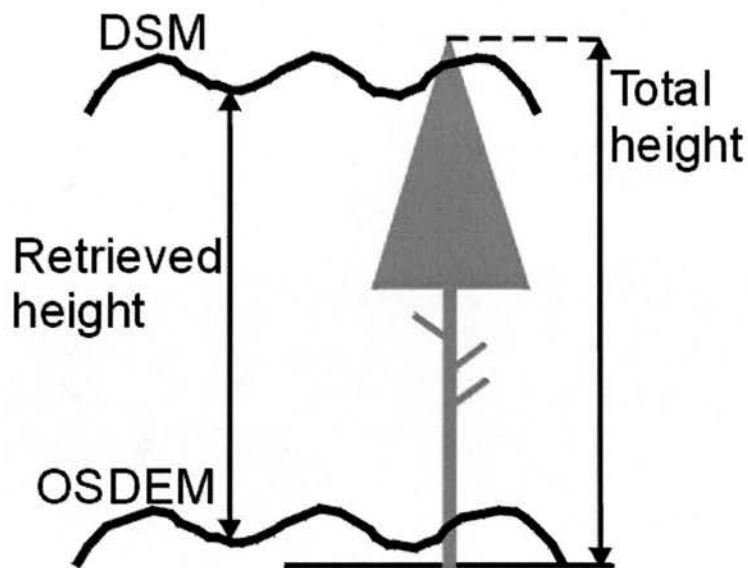


Figure 3.17 DSM-OSDEM procedure to retrieve height.

3.5.3 Heterogeneous height retrieval procedure

Heterogeneous height retrieval followed much the same as described above, the difference being that individual tree total heights were being assessed as opposed to stand top height. Heights of the DSM and DEM (interpolated DEM in Belize or OSDEM in Glen Affric) were extracted for individual tree coordinates measured from field data collection (section 3.4.3). Equation 3.7 was then implemented to retrieve an estimate of the tree height.

$$H_{\text{Tree}} = H_{\text{DSM}} - H_{\text{DEM}} \quad (3.7)$$

The retrieved height was then compared to measured height from field verification, and regression analysis performed to assess the similarities between the measured and retrieved heights by way of P-values as described above.

4 Results of DEM comparison

“Though a tree grow ever so high, the falling leaves return to the ground”

Malayan proverb

4.1 Introduction, aim and objectives

The techniques for tree height retrieval used throughout this work (described in Chapter 3) rely on the use of a digital elevation model (DEM) of the ground to be subtracted from a canopy DEM. For this procedure to be reliable, the ground DEM needs to be an accurate and true representation of the ground surface. As such, the first step towards tree height retrieval was to validate the interferometric digital terrain model (DTM) provided by Intermap. A DTM, or "bald-Earth" model, is a DEM product that simulates true Earth-surface elevations, minus ground features (i.e., trees, buildings, etc.) (NOAA, 2005; Li *et al.*, 2005). This chapter discusses the results of comparisons between the two DEM products, and the implications of the findings on the overall study aim of tree height estimation.

The specific aim of this chapter is to assess the accuracy of the Intermap Digital Terrain Model (DTM). This will be achieved by comparison to the Ordnance Survey DEM. The objectives to meet the aim are (i) to briefly review previous assessments of the accuracy of Intermap products, (ii) to assess the DTM accuracy over non-vegetated ground, (iii) to assess the DTM accuracy under forested land, (iv) to

discuss potential reasons for any differences, and (v) to discuss findings in the context of tree height retrieval.

4.2 Intermap DTM generation

The Intermap DTM is a derived product which is extracted from the Digital Surface Model (DSM; Intermap, 2004; See Section 3.3). Intermap have developed a 'Terrain Fit' algorithm which uses an automated process to sample the DSM for areas perceived to be bare ground, and interpolates between these points to create a 'bald-Earth' model or DTM (Wang *et al.*, 2001). Intermap then perform manual editing of the derived DTM is then performed to reduce and remove potential errors in the product.

4.3 Previous DEM accuracy assessment

Intermap's Star-3i sensor is a relatively new instrument, which first began collecting data in 1997, with the current upgraded sensor collecting data since 2002 (Tennant *et al.*, 2003). As such, only a number of studies have assessed the claimed accuracy of the Star-3i products, with a number of the assessments being evaluated on data collected prior to the upgrade. The majority of assessments have been performed internally within Intermap, with a handful of independent assessments. As far as this author is aware, and as demonstrated by the lack of publications, there has been little, if any, use of these products for deriving tree height estimations. It should be noted that stated accuracies have altered since the upgrade in 2002, and as such the accuracies have been improved. The following sections provide a summary of horizontal and vertical accuracy assessments for both pre- and post-upgrade.

4.3.1 Horizontal accuracy

The horizontal accuracy of the Intermap DEM products is inferred by assessing the horizontal accuracy of the corresponding orthorectified radar image (ORRI). Tighe (2003) summarises three independent assessments of the horizontal accuracy after the sensor upgrade. When compared to an aerial photo generated DEM the mean XY RMSE was 1.2m; compared to GPS points gave 1.8m RMSE and with Ordnance Survey Landline data a RMSE of 1.5m was achieved. All of these fall within the stated post-upgrade accuracy of 2m (Intermap, 2004). Further studies of post-upgrade accuracy also found similar results.

For reference, also included here are some examples of accuracy studies performed on data collected before the sensor upgrade. The horizontal accuracy of the orthorectified radar image (ORRI) was assessed by Li *et al.* (2001) using photogrammetrically derived checkpoints. This was prior to the recent upgrade and found the overall accuracy to be 2.7m RMSE, with a RMSE of 1.7m in X and 2.1m in Y, concluding there to be no obvious difference between easting and northing directions. Similarly Birk and Bullock (1999) assessed the horizontal accuracy using differential GPS (DGPS) and found overall RMSE of 1.5m in X and 1.0m in Y.

All the accuracies assessed for horizontal accuracy lie within half a DTM pixel, i.e. 2.5m, with the majority falling within the stated accuracy of 2m. The overall aim of this study is to assess the ability of these DEM products for estimating tree height by averaging over large areas (e.g. 50 x 50m plots, equating to 100 pixels). Given this,

a horizontal accuracy of less than 2m is deemed to be sufficient for the purpose of this study.

4.3.2 Vertical accuracy

An additional consideration for this study is the vertical accuracy of the Intermap DEM products. Prior to the Star-3i system upgrade in 2002 (Tennant *et al.*, 2003), the vertical accuracy of the DSM and the DTM was tested against Lidar over a number of land cover types (before upgrade) (Wang *et al.*, 2001; Mercer, 2001.). These studies found that over bald areas and flat areas, the DSM achieved an accuracy of 0.76m RMSE and the DTM a RMSE of 0.68m. Similar results were found over flat areas where the DSM gave 0.42m RMSE and the DTM 0.60m. However, in areas of moderate mountain conditions (no definition given) the RMSE for the DSM and DTM were 1.28m and 1.33m respectively. Wang *et al.* (2001) mention that a 2m horizontal location error, when coupled with a 45 degree terrain slope, would create a 2m vertical error in the DTM; this is one possible explanation for errors in sloped terrain. When tested in areas of forests, they found a RMSE of 3.16m for the DTM and concluded that this was primarily due to the bald-Earth interpolation procedure not handling these areas appropriately, and that the forest areas were contributing to the error (Mercer, 2001). When the forest was masked out the RMSE was found to be 2.19m (Wang *et al.*, 2001).

Mercer (1998) summarised 4 studies undertaken to assess the vertical accuracy of the DTM (before upgrade). These studies found that over flat bare ground the RMSE was in the order of 1.3-1.5m, while it was 1.7m on slopes (up to $\pm 35^\circ$), and 1.6-2.2m

on mixed terrain (flat and moderately sloped terrain up to 35°). The full range of RMSE was between 0.8-2.2m.

Mercer and Gill (1998) studied the accuracy of the Star-3i DEMs in urban areas with comparison to aerial photo data and laser data. With comparison to the aerial photos, the DTM produced a mean difference of around 0.5m over small areas, with smaller scale differences of around 2m. When compared to the laser data in an area of higher buildings, the DSM accuracy was reduced to around 1.5m, with the differences being interpreted to be primarily due to effects of shadow and layover.

Birk and Bullock (1998) assessed the accuracy over moderate terrain in comparison to photogrammetric data. Without ground control points (GCPs), a RMSE of between 0.8-1.7m was achieved. It was stated that with the use of GCPs the accuracy may be improved to less than 1m RMSE. Similarly, flying at higher altitudes, an accuracy of 2.5m could be achieved without GCPs. With GCPs, the accuracy should be able to be improved to less than 2m RMSE. Li *et al.* (2001) looked at a test site consisting of mixed terrain (road, residential and mountains) with comparison to photogrammetric checkpoints, with results of a mean difference of 0.5m (Intermap higher) and RMSE of 1.2m, and concluded that this difference may be the result of some minor uncompensated systematic effect in the DEM data.

More recent assessments of post-upgrade data have demonstrated an improvement in the vertical accuracy. The Star-3i DTM was assessed in the UK by UCL (Dowman and Fischer, 2003; Fischer and Dowman, 2002; Dowman *et al.*, 2003). It was found

that when comparing the DTM with photogrammetric checkpoints, the RMSE was 0.834m. When compared to aerial photography over a bare field, the RMSE was 0.172m. The DTM was also compared with a Lidar DTM, with a resulting RMSE of 1.013m. Detailed GPS measurements were compared to the DTM measurements, and it was found that over mixed terrain (hilly, flat) along a road a RMSE of 1.67m was obtained. When photogrammetric check points were used on bare earth in open areas, a RMSE of 0.834m was obtained.

Tighe (2003) summarises three assessments (in addition to the study by Dowman *et al.* discussed above) of the vertical accuracy after the sensor upgrade. Studies carried out by the USGS with data with a stated accuracy of 3m over moderate to flat terrain concluded that a RMSE of 1.2m was achieved. A similar study over a different test site concluded that a mean offset of 0.1m was present in the data. The UK Environment Agency reported a RMSE of 0.78m when compared to LiDAR data Tighe (2003).

In summary, the vertical accuracy of the DSM may be as good as 0.5m RMSE over flat, un-vegetated terrain but up to 2m on moderate slopes. Li and Baker (2003) stated that 'it has been found that at 5-m point spacing, 30cm-1m DSM vertical RMSE accuracy and 1-2m DTM vertical RMSE accuracy can be routinely achieved in moderate terrain'. Over vegetated terrain, and in particular, forested areas, the DSM will likely have errors up to many metres, depending on the height and density of the vegetation cover as explored in the current work. The interpolated DTM has

similar results but with improved performance over vegetated areas, assuming the extent of the vegetation is less than about 100m wide.

4.4 Expected sources of error

There are a number of errors inherent to DEM production in general, such as those related to interpolation techniques and DEM representation (e.g. Li *et al.*, 2005), these shall not be discussed in this study. Potential errors and constraints which are specific to SAR created DEMs shall be commented on briefly.

The major limiting factor on interferometric processing is the requirement for high coherence (similarity between images used in interferometry) in order for the phase measurements to have some meaning. The Star-3i system minimises this problem over forests by using a single-pass system so that temporal decorrelation is not an issue. However, low coherence effects may be apparent in the shadow regions at the far edge of forest stands (i.e. next to areas of non-forest).

A limitation on DEM production from SAR is extreme topography. Included in this are all abrupt changes in height of the measured surface, including forest stand edges and steep slopes. Although topographic mapping with SAR can account for much of the geometric distortion in a SAR image it cannot compensate for the extreme geometric distortion known as layover. At low incidence angles (e.g. ERS at 23°), layover caused by topographic variation can account for as much as 50% of the image scene (Caves *et al.*, 1998) in an area such as Speyside. The work of Caves *et al.* was in the context of snow mapping and in this case they suggest that high incidence angles can reduce this loss of coverage down to less than 2%. Similarly, with ERS-SAR, Castel *et al.* (2000) had to reject all data in regions with slopes >15

degrees. However, increased incidence angles can lead to increased shadowing. Shadow is more desirable than layover, as it is clear it is shadow, whereas layover is not always so obvious (Woodhouse, 2004).

4.5 Results of qualitative assessment of Intermap DTM and OSDEM

An initial qualitative analysis was carried out for two purposes. The first was to check the co-registration between the different data sets. The second was to compare the DTM-OSDEM difference with the aerial photographs and orthorectified radar image (ORRI) to see if any obvious correlations existed between differences and ground features. The co-registration assessment was done visually. Absolute registration has been assessed elsewhere (e.g. Fischer and Dowman, 2002; Dowman *et al.*, 2003). No obvious co-registration errors were found and overall the co-registration was found to be more than adequate for the purposes of the study.

A difference image was created between the DTM and OSDEM (Figure 4.1). From a visual interpretation of this image, it was demonstrated that differences between the two data sets were evident. It was also apparent that significant differences were present in certain areas, and that these corresponded with areas of vegetation as observed in the ORRI and aerial photographs (Figure 4.2). The following section quantitatively assesses these differences.

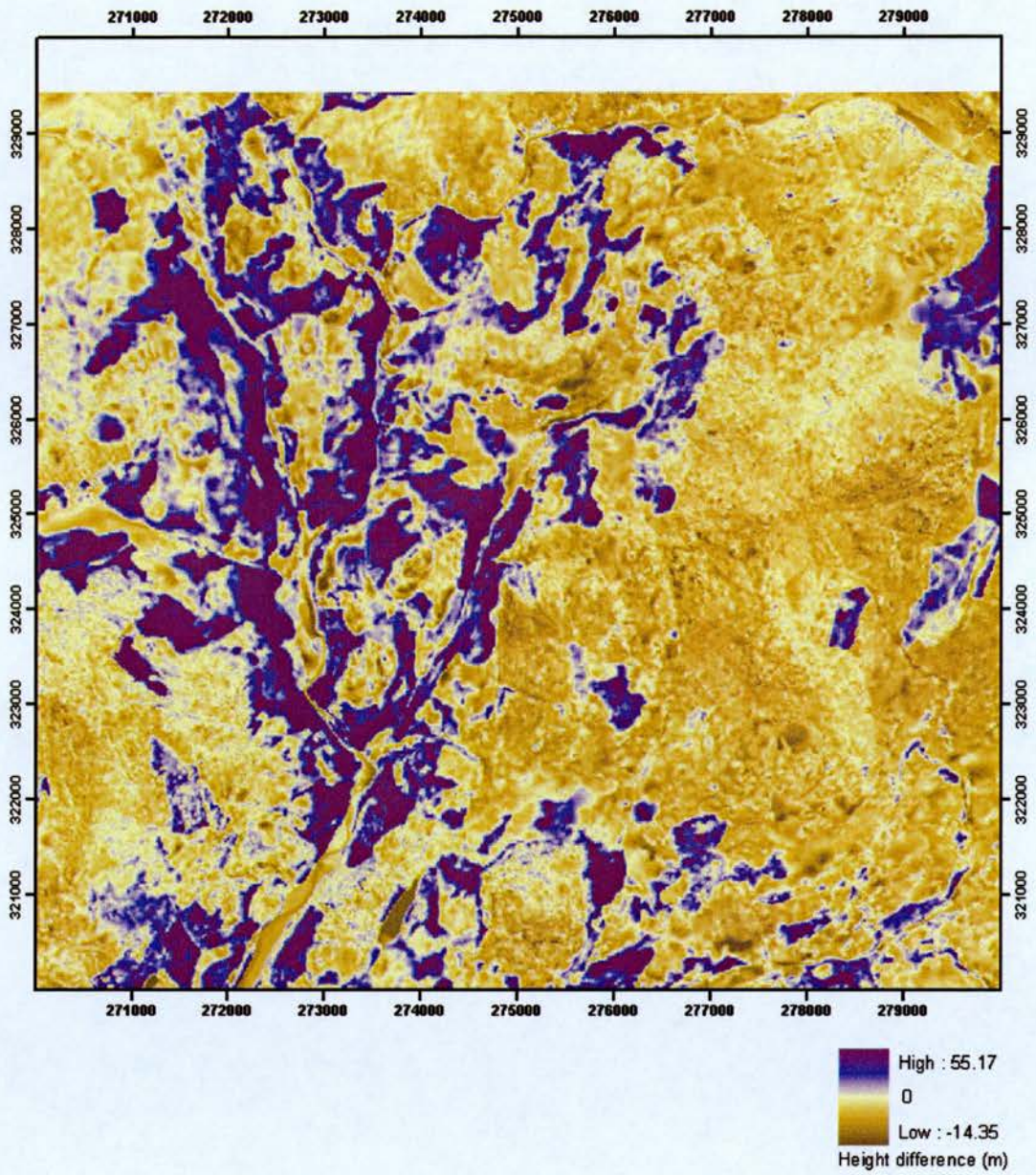


Figure 4.1 Image of differences between DTM and OSDEM. Coordinates are Ordnance Survey National Grid coordinates.

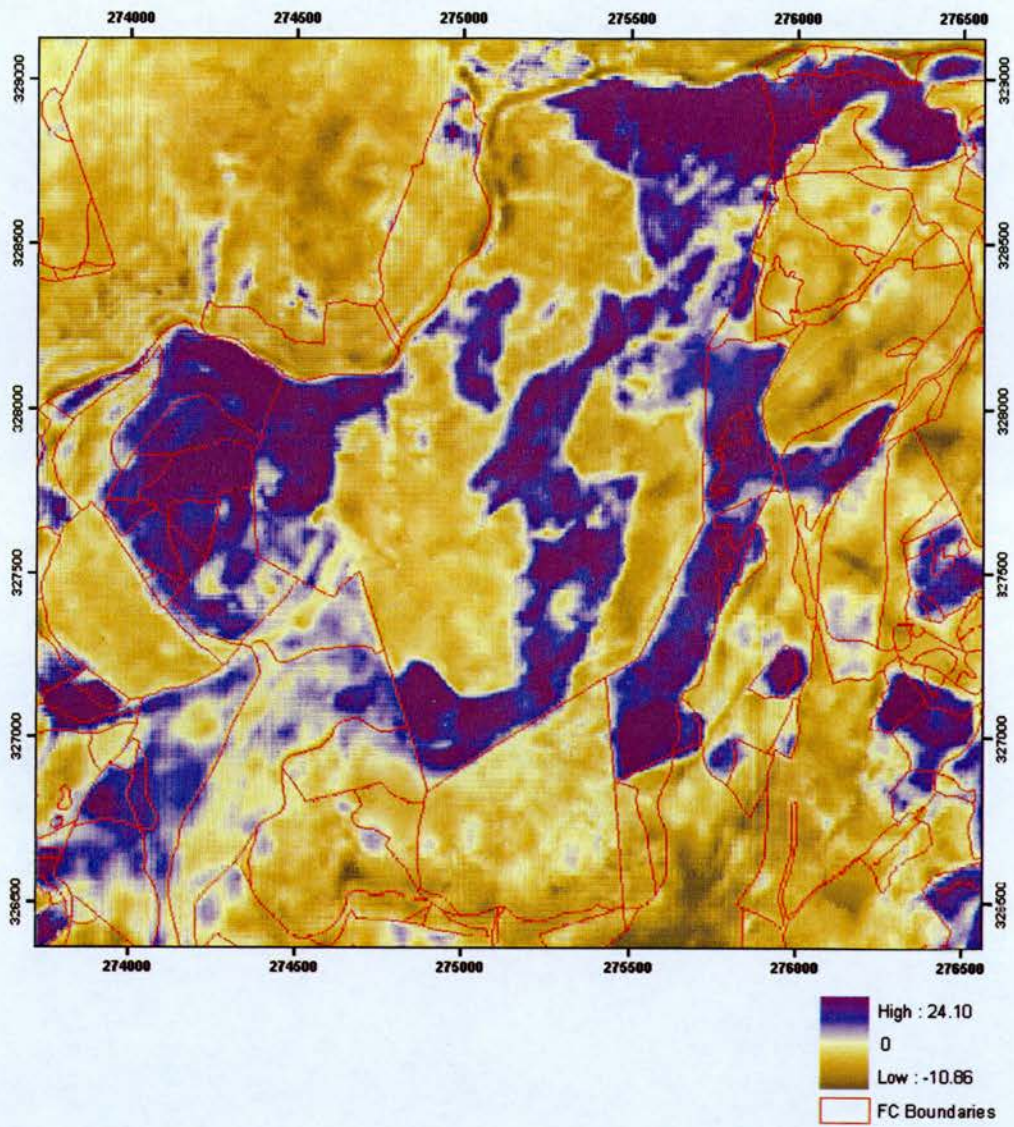


Figure 4.2 Differences correspond to areas of vegetation. Sub-sample of difference image (A, above) and ORRI (B, below). Coordinates are Ordnance Survey National Grid coordinates.

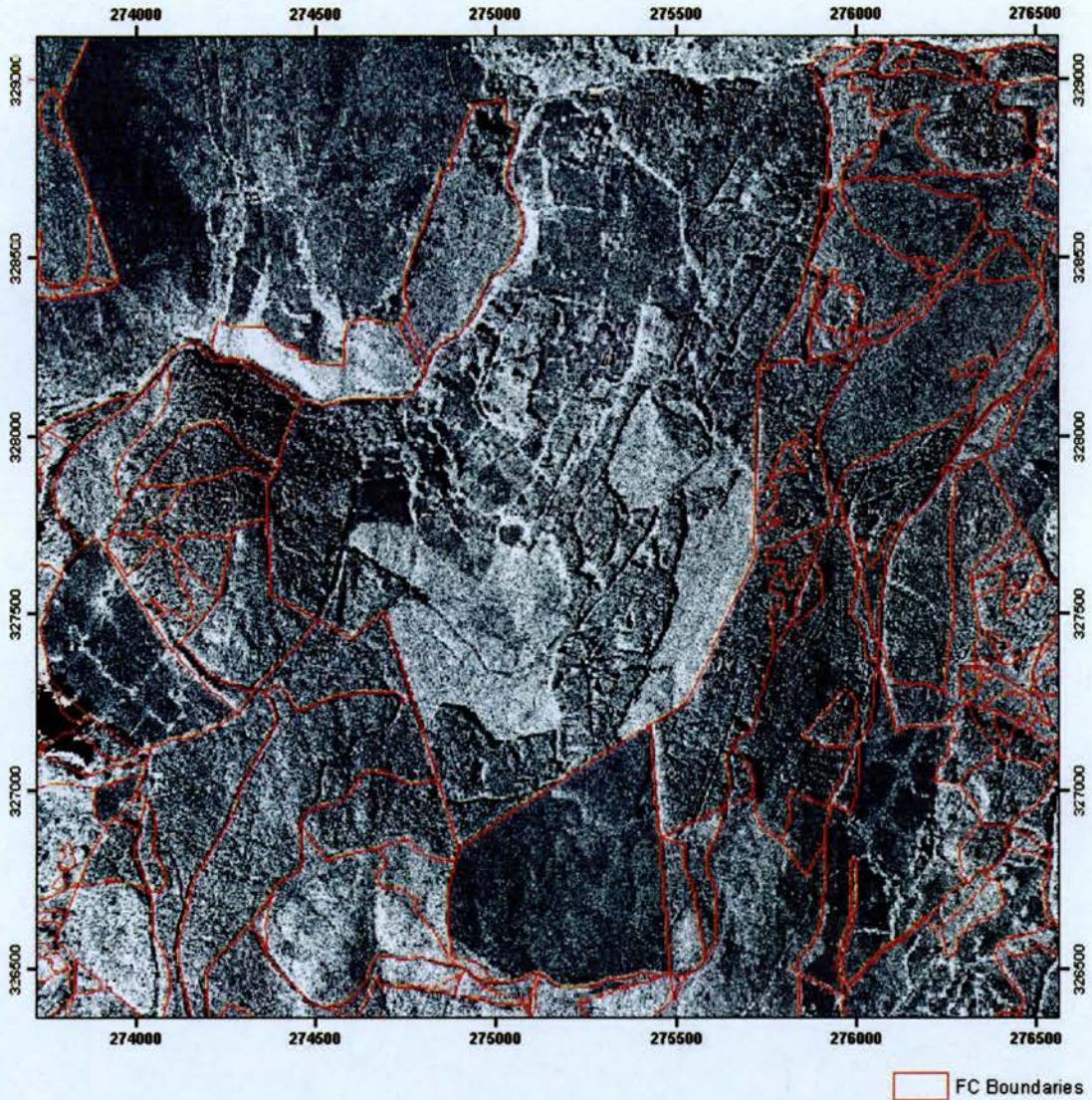


Figure 4.2 (B). Coordinates are Ordnance Survey National Grid coordinates.

4.6 Results of quantitative assessment of Intermap DTM and OSDEM

A comparison of the DTM produced by Intermap with the Ordnance Survey DEM (OSDEM) was carried out (See chapter 3). The primary purpose of this comparison was to check consistency between the two ground elevation models. The Intermap DTM has been validated against GPS and Lidar measurements in other studies and has been found to be accurate to within 1.013 m RMSE (Fischer and Dowman, 2002). The main concern here, however, was the potential of using the DTM or the

OS data as a reference ground surface in order to subtract it from the Intermap DSM, and so it was necessary to have confidence in the consistency between the two ground DEMs. As has been discussed, previous studies have validated the DTM over bare (non-vegetated) terrain, however these studies were undertaken in areas away from large forest tracts, and as such independent validation was required for this study. Further, little assessment to date has been carried out on the accuracy under forest cover; this assessment was critical in the current study as the ground surface DEM products are to be used for height retrieval.

4.6.1 Non-vegetated ground

Results for Coed Y Brenin are summarised in table 4.1 by cover type. Overall, a RMSE of 1.51 m was achieved, with a least RMSE of 1.30 m over soil (no vegetation). Kielder errors are summarised in table 4.2, and show an overall RMSE of 1.20 m, with the least error over clearfell (little or no vegetation) with an RMSE of 1.06 m

Table 4.3 and figures 4.3 and 4.4 show the combined results from Coed Y Brenin and Kielder. Figure 4.5 shows a sub-sample of the data to give an indication of spread around the 1:1 line. The overall RMSE is 1.38 m, with the highest RMSE (1.71 m) over Moorland, and the lowest over Clearfell (1.15 m). Regression of the two data sets (figure 4.3) presents a relationship approaching unity, with an R^2 of 0.9997 and a P-value of 0, providing very strong evidence that the DTM is a good predictor of the OSDEM (a highly significant relationship at the 95% confidence level). These values are slightly larger than has been found in previous studies (e.g. Fischer and Dowman, 2002), but are still within claimed Star-3i accuracy limits. The

accuracies found in this study are not unexpected. Star-3i accuracies are produced over relatively flat un-vegetated terrain, and are stated to be true for slopes $<20^\circ$. As such, the nature of the terrain in Coed Y Brenin and Kielder, namely rapidly undulating terrain and steep slopes, may have a significant influence on the final accuracies achieved. Also, previous accuracy studies have compared the DTM to DEM products which are of a much higher accuracy than the OSDEM (e.g. lidar), and as such it is feasible that some of the errors found in this study are due to the limited accuracy of the OSDEM.

Table 4.1 Summary statistics for Coed Y Brenin DTM comparison (metres)

Cover Type	n	Min Diff	Max Diff	Mean Diff	SD	RMSE
Bare	3981	-1.20	3.59	1.10	0.90	1.46
Grass	1751	-1.79	2.42	0.20	1.15	1.73
Moorland	4671	-4.63	4.76	0.41	1.63	1.71
Clearfell	1545	-1.18	2.87	0.77	0.82	1.25
Soil	1005	-3.55	2.12	-0.32	1.20	1.30
Combined	12953	-2.41	3.08	0.41	1.14	1.51

Values are arithmetic means.

Table 4.2 Summary statistics for Kielder DTM comparison (metres)

Cover Type	n	Min Diff	Max Diff	Mean Diff	SD	RMSE
Bare	3794	-2.04	2.46	0.02	0.84	1.15
Grass	3656	-1.56	4.20	0.54	1.19	1.36
Clearfell	2789	-1.96	2.48	0.13	0.83	1.06
Soil	3218	-2.17	2.47	-0.06	0.90	1.20
Combined	13457	-1.95	2.91	0.16	0.95	1.20

Values are arithmetic means.

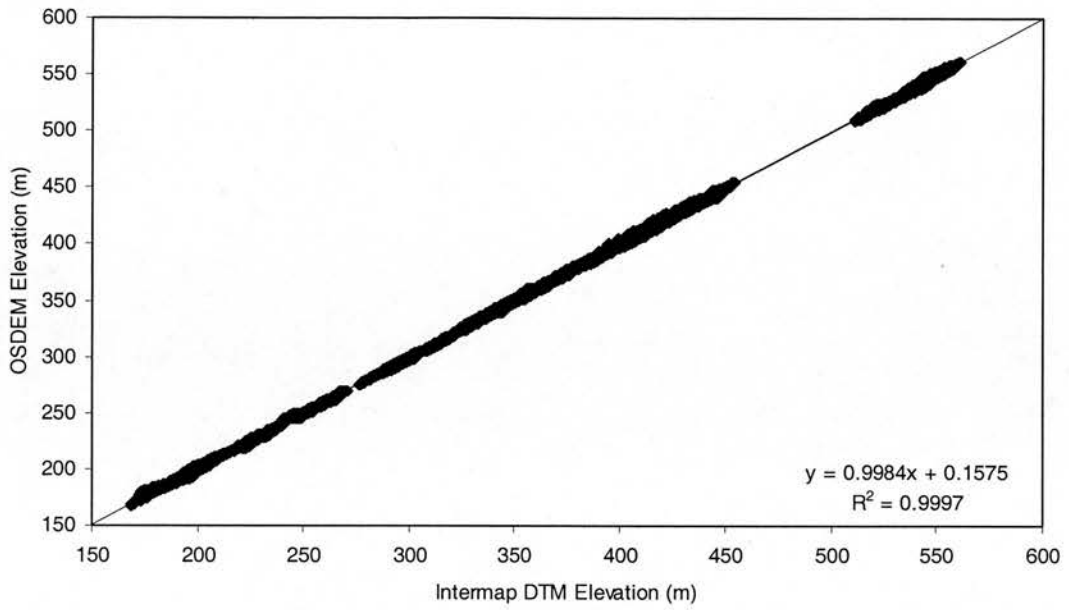


Figure 4.3 Comparison of Intermap DTM to OSDEM for all ground cover types. Note that the relationship is approaching unity, with the R^2 approaching 1. 1:1 line is shown.

Table 4.3 Summary statistics for combined Coed Y Brenin and Kielder DTM comparison (metres)

Cover Type	n	Min Diff	Max Diff	Mean Diff	SD	RMSE
Bare	7775	-1.62	3.02	0.56	0.87	1.31
Grass	5407	-1.70	3.13	0.34	1.17	1.58
Moorland	4671	-4.63	4.76	0.41	1.63	1.71
Clearfell	4334	-1.57	2.68	0.45	0.83	1.15
Soil	4223	-2.86	2.29	-0.19	1.05	1.25
Combined	26410	-2.21	3.01	0.30	1.05	1.38

Values are arithmetic means.

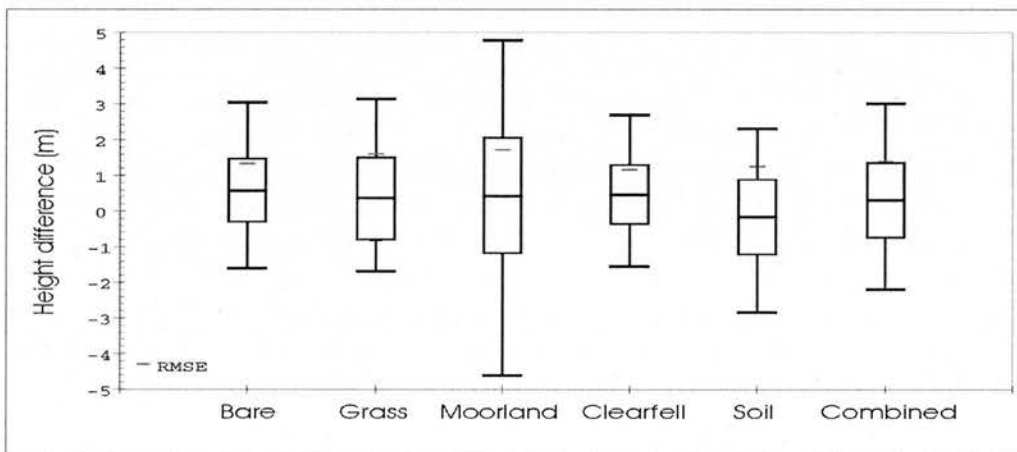


Figure 4.4 Accuracy of DTM compared to OSDEM over open ground, where centre line is mean, box is SD and tails are min and max. (Wallington *et al.*, 2004b)

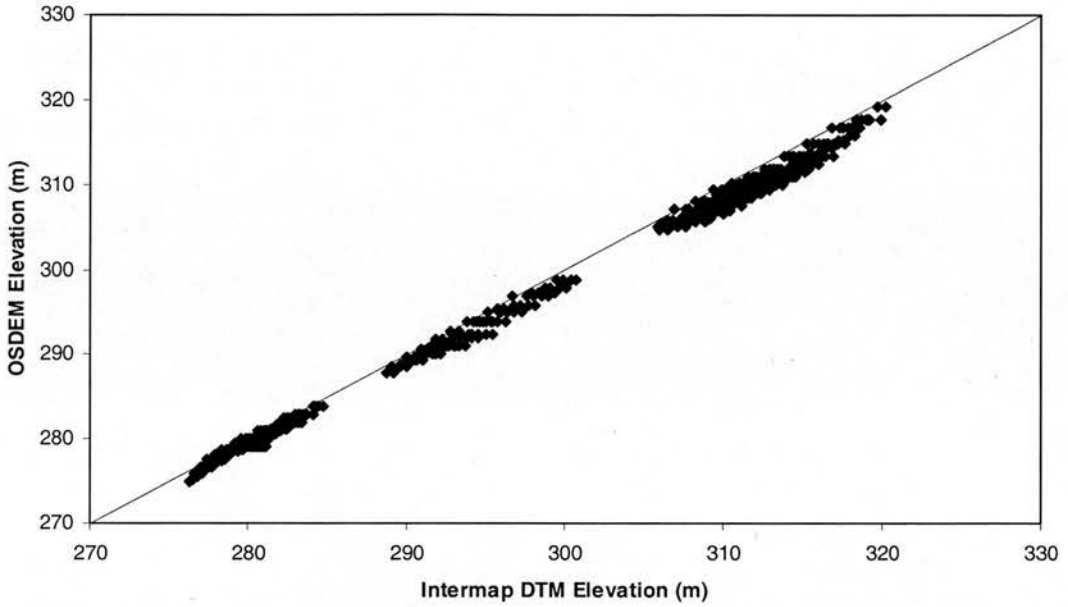


Figure 4.5 Sub-sample of comparison of DTM and OSDEM for all ground cover types. 1:1 line is shown.

4.6.2 Forested ground

Once it had been established that the DTM was within stated tolerances (1.5-2.0 m, this study found an overall RMSE of 1.38 m) over open ground the next stage was to examine the DTM accuracy under forest. A series of plots were taken from the centre of forest stands, and the OSDEM was deducted from the DTM to establish accuracy. Table 4.4 and figure 4.6 summarises the results, and shows an overall RMSE of 13.51 m.

Table 4.4 Summary statistics for DTM comparison under forest (metres)

Forest	n	Min Diff	Max Diff	Mean Diff	SD	RMSE
Coed Y Brenin	2184	8.82	18.28	13.98	2.23	14.26
Kielder	1033	6.54	16.05	11.33	2.15	11.84
Combined	3217	8.11	17.59	13.16	2.21	13.51

Values are arithmetic means.

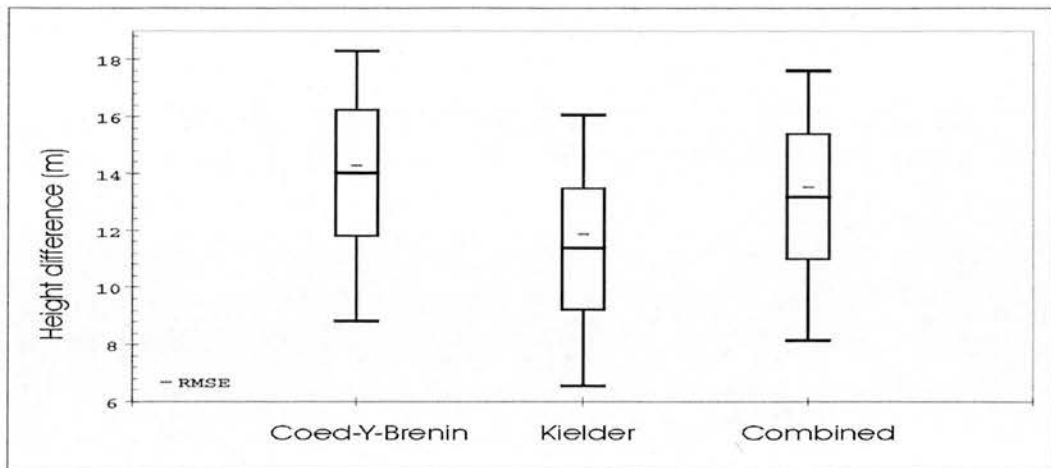


Figure 4.6 Accuracy of DTM compared to OSDEM under forest cover, where centre line is mean, box is SD and tails are min and max, (Wallington *et al.*, 2004b)

4.7 Discussion and potential reasons for differences

4.7.1 Non-vegetated ground

From these results, STAR-3i is comparable to the OSDEM data to within ± 1.4 m, with a bias of 30 cm overall. Localised areas, however, have noticeable systematic bias in the results (figure 4.7). There is an overall slight positive bias as indicated by the mean difference of 30 cm, although there is no indication of a trend dependent on land cover type (figure 4.7). Positive results alone would be indicative of a vegetation bias; however, the presence of negative residuals greater than 2 m indicates one of two likely causes. These and other possibilities are presented below.

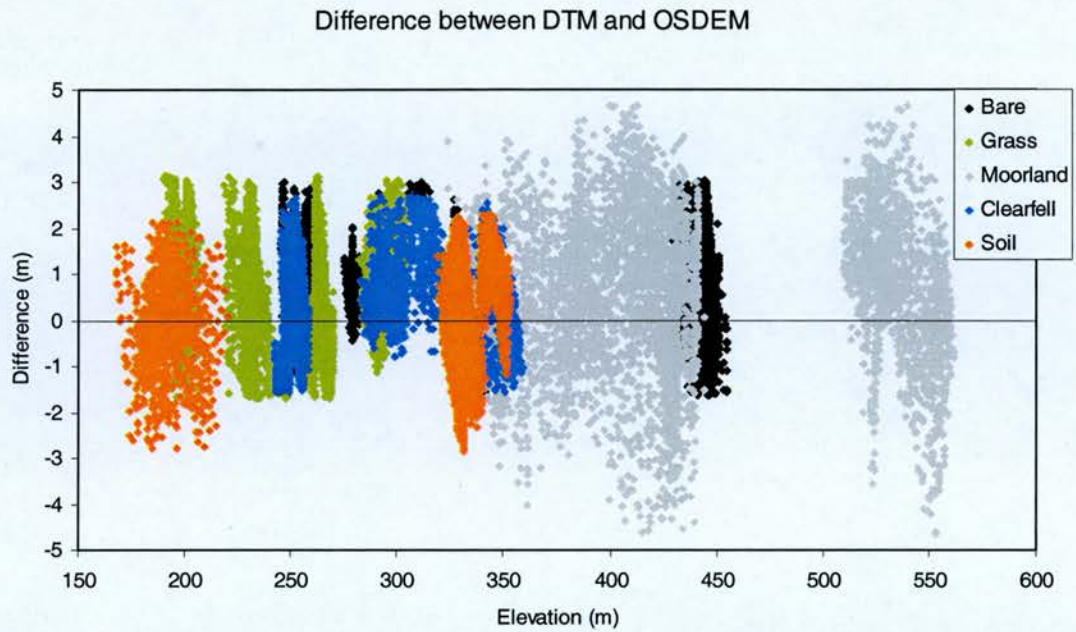


Figure 4.7 Residual plot of differences between DTM and OSDEM, broken down by land cover type.

Local topographic variations may arise due to interpolation errors in the DTM production, whereby the sampling strategy may not be sufficient to accurately represent the surface (Figure 4.8). The Ordnance Survey DEM would not pick this up, as it is a product with 10m posting, and so would also interpolate over features.

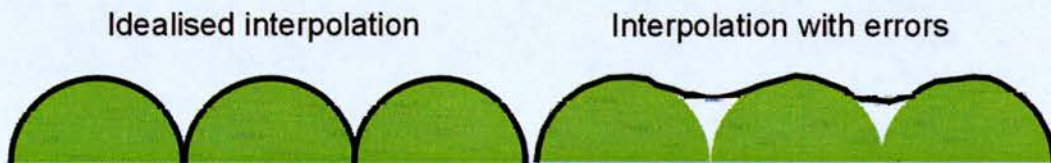


Figure 4.8 Interpolation errors due to local topographic variation.

A second explanation would be that differences arise due to small horizontal errors in the georegistration. In sloped areas this difference would result in different elevations from each DEM data set being compared. The larger the horizontal shift, the larger the error (Figure 4.9).

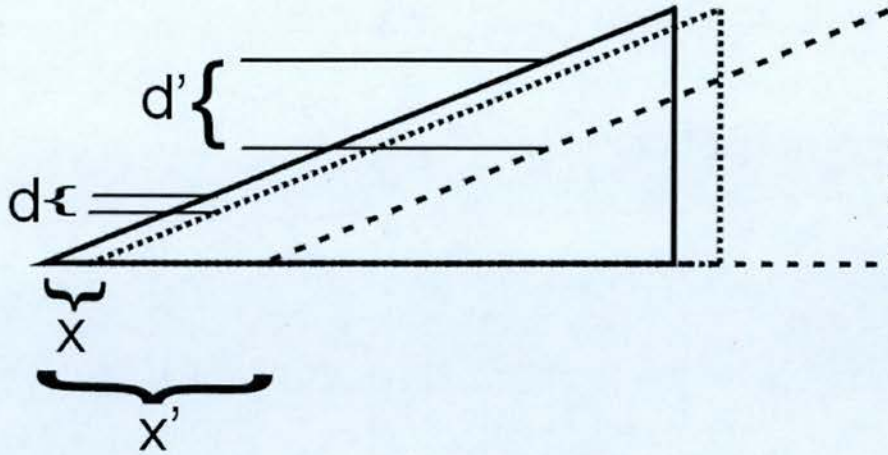


Figure 4.9 Effect on difference between DEM's when horizontal shift occurs coupled with a slope. As DEM is shifted further horizontally, x' , the difference between the DEM's, d' , increases.

The result of small horizontal shifts would be systematic positive/negative biases on up/down slopes. The vertical bias would be in the order of mdx , where m =slope gradient and dx =horizontal shift. Therefore, steep slopes would give a vertical error comparable with the horizontal error. For example, some areas show unusually high discrepancies between the height information. The example is the 'grass' class, which shows a consistent bias of approximately 1.6 m. This could be a topographic effect since it occurs on a lightly vegetated lee slope (from the perspective of the radar system). Small discrepancies in the horizontal location of the pixels would therefore result in apparently exaggerated vertical differences. A horizontal registration error of 2-3 m would be hard to identify when using a 5 m grid.

Another possible reason for the differences could be differences in the data values. The OSDEM data was collated over a number of years beginning during the 1940's, and has a rolling program of updating. This data was produced by manual aerial photogrammetry techniques, with different interpreters contributing to the data. The possibility of different interpretations of ground point location may result in different initial elevation values. It should also be noted that the accuracy of the OSDEM is

stated to be +/- 5 m (OS, 2001). Contrastingly, the Intermap data was collected in a short period of time; in the order of a maximum of two days for individual test areas. Therefore, a further explanation for discrepancies could be due to landscape change (Figure 4.10). Over time the landscape is altered by natural and man-induced processes. A comparison of surfaces which have changed would obviously result in discrepancies. One example of this is the Moorland class with an average of 1.7 m RMSE. Moorland is a very dynamic environment, and is sensitive to variations in short-timescale changes in moisture content as well as longer term changes (Naden and Watts, 2001). Differences in this type of environment are exaggerated by rapidly changing slopes, and the processes described above (e.g. small horizontal shifts or landscape changes) would further effect the accuracy.

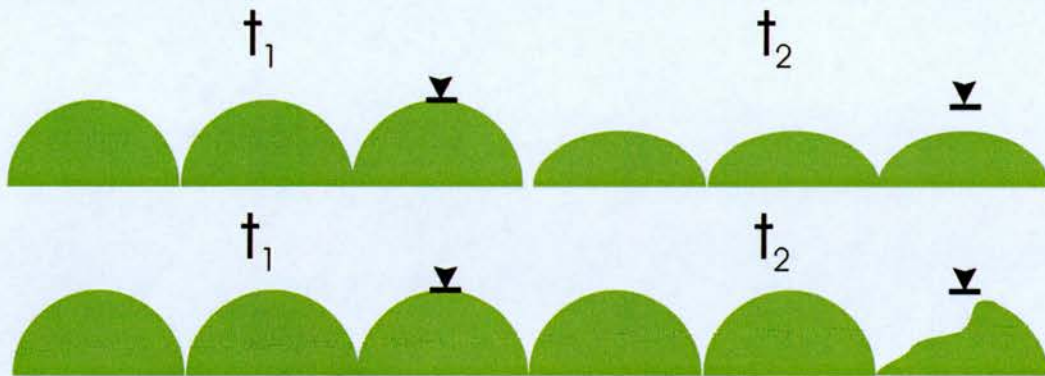


Figure 4.10. Example landscape changes over time. Comparing the heights at t_1 to t_2 at a given point may produce differences, as represented by the measurement markers.

Two further considerations of possible error sources include the area of the radar integration footprint and the interpolation of the DTM from the DSM. The area of the radar integration footprint is approximately 50% larger than the product's 5m postings (Intermap, 2004), resulting in a footprint of around 7.5 m square. All objects within this footprint will contribute to the derived height. The resulting elevation is therefore a smoothed realisation of the actual components contributing to

the elevation. For example a raised hedge and a road will both contribute to the elevation of a footprint covering both of these objects. The DTM is a product derived from the DSM, and relies on the DSM being sampled at a high enough density to represent the ground surface accurately. This technique relies on the ground surface being correctly identified by the TerrainFit algorithm (see section 4.2), and ensuring it does not just select local minima. If local minima were selected, then this may result in the tops of buildings, hedges and forests being included in the DTM interpolation procedure. The following section further discusses these potential limitations.

4.7.2 Forested ground

Fischer and Dowman (2002) found differences of 4m and more when comparing the Intermap DTM to the Environment Agency DTM (produced from Lidar) and the UCL DTM (produced from aerial photography) within areas of woodland along river banks and railway embankments. Similarly, differences of 13.51 m have been found in this study when sampling under forested areas. It was suspected that this large error was due to the limits of the DTM interpolation technique when applied across large areas of forest (Wallington and Woodhouse, 2003). Mercer (2004b) confirmed that the DTM interpolation was affected by the presence of a large block of vegetation. The interpolation works by looking for areas of homogeneity and interprets these as the ground elevation. The algorithm then interpolates from these areas across the heterogeneous regions. For example, car parks either side of a small building are seen as homogenous, whereas the building is seen as heterogeneous in comparison to the surrounding car parks. In this situation, the algorithm interpolates

between the car parks thus removing the building. Unfortunately, the algorithm characterises the middle of large dense forest stands to be homogeneous and so interprets the centre of these forest stands as the ground surface. The edges of the forest stands always form a discontinuity and so are recognised as being heterogeneous (i.e. non-ground surface). Figure 4.11 is a graphical representation of the expected DTM surface created by the way in which the DTM interpolation procedure handles large forest areas. As the DTM moves into the forest, the retrieved DTM height tends towards the top of the vegetation canopy. It is estimated that the ground surface will not be correctly represented in the DTM in areas further than about 50 m from forest edges, and areas within this 50 m will be subject to increasingly large errors in height.

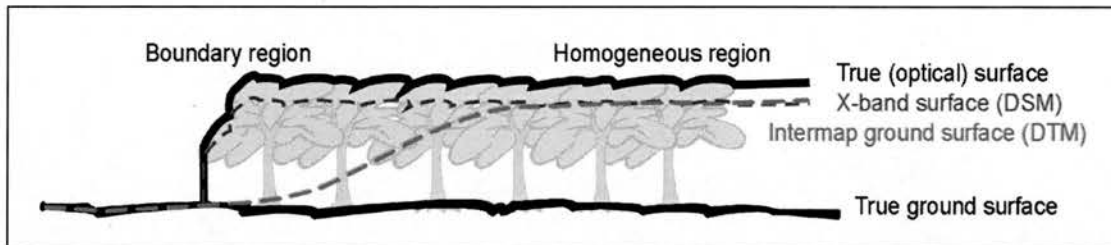


Figure 4.11 Anticipated DTM interpolation limitation. (From Wallington and Woodhouse, 2005).

To test this conjecture, a number of transects through forest stands were undertaken. Figure 4.12 shows one such transect, and demonstrates the assumption of the DTM tending towards the canopy top. This effect is further examined in chapter 7.

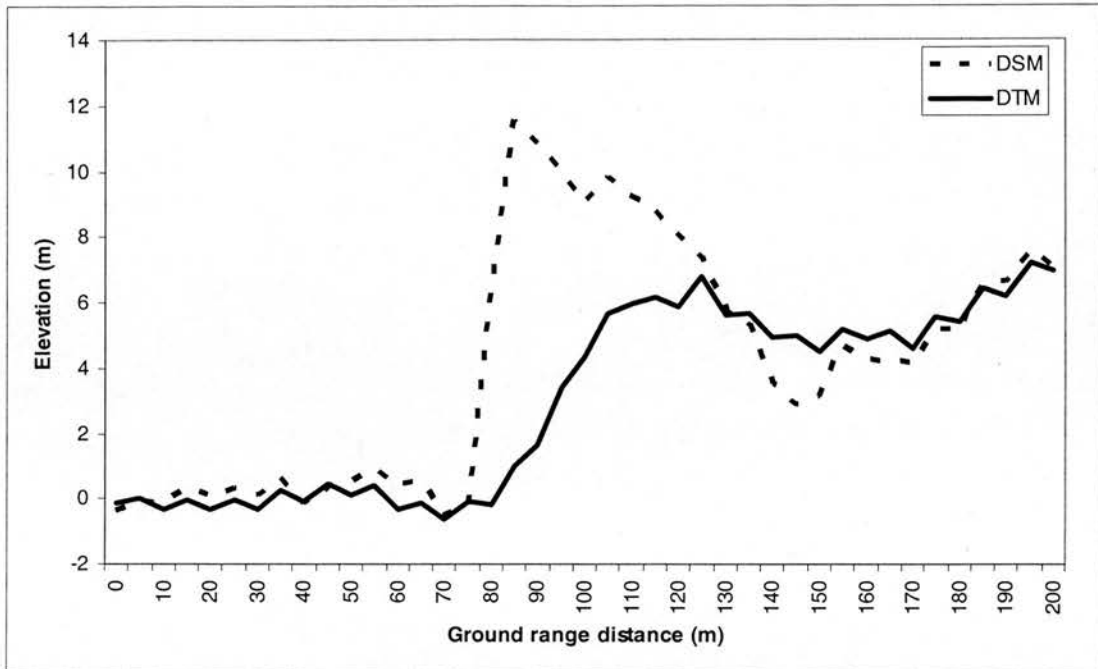


Figure 4.12 Profile through the edge of a forest stand showing the DTM interpolation across large areas of forest. The forest stand begins at approximately 80m and continues beyond 200m. Compare this result with Figure 4.11. (The increased height at the edge of the stand is probably due to edge-effects, see chapter 7. This happens throughout an image scene, and is most evident when the orientation of a stand edge is perpendicular to the radar line of site).

4.8 Conclusion

This chapter has discussed the accuracy of the Intermap DTM with comparison to the Ordnance Survey DEM. Differences were observed between the two ground surface products. Over non-vegetated ground accuracies varied with localised region, but gave an overall RMSE of 1.38m with a standard deviation of 1.05 m. Under forested areas, the differences were significantly greater with an overall RMSE of 13.51 m and a standard deviation of 2.21 m.

Potential reasons for differences between the two products were examined. These reasons included, landscape changes over time, interpretation when creating the DEM's, interpolation issues (as associated with all DEM's), and the effect of small

horizontal shifts in the georegistration of the products, particularly in areas of slope and undulating terrain. Further errors are potentially introduced due to the radar footprint incorporating a number of objects, thereby producing an elevation integrated from the collective contributions of all the targets combined. One of the significant causes of differences was the presence of vegetation, and in particular large areas of dense forest. The Intermap TerrainFit algorithm for creating the DTM from the DSM suffers a limitation when encountering large homogenous areas such as forest plantations. The forest canopy is assigned the same elevation values as surrounding ground areas, with interpolated elevations between the two extremes. The result is a ground elevation which contains a bias in the order of the height of the forest.

The results presented are of interest in their own right, and the presence of a vegetation bias in an increasingly widely available commercial DTM product is one which users should be aware of. The results are important to this study because the DTM is used to extract tree height information in conjunction with the DSM. The use of the Intermap DTM as a ground surface for subtraction from the DSM may now be in question as to whether it will provide realistic or valid results for tree height retrieval. The OSDEM has itself been validated as a result of this study, and has been shown to be within stated Ordnance Survey accuracies, and over the particular test areas is considerably better. The accuracies found over un-vegetated ground are assumed to be consistent under forest cover. This has not been tested directly; however, the accuracy over recent clearfell sites was less than 1.25 m. An

alternative proposal is to use the OSDEM as a ground surface to be used in height retrieval.

This chapter has highlighted the accuracies of the Intermap DTM and the OSDEM over un-vegetated and forested land. These results have an impact on tree height retrieval, as discussed in chapter 5.

5 Results of tree height estimation over homogenous plantation

“He is a fool who looks at the fruit of lofty trees, but does not measure their height”¹

Quintus Curtius Rufus (Roman historian, c. 2nd century)

5.1 Introduction, aim and objectives

The previous chapter discussed the accuracy of the ground DEMs (DTM and OSDEM). This chapter will discuss the use of these in conjunction with the canopy digital surface model (DSM) for estimating forest stand height (top height; see section 1.2.3). Two procedures were undertaken in homogeneous plantation forests: section 5.5 describes the results of deducting the Star-3i DTM from the DSM and section 5.6 describes results for deducting the OSDEM from the DSM. This second procedure was undertaken due to potential height estimation error due to DTM ground surface representation error beneath large forest stands (see section 4.6.2).

The specific aim of this chapter is to assess Intermap InSAR derived DEM products for estimating tree height. The objectives to meet the aim are (i) to qualitatively assess the height estimations produced using InSAR, (ii) to quantitatively assess height retrieval using DSM-DTM over homogenous plantations, and (iii) to quantitatively assess height retrieval using DSM-OSDEM over homogenous plantations.

¹ *Lat. - Stultus est qui fructus magnarum arborum spectat, altitudinem non metitur. - De Rebus Gestis Alexandri Magni (VII, 8).*

5.2 Homogeneous tree height retrieval

Figure 5.1 summarises the homogeneous tree height retrieval procedure discussed in section 3.5.2. Tree height in this chapter is defined as top height for stand measurements (see section 1.2.3).

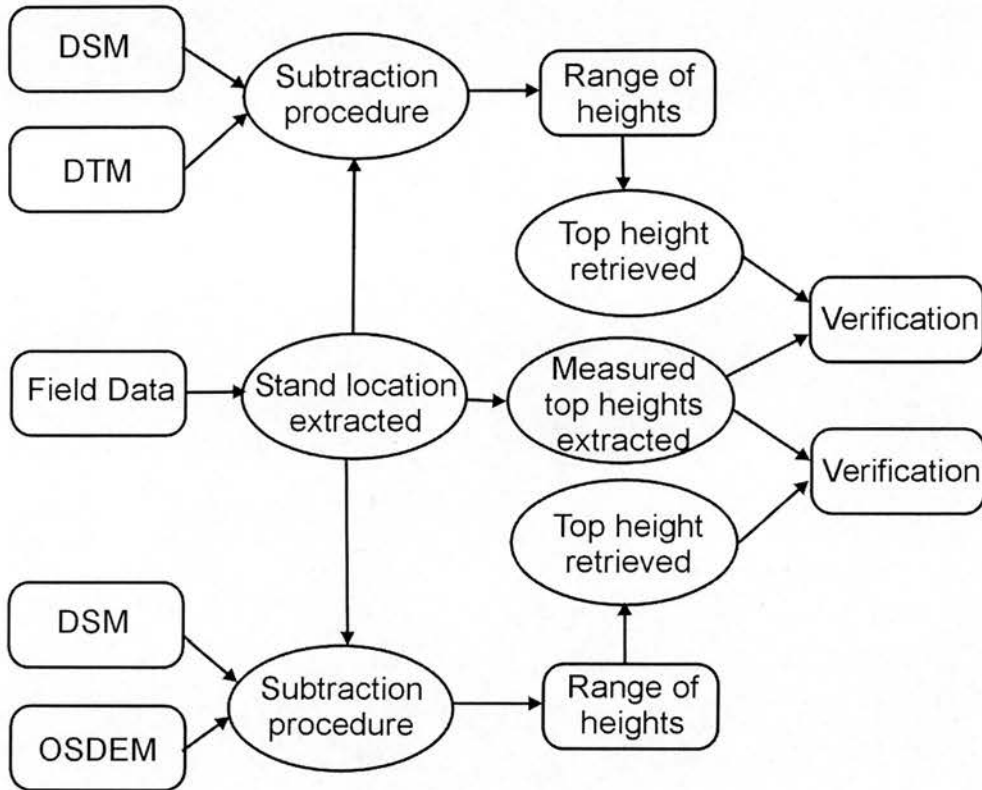


Figure 5.1 Flow chart summary of homogeneous tree height retrieval.

5.3 Expected sources of error

As well as considerations and expected errors on DEM creation, and the sources of DEM error discussed in chapter 4, some other radar related factors should be considered. Penetration into the canopy is a factor to be taken into account. Dependent on the wavelength (see table 2.1) used, penetration into the canopy can vary (related to wavelength interaction with a target of a similar size). Figure 2.1

gives a graphical representation on the penetration depth of differing SAR wavelengths. Studies have shown that penetration values of 14-24 m for P-band, 9-12 m for L-band and 3-6 m for C-band (Saatchi and McDonald, 1997; Chauhan *et al.*, 1991). The Star-3i system operates at X-band, being a short radar wavelength (3cm) this interacts with the vegetation near the top of the canopy. It should be noted, and expected, that some penetration does occur. At any wavelength the scattering phase centre is a weighted average of the location and strength of all the signals in a range bin. The high extinction at X-band means that the contributions are weighted towards the top of the canopy. The resulting scattering phase centre (the apparent location of the canopy) may therefore be a few metres lower than the actual canopy, i.e. a few metres below tree total height (figure 2.1); for example, Martinez *et al.* (2000) modelled radar signal interaction with vegetation and found X-band penetration depths of several metres. An additional factor to consider is that the radar scattering phase centre (SPC) is also averaged horizontally. The resulting maximum retrieved heights are averaged - so even for a cone-shaped crown, the resulting SPC represents an "average structural height", rather than a total height (see section 1.2.3). Therefore, it is to be expected that height under-estimation will occur. The question that this study attempts to answer is whether this underestimation is consistent or predictable. Consistency or predictability, by their nature, allow for correction of the underestimation by modelling the differences. The exact extent of the underestimation will depend on a number of factors related to forest parameters such as crown shape and stem number density and radar geometry related properties such as incidence angle, slope and penetration depth. Penetration depth is itself dependent upon canopy structure parameters, such as densities and

sizes of elements (leaves, needles, twigs, etc). Further examination of potential error sources and reasons for underestimation are discussed in chapter 7.

5.4 Qualitative assessment

An initial qualitative analysis was carried out for two purposes. The first was to visually check the co-registration between the different data sets. The second was to visually assess the DSM-DTM difference in comparison to aerial photographs and the ORRI, to assess whether height differences were representative of vegetation location. The co-registration assessment was done visually since absolute registration assessment was beyond the scope of the current project and has been assessed elsewhere (see chapter 4). No obvious co-registration errors were found beyond expected and overall the co-registration was found to be within stated accuracies (Intermap, 2004), and as such could be used for forest stand height assessment. A visual assessment was also performed for the comparison between the DSM-DTM difference, the location of forest stands and the apparent tree height in the aerial photographs (section 5.5.1). It was hoped that the DSM-DTM difference would be indicative of average tree height. As a comparison, the same procedure was carried out for the DSM-OSDEM (section 5.6.1).

5.5 DSM-DTM height retrieval over homogenous plantations

5.5.1 Results of qualitative assessment

Visual assessment of the DSM-DTM difference image for Coed y Brenin showed that height differences were present between the DSM and DTM. The differences in the data were assumed to be an indication of vegetation presence in the study area (figure 5.2). The areas of difference were not consistently representative of where

forest stands were located, as demarcated by the Forestry Commission stand boundaries (figure 5.3). Height differences appeared to be greater towards the edge of stands, decreasing away from the edge.

Forest stands which appeared to be higher in the aerial photographs also had a greater DSM-DTM difference when compared to open ground (figure 5.4). However, there was no obvious trend, and values from within individual stands had a large range. The DSM-DTM difference also appeared to be considerably smaller than the apparent visual tree height in the photographs.

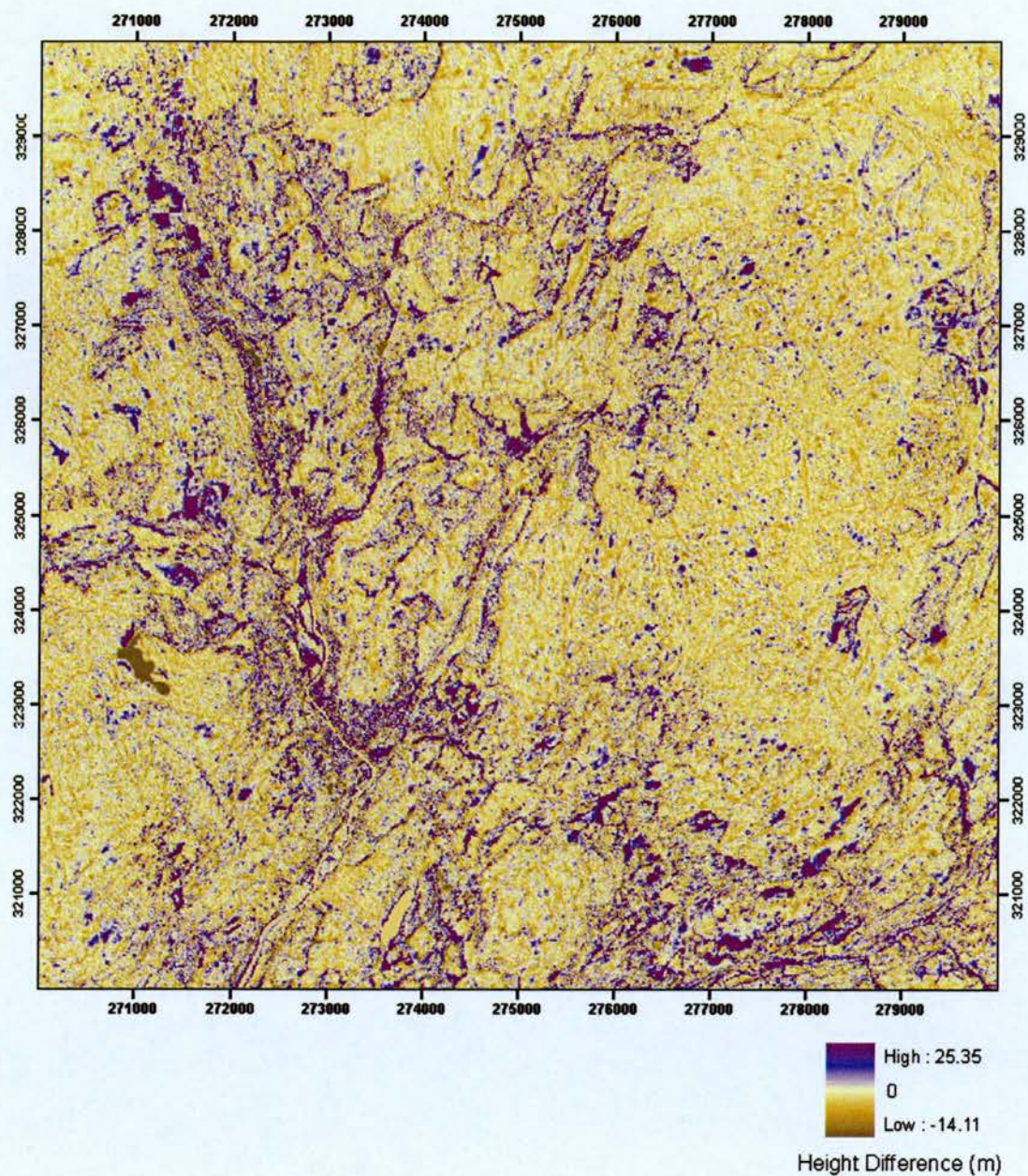


Figure 5.2 DSM-DTM height difference image, Coed y Brenin. Brighter areas represent greater height difference. Compare to figure 5.5. Coordinates are Ordnance Survey National Grid coordinates.

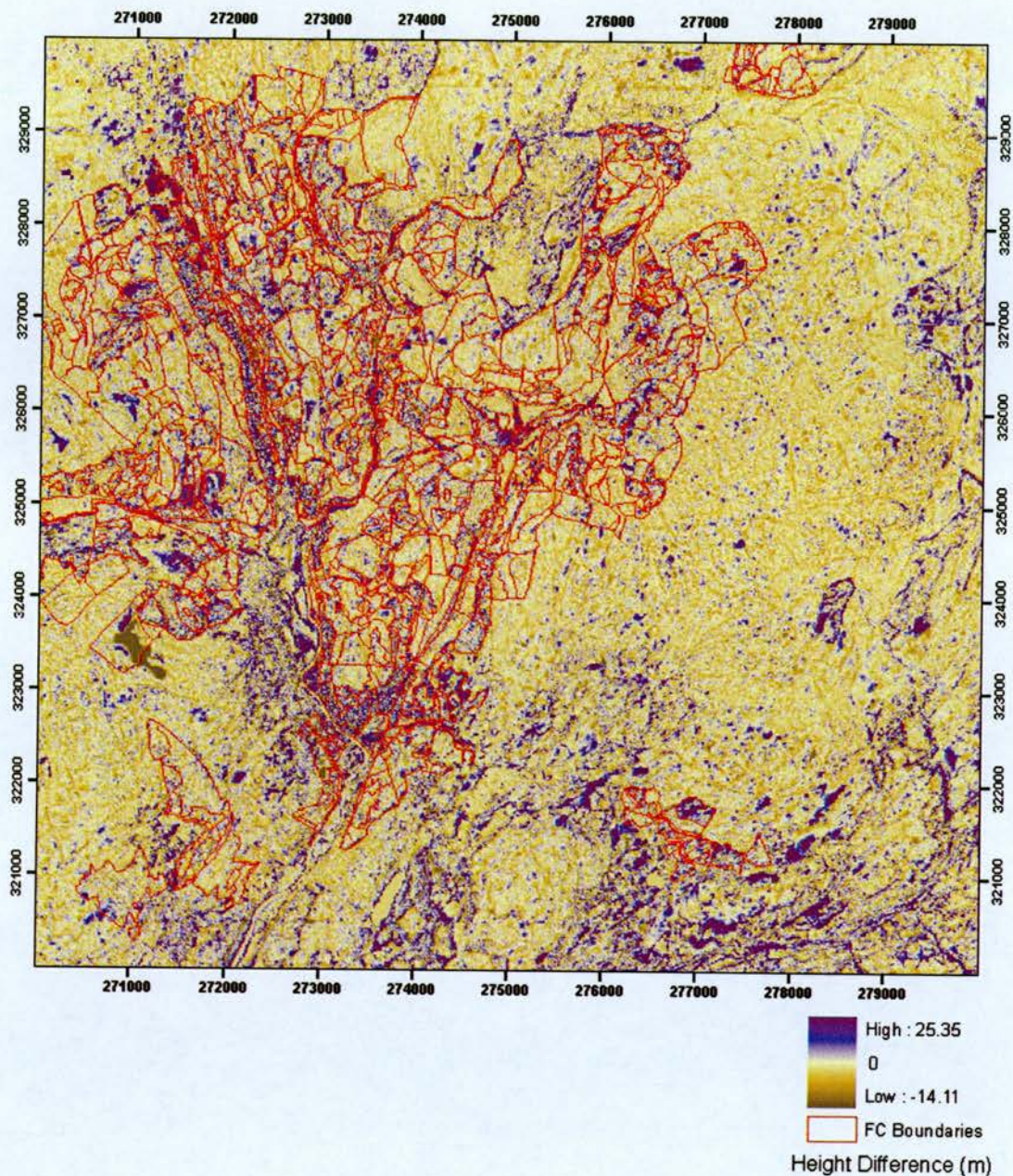


Figure 5.3 DSM-DTM height difference with Forestry Commission boundaries overlaid, Coed y Brenin. Brighter areas represent greater height difference. Compare with figure 5.6. Coordinates are Ordnance Survey National Grid coordinates.

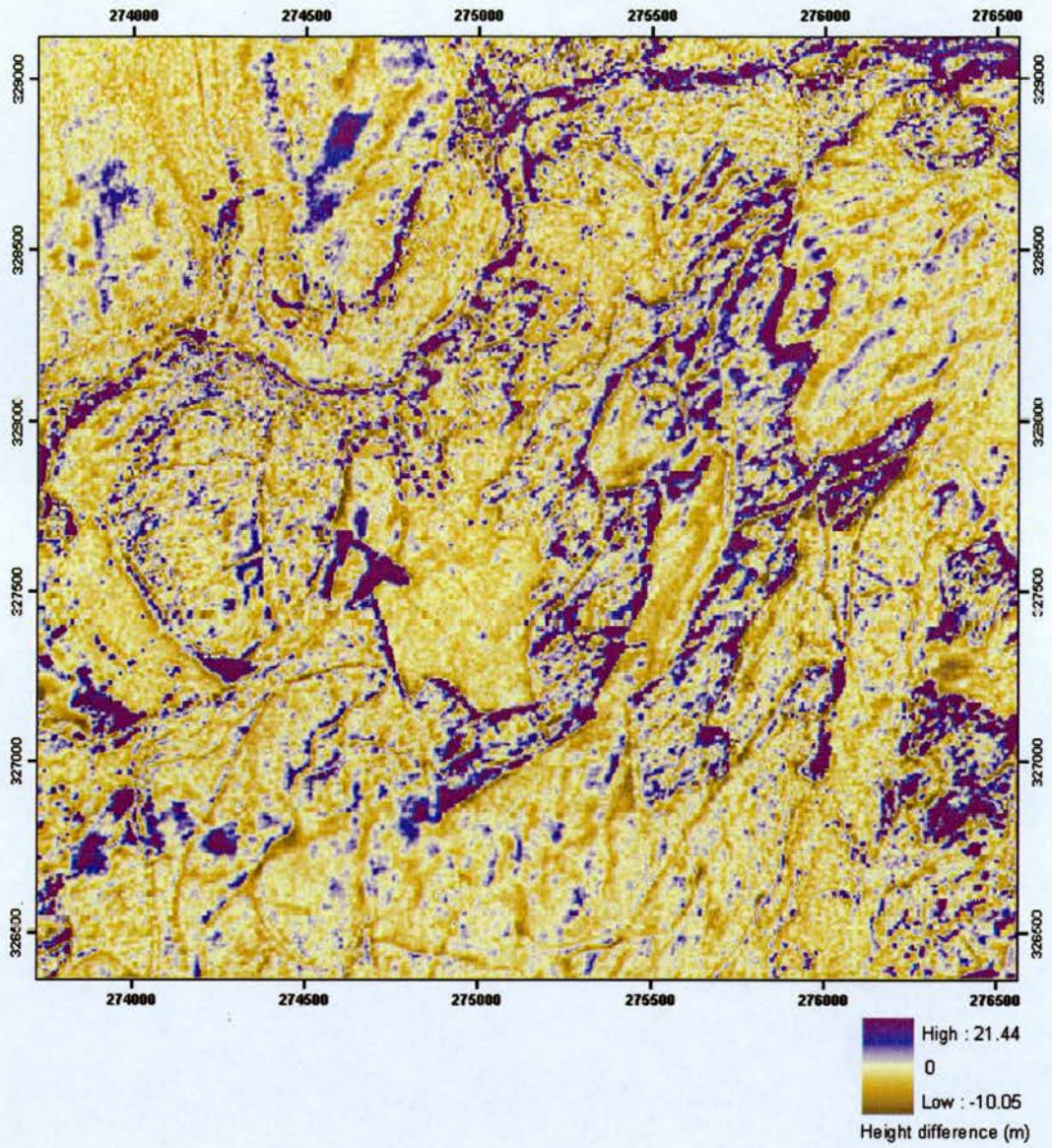


Figure 5.4 DSM-DTM difference image (A, above), corresponding aerial photograph (B) and ORRI (C); subset of Coed y Brenin. Compare to figure 5.8. Coordinates are Ordnance Survey National Grid coordinates.

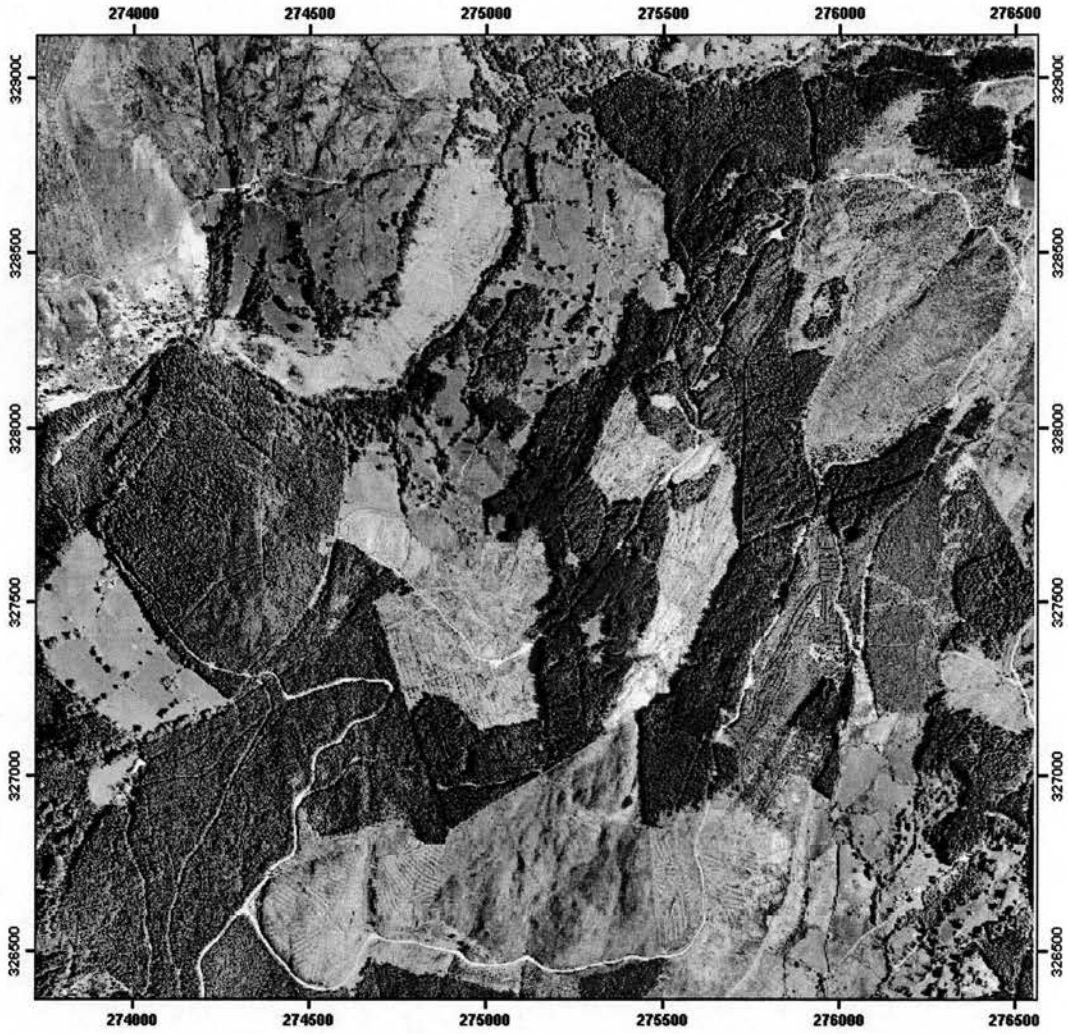


Figure 5.4 (B). Coordinates are Ordnance Survey National Grid coordinates.

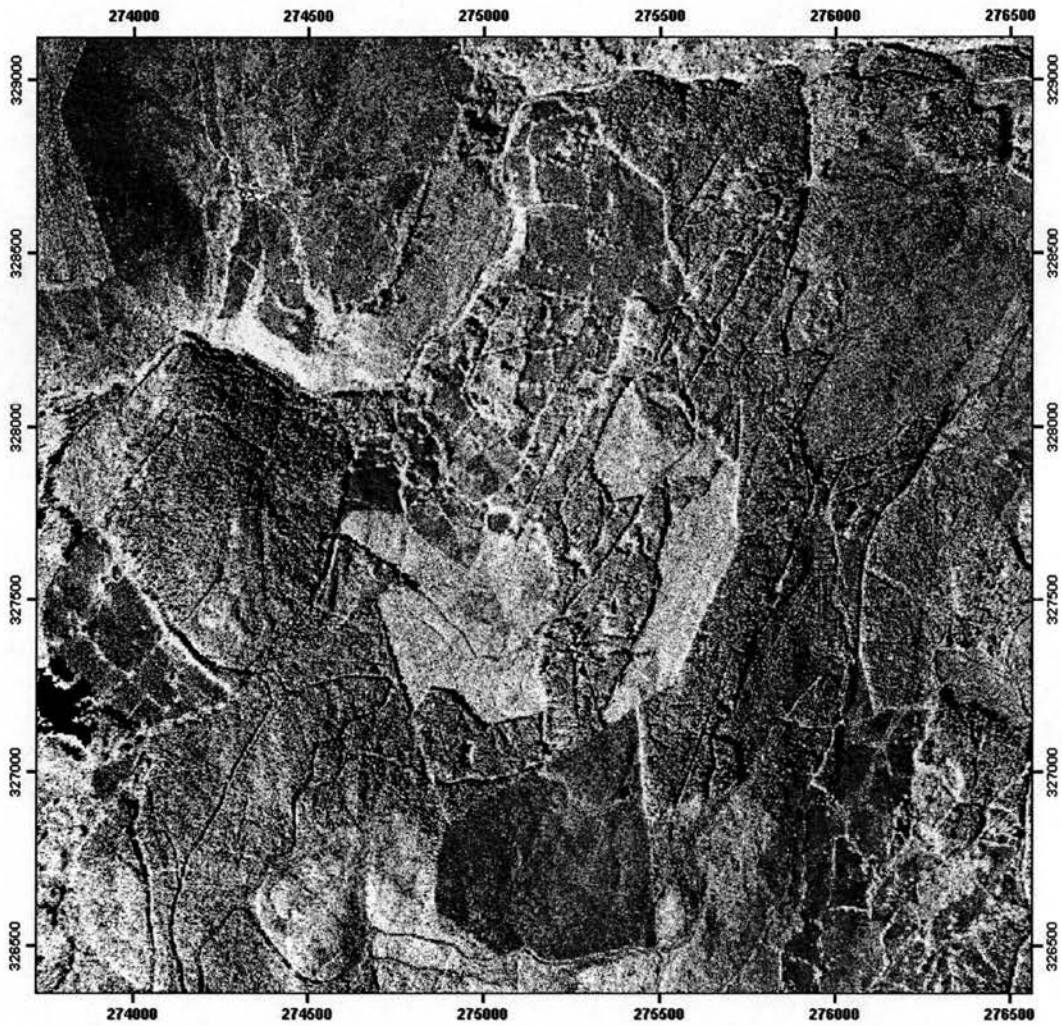


Figure 5.4 (C). Coordinates are Ordnance Survey National Grid coordinates.

5.5.2 Results of quantitative assessment

Tree height estimates produced using the Intermap Star-3i DSM minus Intermap ground (bald Earth) surface DEM (DTM) were assessed and compared to true stand height. Table 6.1 shows results per stand from Coed Y Brenin and table 6.2 for Kielder.

Table 5.1 Top height retrieval using Intermap DSM-DTM in Coed y Brenin (metres)

Cmpt	Measured	Estimate	Average	Min	Max	Diff	% Error
586L	29.00	0.80	-0.26	-2.74	3.46	28.20	97.24
558A	24.00	0.90	-0.91	-4.23	1.52	23.10	96.25
586M	23.00	1.04	0.49	-1.47	1.85	21.96	95.48
641A	46.00	2.11	0.36	-3.36	3.19	43.89	95.41
586H	29.00	1.41	0.29	-1.73	2.37	27.59	95.14
623C	26.00	1.48	-0.01	-2.62	2.95	24.52	94.31
621B	26.00	1.64	-0.37	-6.80	3.18	24.36	93.69
621F	28.00	2.22	0.50	-2.16	3.85	25.78	92.07
629C	31.00	2.52	0.99	-1.55	4.12	28.48	91.87
593G	20.00	1.70	0.37	-3.41	2.42	18.30	91.50
600C	22.00	2.04	-0.02	-3.19	4.08	19.96	90.73
545H	27.00	4.10	1.68	-2.65	6.42	22.90	84.81
640E	32.00	5.02	1.34	-6.97	7.69	26.98	84.31
601I	26.00	4.45	1.62	-2.37	6.35	21.55	82.88
640F	32.00	5.64	1.75	-6.62	8.37	26.36	82.38
544C	32.00	6.69	1.71	-3.45	10.01	25.31	79.09
637A	24.00	5.05	2.36	-1.87	7.59	18.95	78.96
637K	22.00	4.68	1.75	-3.21	7.45	17.32	78.73
589F	17.00	4.01	2.99	-1.21	6.74	12.99	76.41
593B	24.00	7.78	3.90	-2.74	10.82	16.22	67.58

Table 5.2 Top height retrieval using Intermap DSM-DTM in Kielder (metres)

Cmpt	Measured	Estimate	Average	Min	Max	Diff	% Error
3412A	20.83	0.85	0.27	-0.64	1.34	19.98	95.92
3617A	18.93	0.82	0.11	-0.95	1.26	18.11	95.67
1024C	32.82	1.62	0.78	-1.53	2.20	31.20	95.06
3626A	24.96	1.24	0.27	-0.68	1.79	23.72	95.03
3603E	21.67	1.09	0.52	-0.34	1.91	20.58	94.97
1026A	28.15	1.44	0.42	-1.40	2.12	26.71	94.88
3405D	21.35	1.47	0.34	-1.92	1.89	19.88	93.12
3642A	28.80	2.10	-0.12	-4.70	2.78	26.70	92.71
3406F	20.33	2.43	0.64	-2.61	3.62	17.90	88.05

Tree height estimation performed using the DSM-DTM procedure produces significant errors. Height estimation in Coed y Brenin produced errors ranging from 68% to 97%, and in Kielder the errors ranged from 88% to 96%. Overall, the average error in Coed y Brenin was 23.74 m \pm 10.40 m (87.4% \pm 38.32%) and in

Kielder was $22.75 \text{ m} \pm 14.86 \text{ m}$ ($93.9\% \pm 61.36\%$), with a combined overall RMSE of $23.46 \text{ m} \pm 9.37 \text{ m}$ ($89.46\% \pm 35.79\%$) (Table 6.3). Regression analysis determined an R^2 of 0.02, and a P -value of 0.47, (not a significant relationship at the 95% confidence level) thus indicating that there is no evidence to suggest that the retrieved heights are a good predictor of the measured heights. Therefore, the null hypothesis (H_0 , retrieved heights are not a significant predictor of measured heights) would have to be accepted, and the alternative hypothesis (H_1 , retrieved heights are a significant predictor of measured heights) would have to be rejected.

Table 5.3 Summary of top height retrieval using Intermap DSM-DTM

Forest	Average error				Combined error			
	m	SE* (m)	%	SE* (%)	m	SE* (m)	%	SE* (%)
Coed Y Brenin	23.74	10.40	87.44	38.32				
Kielder	22.75	14.86	93.93	61.36	23.43	9.37	89.46	35.79

Values are arithmetic means. *SE = Standard Error at 95% confidence interval.

5.5.3 Discussion

Given the above results, with errors reaching 97%, it was found that the DSM-DTM procedure is unacceptable for tree height estimation. The limitation on using this procedure is assigned to the DTM interpolation procedure not being able to correctly represent the ground surface under large bodies of vegetation, such as forest plantations (section 4.7.2). This results in a retrieved tree height which decreases as one moves further into the stand (Figure 5.6; Wallington and Woodhouse, 2003). This also explains why a decreasing height difference was observed in section 5.5.1. As a result of this, the OSDEM was used to represent the ground surface, therefore height retrieval was performed using the DSM-OSDEM procedure (section 5.6).

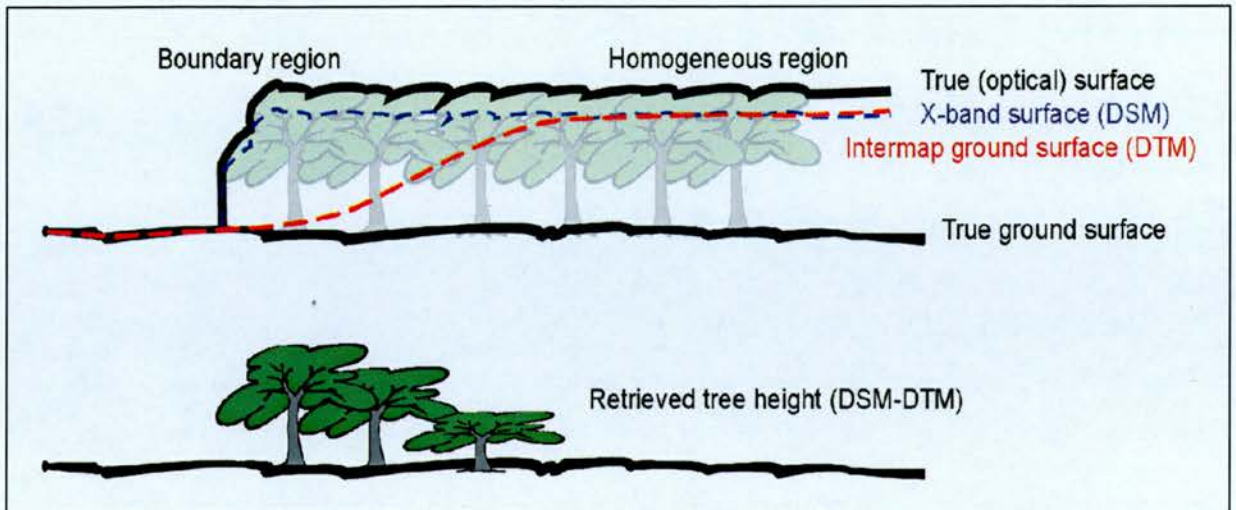


Figure 5.5 DTM interpolation limitation (top) and corresponding (underestimated) retrieved tree height (bottom). Relate to figure 5.4. (Wallington and Woodhouse, 2003)

5.6 DSM-OSDEM height retrieval over homogenous plantation

5.6.1 Results of qualitative assessment

Visual assessment of the DSM-OSDEM difference image for Coed y Brenin showed that height differences were present between the DSM and OSDEM. The differences in the data were an indication of vegetation presence in the study area (figure 5.6). The areas of difference were representative of where forest stands were located, as demarcated by the Forestry Commission stand boundaries (figure 5.7).

Forest stands which appeared to be higher in the aerial photographs also had a greater DSM-OSDEM difference when compared to open ground (figure 5.8). The height difference appeared to be more consistent within the stand boundaries (i.e. consistently higher than open ground), although there is internal stand variation.

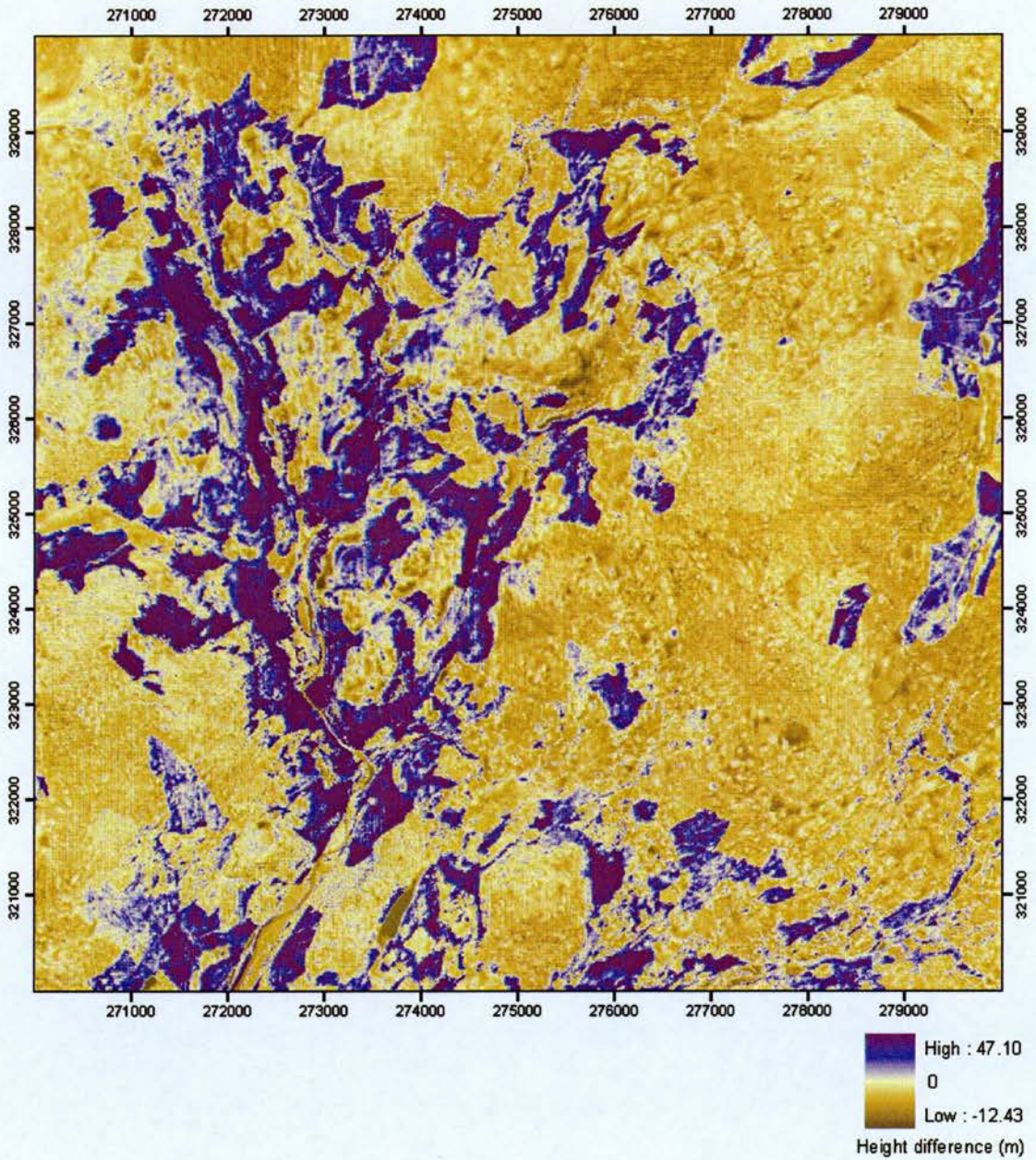


Figure 5.6 DSM-OSDEM height difference image, Coed y Brenin. Brighter areas represent greater height difference. Compare to figure 5.2. Coordinates are Ordnance Survey National Grid coordinates.

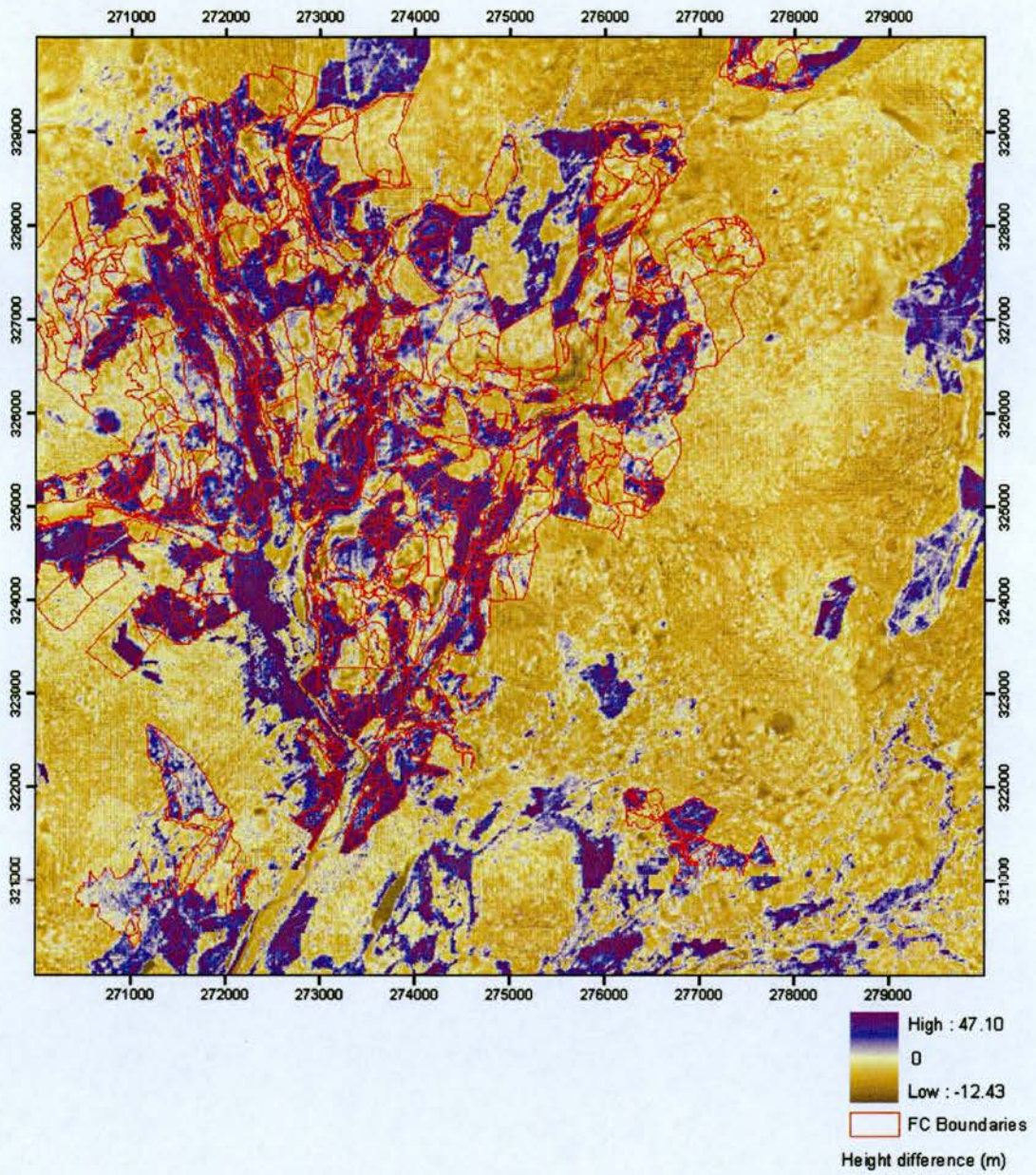


Figure 5.7 DSM-OSDEM height difference with Forestry Commission boundaries overlaid, Coed y Brenin. Brighter areas represent greater height difference. Compare to figure 5.3. Coordinates are Ordnance Survey National Grid coordinates.

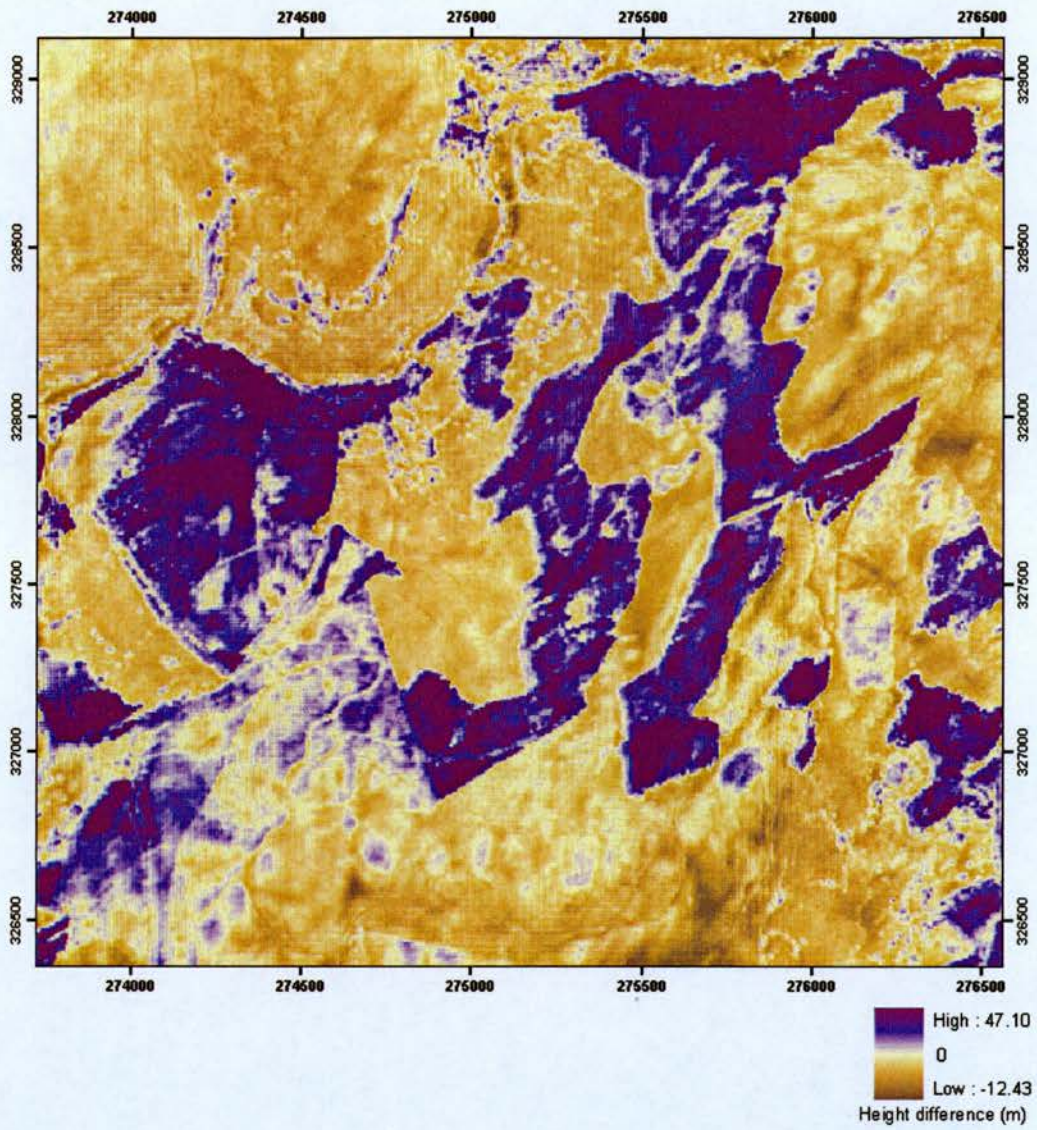


Figure 5.8 DSM-OSDEM difference image (A, above), corresponding aerial photograph (B) and ORRI (C); subset of Coed y Brenin. Compare to figure 5.4. Coordinates are Ordnance Survey National Grid coordinates.

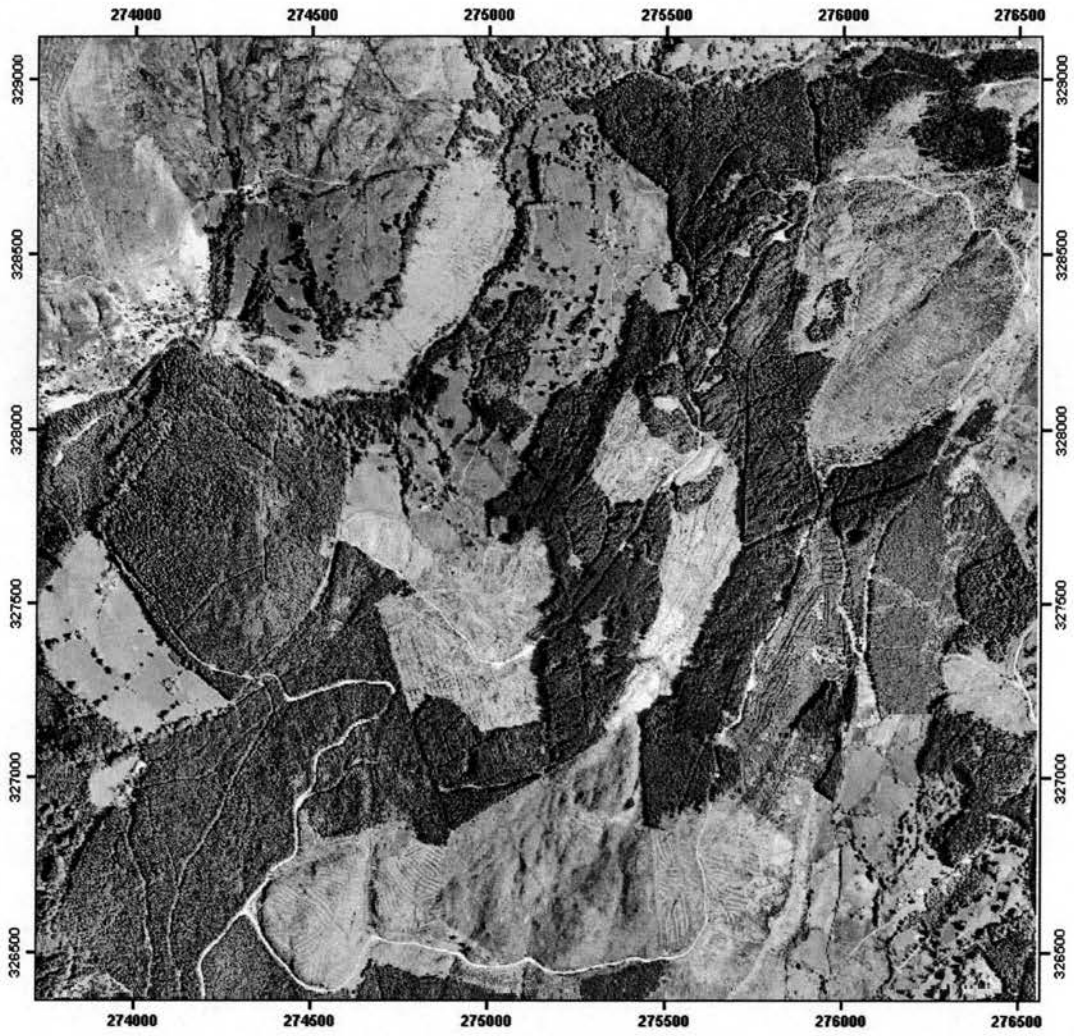


Figure 5.8 (B). Coordinates are Ordnance Survey National Grid coordinates.

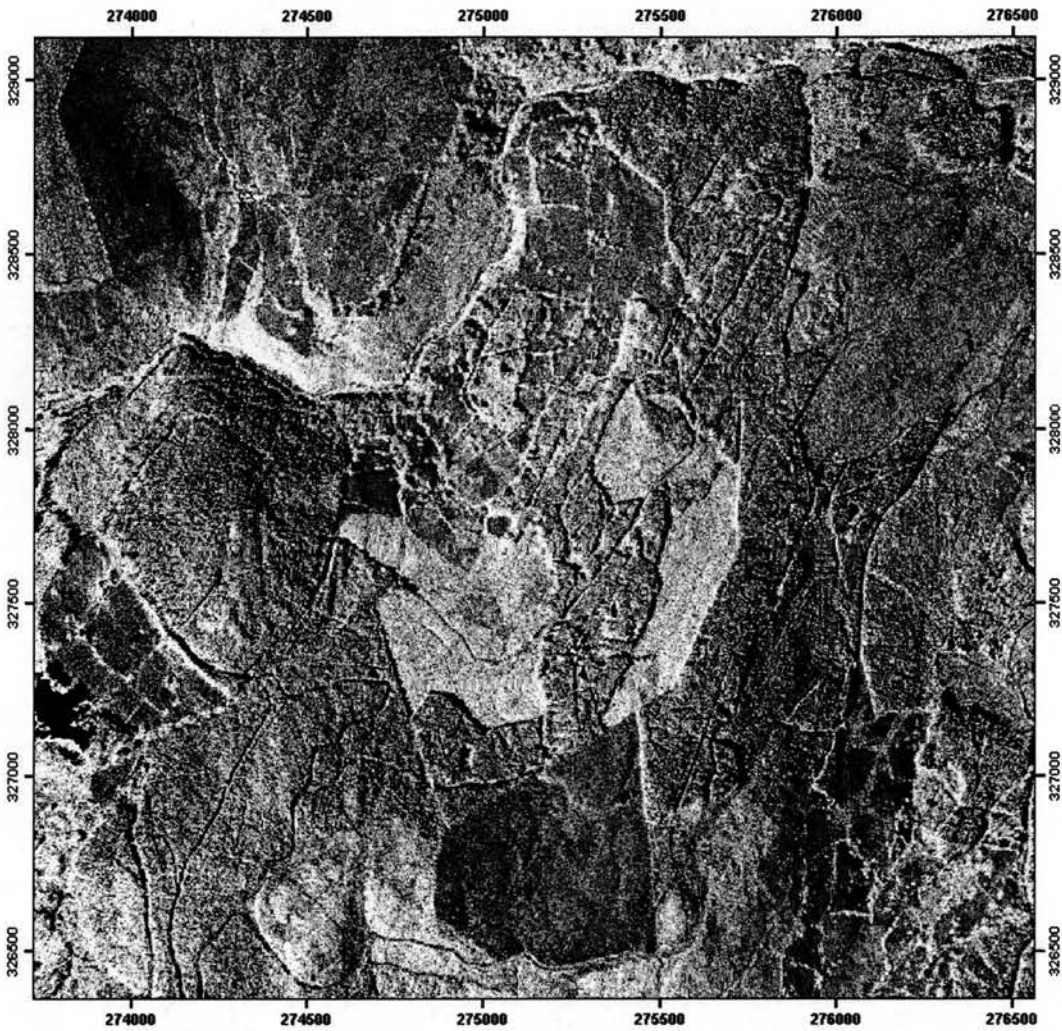


Figure 5.8 (C). Coordinates are Ordnance Survey National Grid coordinates.

5.6.2 Results of quantitative assessment

Tree height estimates produced using the Intermap Star-3i DSM minus Ordnance Survey (bald Earth) surface DEM (OSDEM) were assessed and compared to true stand height. Results of height retrieval per stand are shown below for Coed y Brenin (section 5.6.2.1), Kielder (section 5.6.2.2), Glen Affric (section 5.6.2.3) and Aberfoyle (section 5.6.2.4).

5.6.2.1 Coed y Brenin

Retrieved height for stands in Coed y Brenin show a marked improvement when compared to the DSM-DTM procedure. Height retrieval errors ranged from 3.85-75.93% when compared to validation data (table 5.4), with a mean error of $26.73\% \pm 10.92\%$ (table 5.8). Retrieved heights were underestimations as expected. Linear regression provided an average underestimation of 30%, an R^2 of 0.23 (figure 5.9 bottom) and a P -value of 0.0028, a highly significant relationship at the 95% confidence level, indicating that the retrieved heights are a strong predictor of the measured heights. A number of outliers are apparent (figure 5.9), and potential reasons for these are discussed in chapter 7.

Table 5.4 Top height retrieval using Intermap DSM-OSDEM in Coed y Brenin (metres)

Cmpt	H ₁₀₀ Meas.	H ₁₀₀ Est.	Mean	Min	Max	Diff	% Error
586L	29.00	6.98	4.26	-0.76	8.94	22.02	75.93
641H	43.00	17.93	17.24	12.40	22.04	25.07	58.31
641A	46.00	26.52	23.81	18.39	29.52	19.48	42.35
544C	32.00	20.24	16.77	-1.26	12.20	11.76	36.76
640F	32.00	21.1	14.20	3.44	27.11	10.90	34.06
586M	23.00	15.72	14.36	10.75	18.13	7.28	31.65
589F	17.00	11.91	9.94	1.95	13.98	5.09	29.94
637A	24.00	17.2	15.07	10.58	19.02	6.80	28.33
640E	32.00	23.35	16.00	6.23	25.88	8.65	27.03
558A	24.00	17.61	15.31	10.84	19.60	6.39	26.63
637K	22.00	16.24	12.48	5.89	17.16	5.76	26.18
593B	24.00	17.89	13.61	1.43	20.62	6.11	25.46
621F	28.00	21.35	19.57	16.12	23.60	6.65	23.75
586H	29.00	22.86	20.68	17.23	24.36	6.14	21.17
593G	20.00	15.81	12.97	8.22	17.87	4.19	20.95
621B	26.00	20.91	16.85	6.03	22.34	5.09	19.58
622A	9.00	7.24	4.56	0.32	8.28	1.76	19.57
593E	34.00	28.07	25.00	17.88	30.04	5.93	17.44
600C	22.00	18.22	15.95	-0.95	7.44	3.78	17.18
601I	26.00	21.54	17.42	11.09	24.16	4.46	17.15
623C	26.00	24.46	21.73	15.86	26.99	1.54	5.92
629C	31.00	29.24	26.79	22.36	30.64	1.76	5.68
545H	27.00	25.96	17.64	3.01	30.15	1.04	3.85

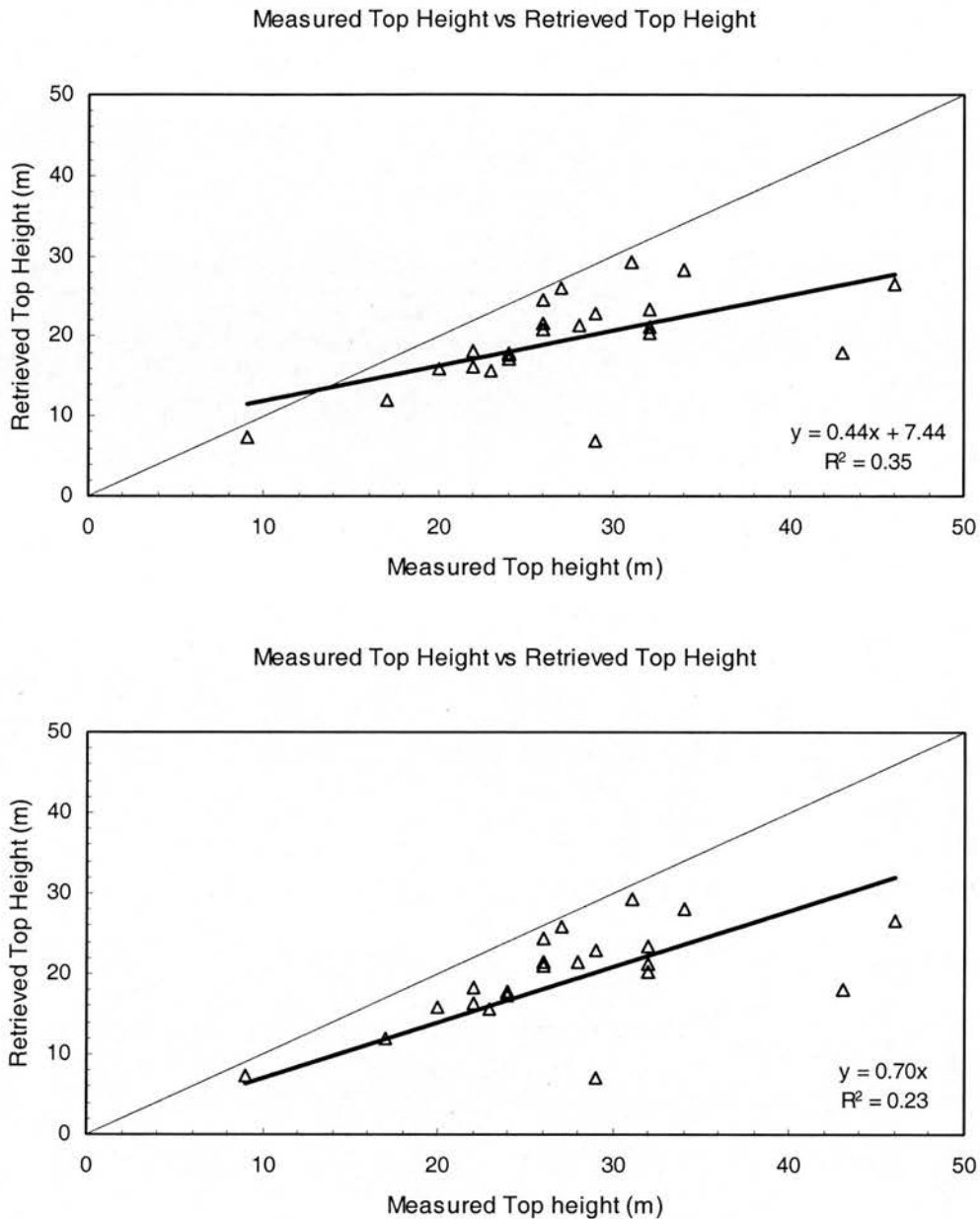


Figure 5.9 Top height retrieval in Coed y Brenin. Top: linear regression. Bottom: regression forced through 0,0 to indicate amount of underestimation.

5.6.2.2 Kielder

Height retrieval errors in Kielder ranged from 13.88-78.98% when compared to validation data (table 5.5), with a mean error of $41.77\% \pm 24.68\%$ (table 5.8). Retrieved heights were again underestimations as expected. Linear regression provided an average underestimation of 31%, an R^2 of 0.75 (figure 5.10 bottom) and

a P -value of 0.0002, a highly significant relationship at the 95% confidence level, indicating that the retrieved heights are a very strong predictor of the measured heights. A number of outliers are apparent (figure 5.10), and potential reasons for these are discussed in chapter 7.

Table 5.5 Top height retrieval using Intermap DSM-OSDEM in Kielder (metres)

Cmpt	H ₁₀₀ Meas.	H ₁₀₀ Est.	Mean	Min	Max	Diff	% Error
3636G	4.23	0.89	0.17	-1.53	1.20	3.34	78.98
3452A	6.30	1.50	0.81	-0.47	2.01	4.80	76.19
3405D	21.35	5.49	3.80	0.81	7.25	15.86	74.29
3406F	20.33	7.08	2.61	-4.00	10.34	13.25	65.18
1026A	28.15	18.85	17.51	16.17	20.71	9.30	33.04
3626A	24.96	17.77	15.68	11.30	19.31	7.19	28.81
3603E	21.67	16.27	15.64	14.53	16.84	5.40	24.91
3617A	18.93	14.31	12.81	10.31	15.68	4.62	24.40
3642A	28.80	22.74	19.16	13.11	24.13	6.06	21.04
3412A	20.83	16.92	16.18	15.23	17.61	3.91	18.76
1024C	32.82	28.26	27.11	23.04	29.07	4.56	13.88

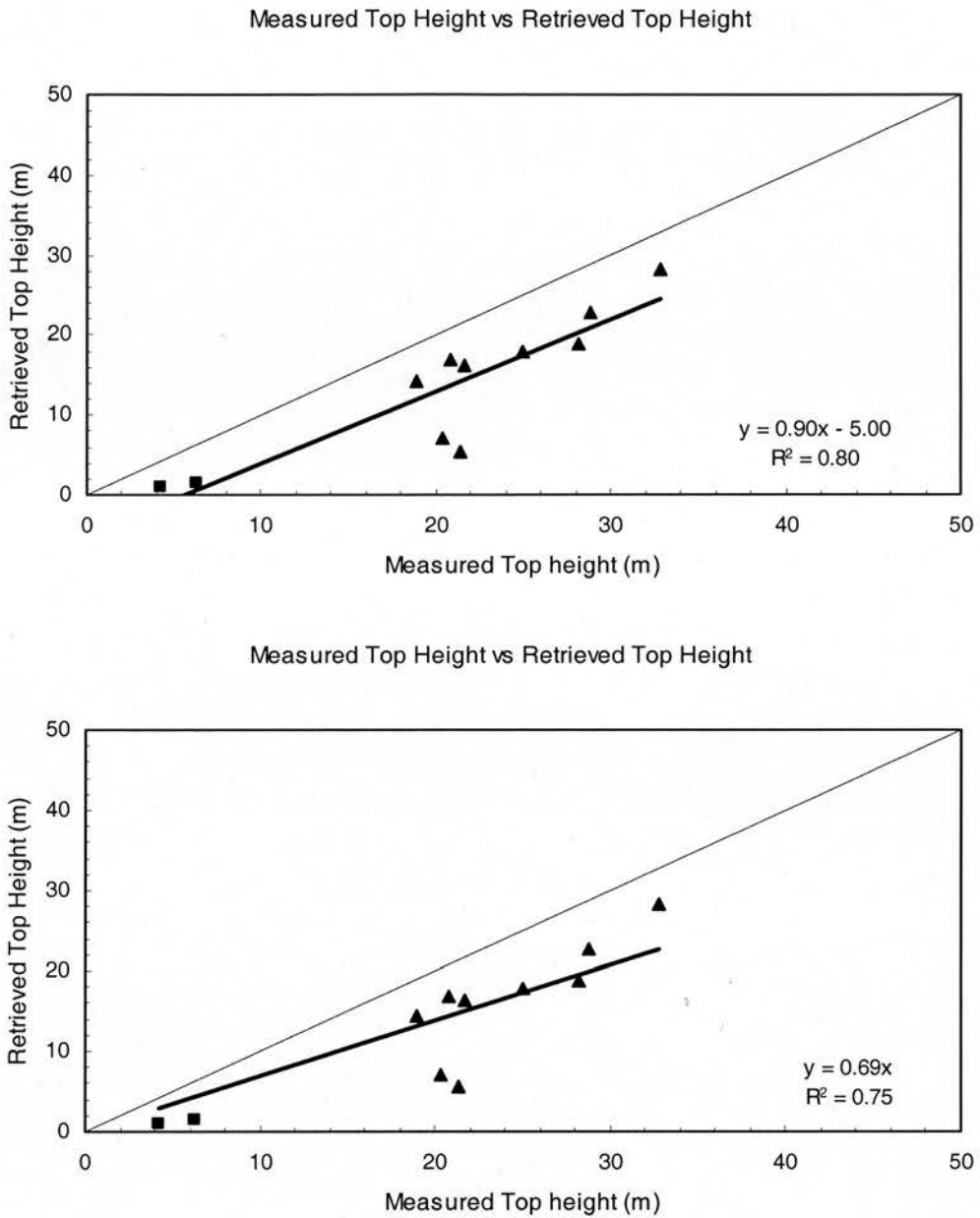


Figure 5.10 Top height retrieval in Kielder. Top: linear regression. Bottom: regression forced through 0,0 to indicate amount of underestimation. Different symbology in figures indicates different data collection instances.

5.6.2.3 Glen Affric

Height retrieval errors in Glen Affric ranged from 1.72-71.93% when compared to validation data (table 5.6), with a mean error of $38.98\% \pm 15.28\%$ (table 5.8). Retrieved heights were underestimations as expected. Linear regression provided an average underestimation of 40%, an R^2 of 0.02 (figure 5.11 bottom) and a P -value of

0.162, indicating that there is no significant relationship at the 95% confidence level, and the retrieved heights are not a good predictor of the measured heights. Regression indicates a possible relationship, but there is insufficient data to demonstrate significance. A number of outliers are apparent (figure 5.11), and potential reasons for these are discussed in chapter 7.

Table 5.6 Top height retrieval using Intermap DSM-OSDEM in Glen Affric (metres)

Cmpt	H ₁₀₀ Meas.	H ₁₀₀ Est.	Mean	Min	Max	Diff	% Error
2321A	17.63	4.95	15.20	11.10	19.00	12.68	71.93
2323D	15.60	4.45	4.15	2.20	5.39	11.15	71.48
2322A	14.07	4.35	2.84	-1.35	7.55	9.72	69.07
2324A	25.23	8.40	22.96	8.10	34.90	16.83	66.70
2321C	16.08	7.44	14.62	10.20	17.80	8.65	53.76
2106A	19.67	9.81	16.97	9.70	22.60	9.85	50.10
2324C	15.02	8.41	12.51	7.90	16.40	6.60	43.98
2313B	19.78	11.33	16.85	7.50	22.40	8.45	42.71
2321B	17.20	9.89	14.68	9.20	18.60	7.31	42.50
2322A	16.50	9.80	6.80	2.12	11.99	6.70	40.60
2322B	18.52	11.23	16.77	11.00	23.20	7.28	39.33
2322B	18.38	11.23	15.13	7.40	19.20	7.15	38.89
2306D	17.07	10.65	14.33	9.20	20.70	6.42	37.59
2306D	16.32	10.65	14.38	9.20	19.20	5.67	34.72
2324C	12.75	8.41	10.53	4.70	14.50	4.34	34.02
2313B	16.60	11.12	8.03	3.64	11.91	5.48	33.03
2105A	17.82	12.04	15.82	11.10	20.70	5.78	32.44
2310E	18.82	13.02	16.66	11.20	20.90	5.79	30.79
2322B	17.68	12.39	9.09	4.09	14.03	5.29	29.91
2320A	17.42	12.79	9.75	4.96	15.25	4.62	26.54
2105C	17.28	12.82	16.32	12.00	19.90	4.46	25.83
2322A	15.87	12.29	10.49	6.79	13.53	3.58	22.56
2312B	18.72	15.09	17.25	11.90	21.70	3.63	19.39
2103A	19.75	16.78	19.00	11.60	23.80	2.97	15.03
2323E	10.67	10.48	7.69	3.61	11.72	0.18	1.72

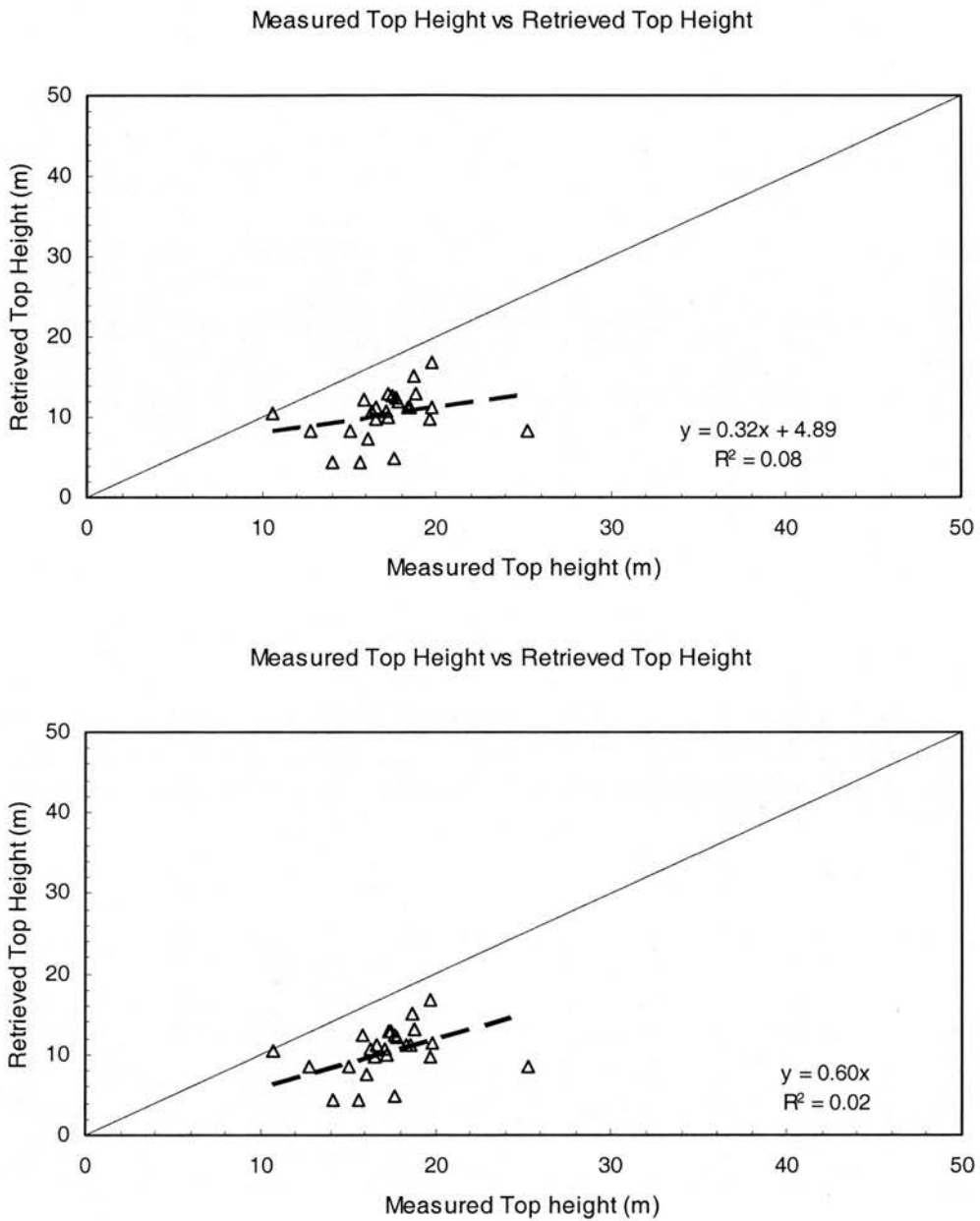


Figure 5.11 Top height retrieval in Glen Affric. Top: Linear regression. Bottom: regression forced through 0,0 to indicate amount of underestimation. Dashed line indicates a possible relationship, but there is insufficient data to demonstrate significance.

5.6.2.4 Aberfoyle

Height retrieval errors in Aberfoyle ranged from 15.79-25.16% when compared to validation data (table 5.7), with a mean error of $18.76\% \pm 16.44\%$ (table 5.8). Retrieved heights were underestimations as expected. Linear regression provided an

average underestimation of 18%, an R^2 of 0.90 (figure 5.12 bottom) and a P -value of 0.010, a significant relationship at the 95% confidence level, indicating that the retrieved heights are a moderate predictor of the measured heights. A number of outliers are apparent (figure 5.12), and potential reasons for these are discussed in chapter 7.

Table 5.7 Top height retrieval using Intermap DSM-OSDEM in Aberfoyle (metres)

Cmpt	H ₁₀₀ Meas.	H ₁₀₀ Est.	Mean	Min	Max	Diff	% Error
2251H	22.02	16.48	14.52	11.00	18.00	5.54	25.16
2251F	19.33	15.76	12.83	5.00	17.00	3.57	18.47
2184E	21.68	17.72	15.48	11.00	19.00	3.96	18.27
2219A	27.18	22.80	21.33	18.00	24.00	4.38	16.11
2219B	22.61	19.04	15.90	10.00	20.00	3.57	15.79

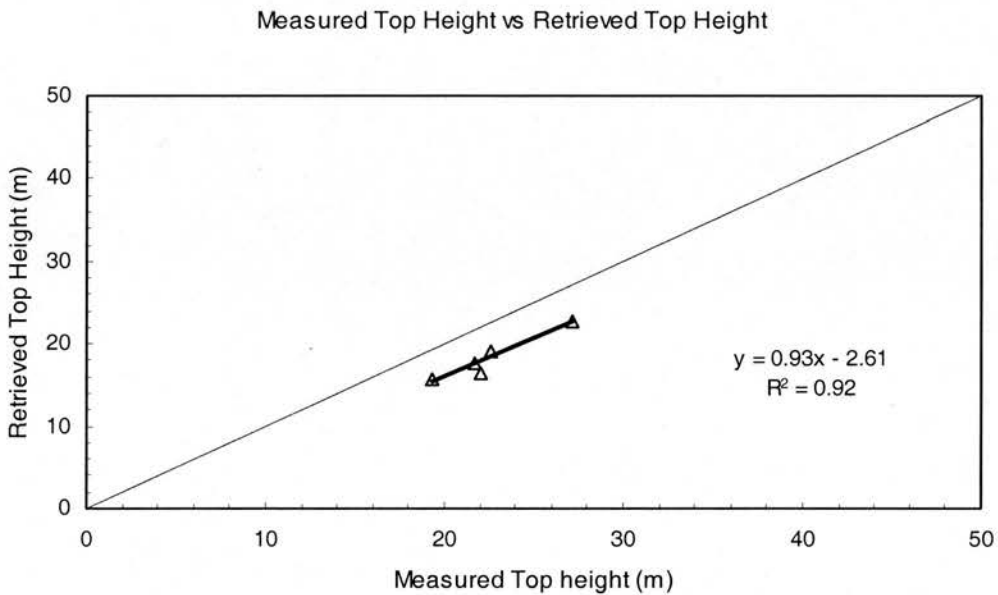


Figure 5.12 (top)

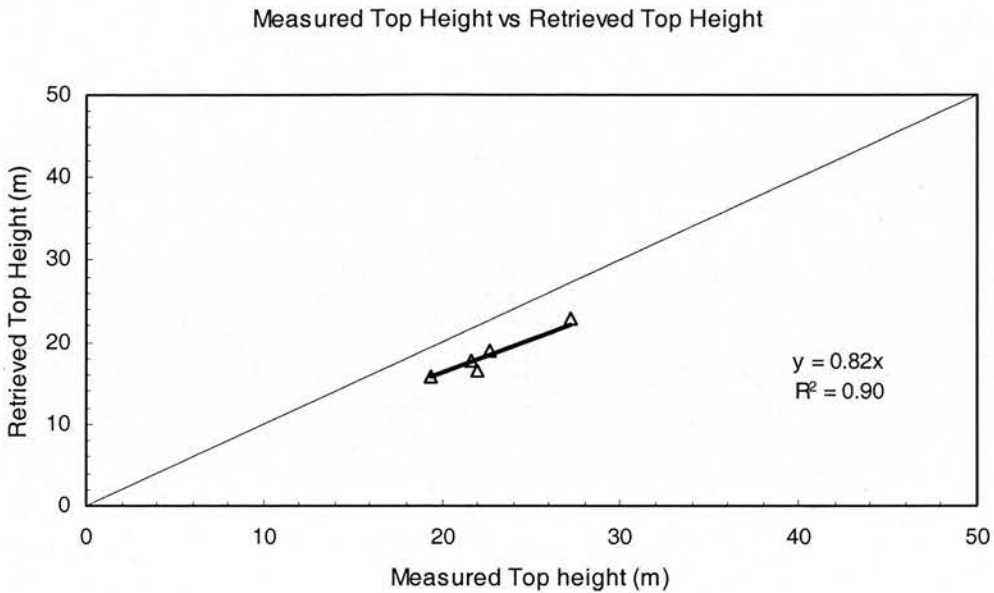


Figure 5.12 Top height retrieval in Aberfoyle. Top: Linear regression. Bottom: regression forced through 0,0 to indicate amount of underestimation.

5.6.2.5 Combined results

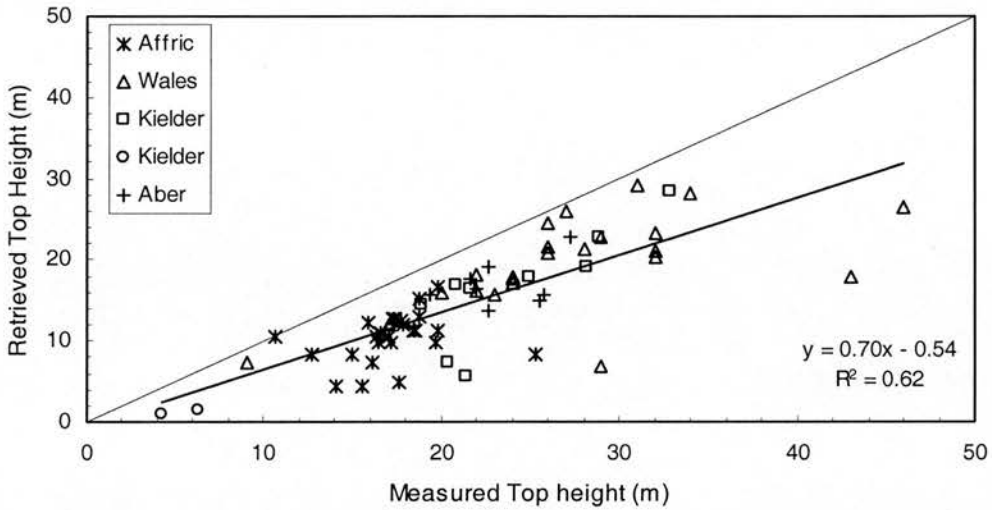
Combined height retrieval errors across the four test sites ranged from 4.20m to 7.72m, with the average error ranging from 18.76-41.77% when compared to validation data, with an average error of $33.48\% \pm 8.20\%$ (table 5.8), which is a similar magnitude to those found using X-band data (e.g. Weydahl *et al.*, 2003; Walker, *et al.*, 2004; Brown and Saranbandi, 2003). Retrieved heights were underestimations as expected. Linear regression provided an average underestimation of 32%, an R^2 of 0.62 (figure 5.13 bottom) and a P -value of $1.54E^{-14}$, a highly significant relationship at the 95% confidence level, indicating that the retrieved heights are a very strong predictor of the measured heights. A number of outliers are apparent (figure 5.13), and potential reasons for these are discussed in chapter 7.

Table 5.8 Summary of top height retrieval using Intermap DSM-OSDEM

Forest	Mean error				Combined error			
	m	SE* (m)	%	SE* (%)	m	SE* (m)	%	SE* (%)
Coed Y Brenin	7.72	3.16	26.73	10.92				
Kielder	7.12	4.21	41.77	24.68				
Glen Affric	6.82	2.67	38.98	15.28				
Aberfoyle	4.20	3.68	18.76	16.44	6.99	1.71	33.48	8.20

*SE = Standard error at 95% confidence interval.

Measured Top Height vs Retrieved Top Height



Measured Top Height vs Retrieved Top Height

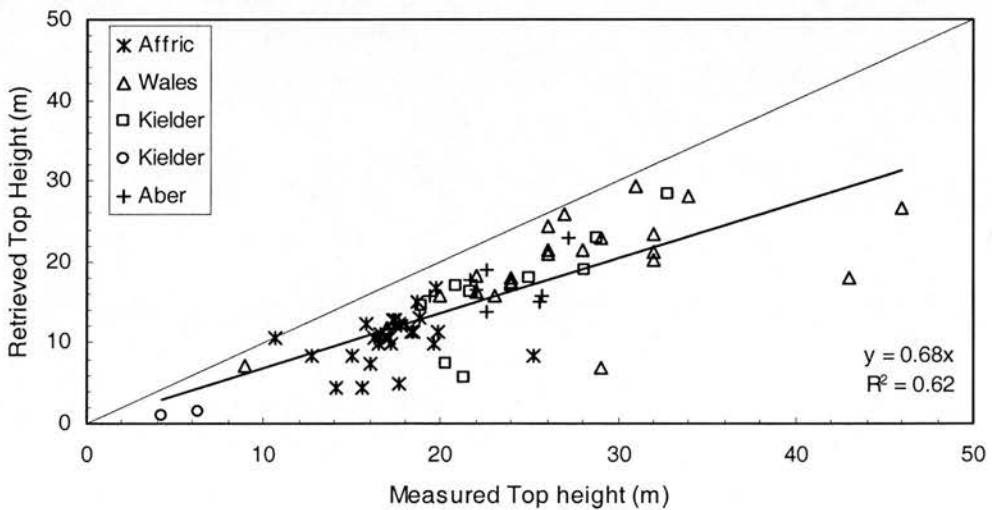


Figure 5.13 Top height retrieval in all test sites. Top: Linear regression. Bottom: regression forced through 0,0 to indicate amount of underestimation. Different symbology for Kielder data indicate different data collection instances.

5.7 Single species height retrieval

Previous sections have discussed top height retrieval with a range of species. This section assesses height retrieval within a single species. Two of the most abundant species within the test plots are discussed here, Sitka spruce (*Picea sitchensis*), which is also the UK's most common timber crop, and Scots pine (*Pinus sylvestris*), which is a key native and semi-natural species. Within Sitka spruce stands, height retrieval underestimations ranged from 18-24% with R^2 values of 0.84-0.97 (figure 5.14), and P -values ranging from 0.010 to $1.43E^{-6}$, a significant relationship at the 95% confidence level, indicating that the retrieved heights are a strong predictor of the measured heights. This shows an improvement on underestimations with multiple species, where underestimation was around 32% with an R^2 of 0.61 (section 5.6.2.5). The most interesting point to note here is the consistency of the height retrieval across three different test sites. Within Scots pine stands, height retrieval underestimation was 40% with an R^2 value of 0.04 (figure 5.15) and a P -value of 0.302, not a significant relationship at the 95% confidence level, indicating that the retrieved heights are not a significant predictor of the measured heights. This displays a marked difference to the Sitka spruce stands, with the most notable difference being the lack of a relationship for underestimation in the Scots pine stands (R^2 of 0.04) when compared to Sitka spruce stands (R^2 of 0.84-0.97). There is clearly a difference in height retrieval when assessing at the species level. Differences between species are believed to be due to differing canopy characteristics. See chapter 7 for further discussions on possible reasons for underestimation due to canopy characteristics.

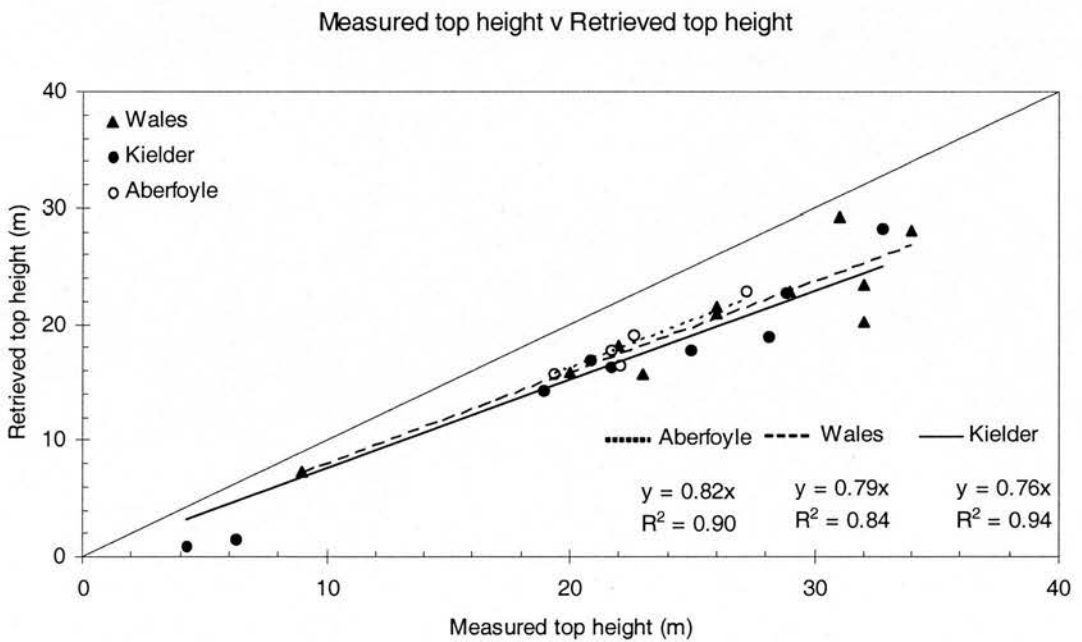
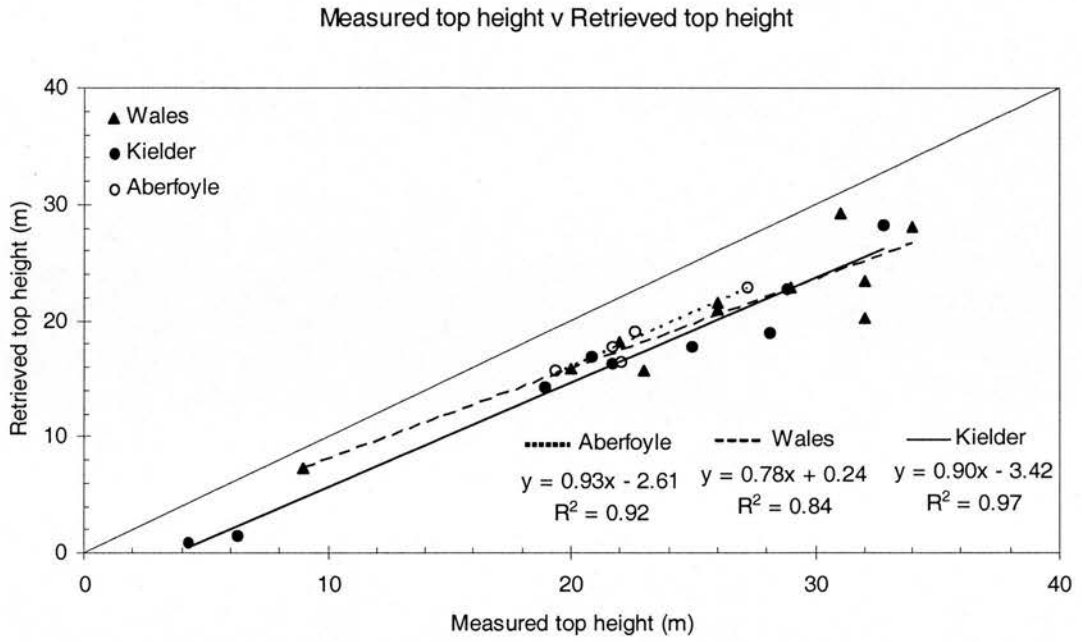


Figure 5.14 Sitka spruce top height retrieval in Aberfoyle, Kielder and Coed y Brenin. Top: Linear regression. Bottom: regression forced through 0,0 to show combined underestimation.

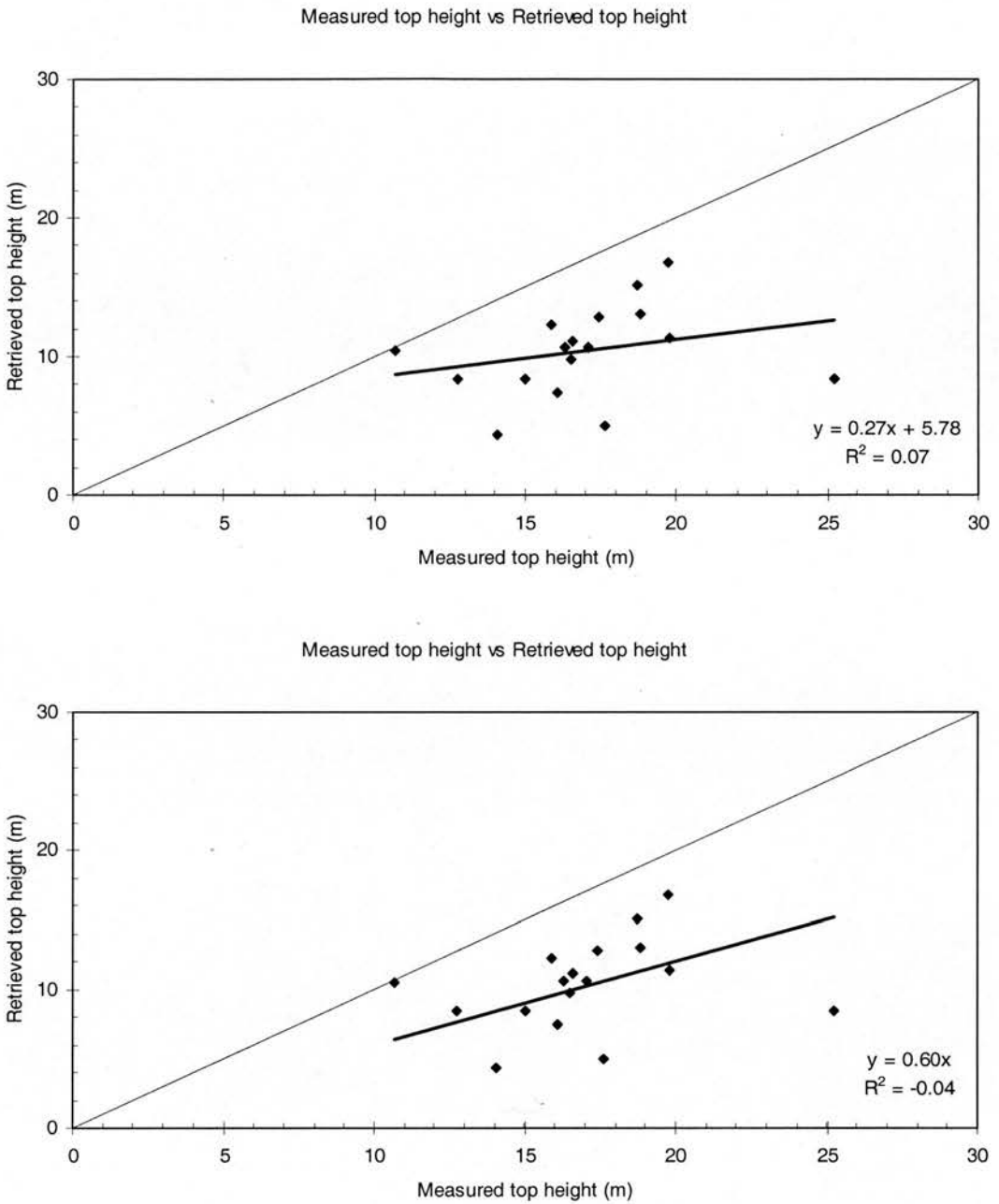


Figure 5.15 Scots pine top height retrieval in Glen Affric. Top: Linear regression. Bottom: regression forced through 0,0 to show combined underestimation

5.8 Tree height maps

To this point, height retrieval of individual stands has been discussed. However, the ability of SAR to map large areas rapidly lends itself to more wide scale mapping. The qualitative assessments of height difference undertaken in sections 5.5 and 5.6

gave an indication of vegetation akin to a map. By putting numbers to, and classifying, these images it is possible to produce retrieved tree height maps of entire forest landscapes. Initially, the DSM-DTM procedure was undertaken, resulting in a tree height map (figure 5.16). As was expected, a poor representation of tree height was achieved; reasons for this have been discussed in chapter 4 and section 5.5. Secondly, the DSM-OSDEM procedure was performed, resulting in a more representative tree height map (figure 5.17). It should be noted that these maps are of retrieved height, and so still represent an underestimation of the true height in the order of 30% (section 5.6.2). Good agreement is seen when compared to Forestry Commission stand boundaries (figure 5.18). Section 5.9 further discusses methods of improving the height retrieval. Further uses of forest height maps are discussed in chapter 8.

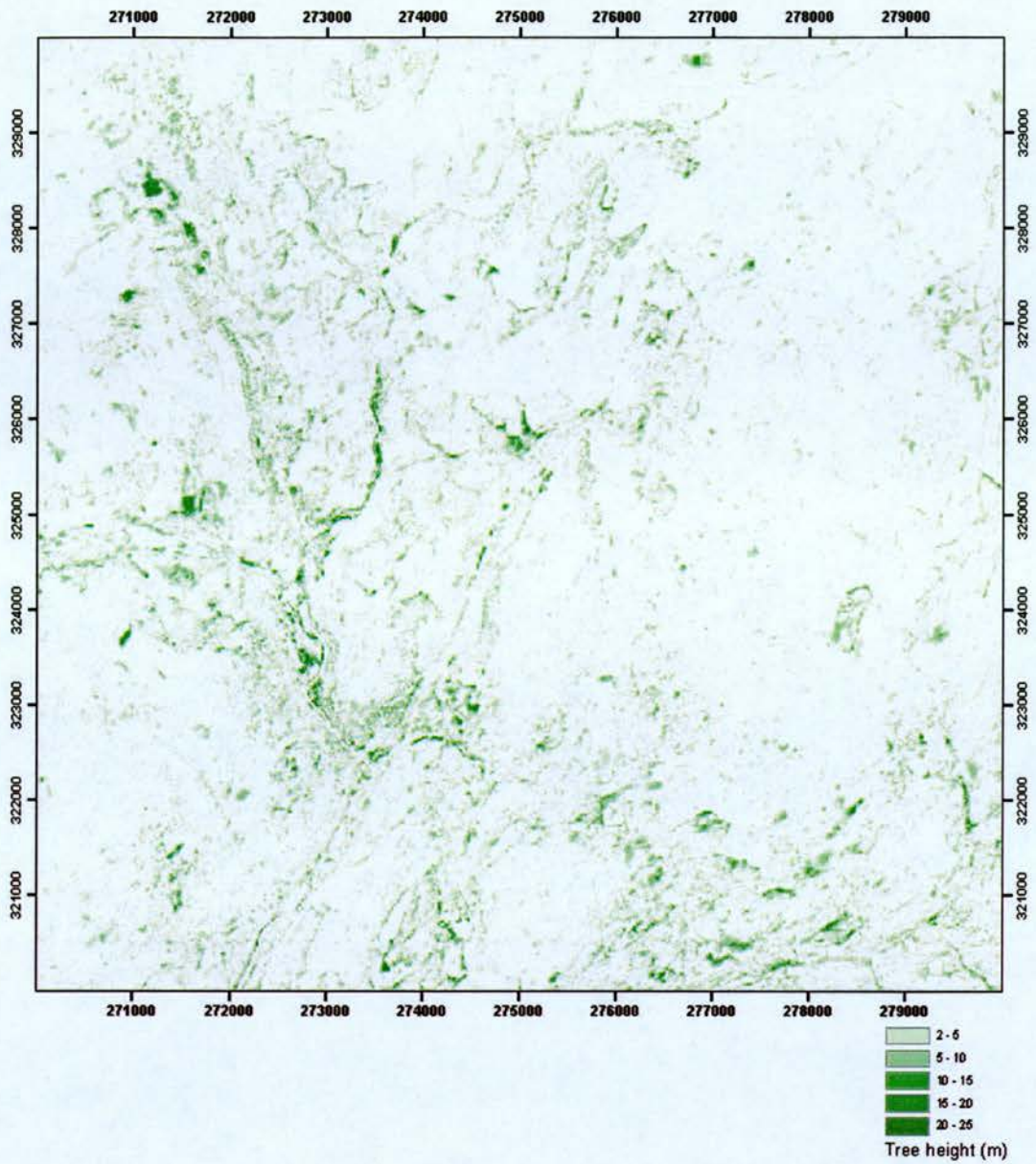


Figure 5.16 Retrieved tree height map produced from DSM-DTM procedure, Coed y Brenin. Compare to figure 6.17. Coordinates are Ordnance Survey National Grid coordinates.

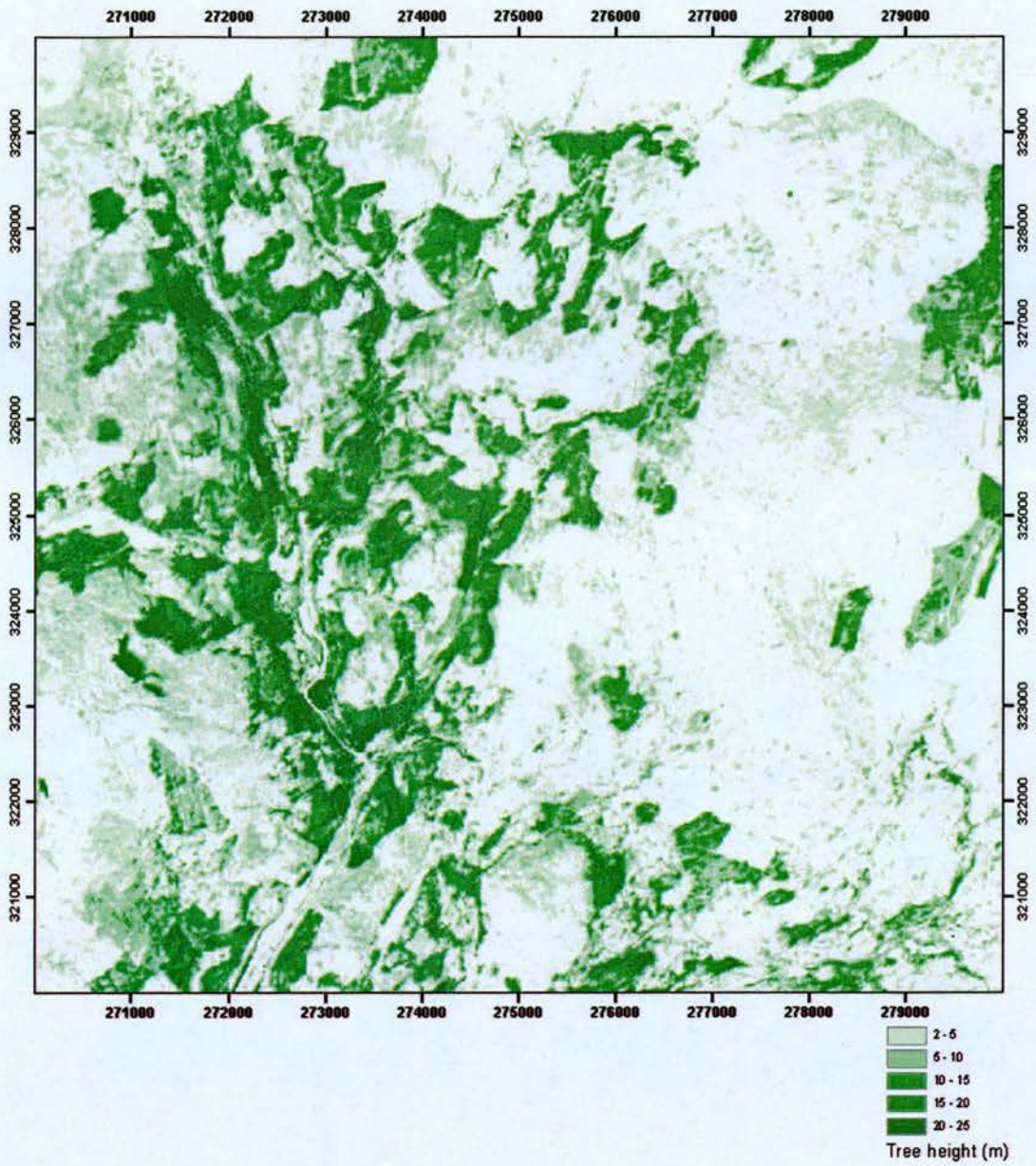


Figure 5.17 Retrieved tree height map produced from DSM-OSDEM procedure, Coed y Brenin. Compare to figure 6.16. Coordinates are Ordnance Survey National Grid coordinates.

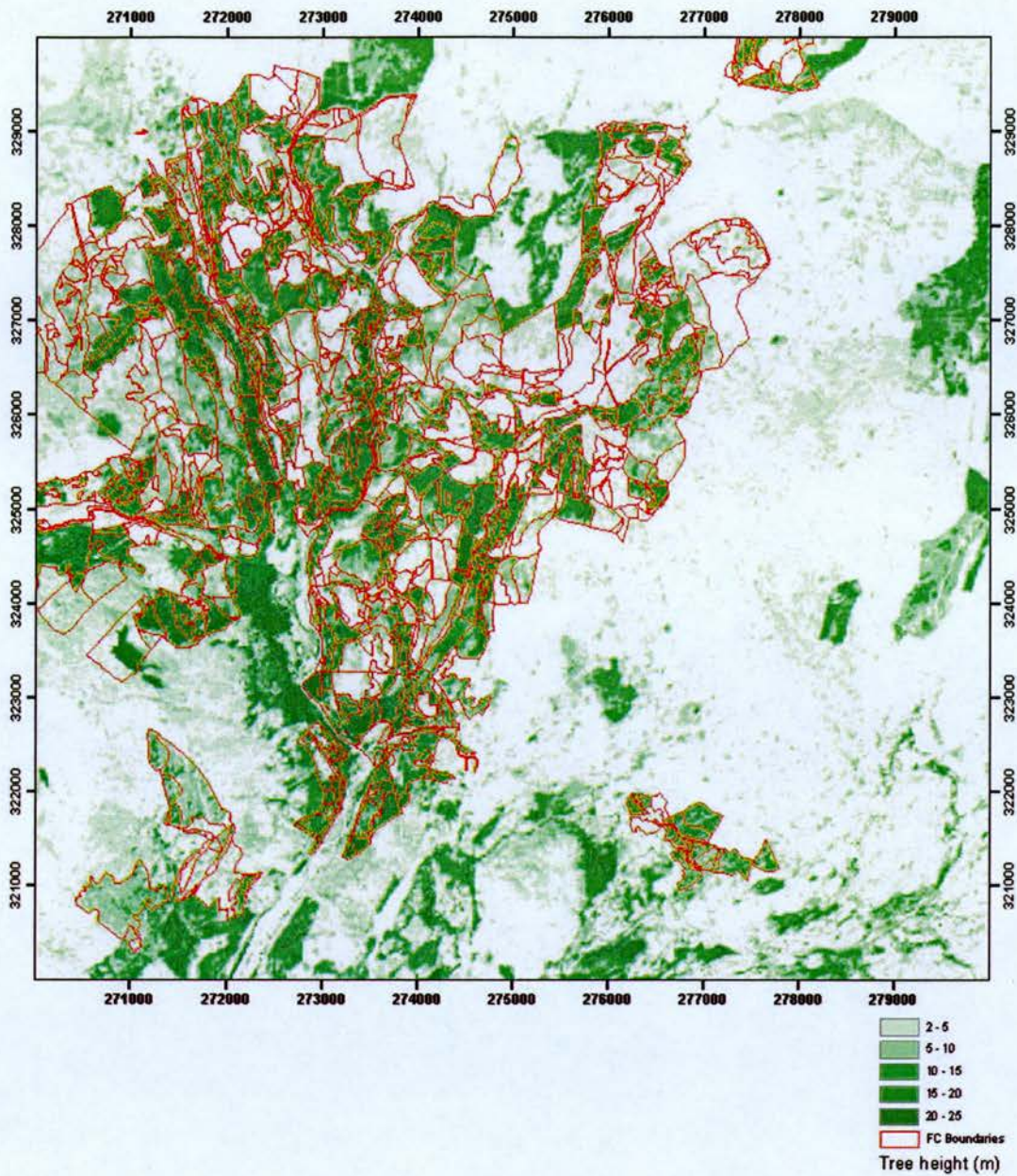


Figure 5.18 Retrieved tree height map produced from DSM-OSDEM procedure with Forestry Commission stand boundaries overlaid, Coed y Brenin. Coordinates are Ordnance Survey National Grid coordinates.

5.9 Improved height estimation using ground data

As mentioned previously, the retrieved heights are underestimations of the actual measured stand top height. This will always be the case when using SAR for this application due to signal penetration and horizontal averaging (see section 5.3).

Although the retrieved heights give a reasonable estimation of top height, the estimation can be improved through the use of ground data calibration. For example, in section 5.6.2.5 the average underestimation based on regression was 32% (figure 5.13 bottom). A simple way of correcting the retrieved height is to invert the height retrieval for all test sites (figure 5.19), and use the regression equation to correct the retrieved heights. It may also be suitable to use a more localised inverted correction, whereby only height retrievals from a particular test site are inverted, and this regression equation applied to the initial retrieved heights for that test site (figure 5.20).

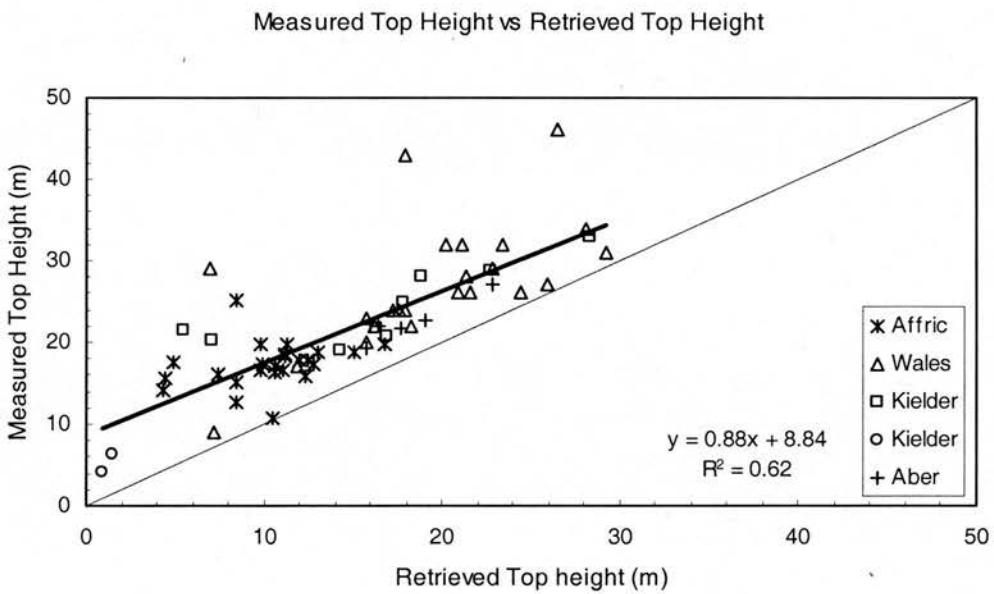


Figure 5.19 Inverted height retrieval for all test sites.

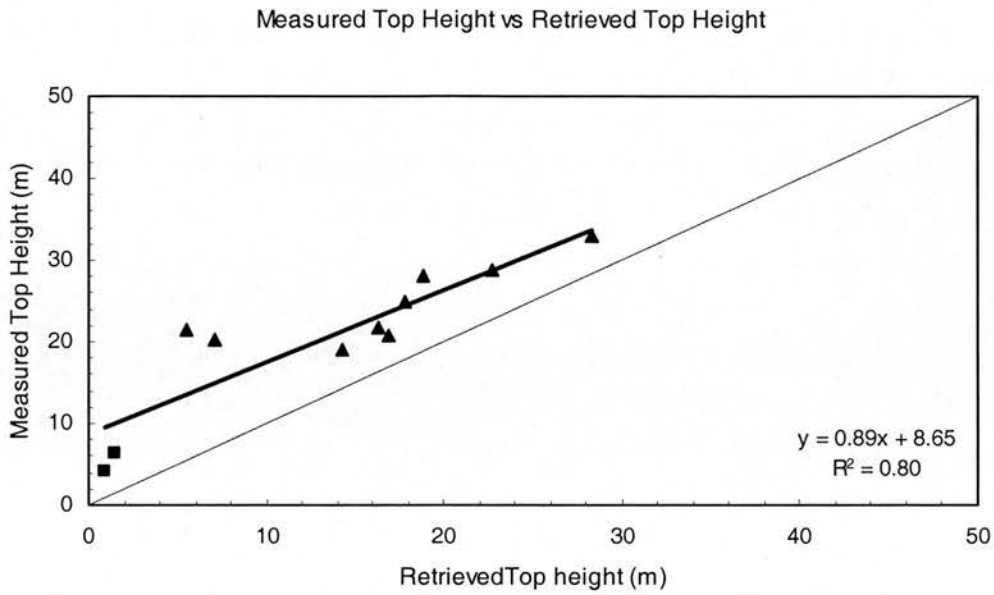


Figure 5.20 Inverted height retrieval for Kielder.

Table 5.9 shows results of these corrections for stands in Kielder. Height retrieval errors are seen to reduce from an average of 42% to 27% (figure 5.21). However, a better improvement to retrieved height, in terms of the average metres difference (figure 5.22), is achieved by using the relevant regression equations as opposed to simply adding on 32% of the retrieved height. By simply adding to the height, a mean difference of 2.75 m is present, whereas with the regression methods, differences of less than 10 cm are obtainable. Of note, is the increase in error attributed to the stand with measured height 4.23 m. By using the regression methods, a significant increase in error occurs, from 79% to 123%. This error is due to the fit of the regression line around the lower retrieved heights. A similar situation occurs with the stand of measured height 6.30 m; there is a reduction in error, although not as drastically as other stands. It is assumed that the large error attributed to these two stands is due to the signal penetrating through to the ground

surface, thus greatly increasing the ground contribution to the scattering phase centre, which lowers retrieved height, and thus the error relative to total height is high. The linear regression model fitted to the data does not appear to fit well to small trees (e.g. smaller than 6.5 m), and overcompensates the height correction, thus increasing error. Therefore data <6.5 m have been removed from the statistical analysis due to the poor fit as discussed above. Application of linear regression to top heights greater than 18m only allows corrected retrieved height to be achieved with errors reduced to $12.27\% \pm 8.02\%$, with a mean difference of $0.92 \text{ m} \pm 0.60 \text{ m}$ when using the generic correction (table 5.9). However, it should be noted that the errors range from -2.90 m to 7.68 m, such that the mean error is <1m. Application of linear regression to stands out with the range of heights the regression was calculated on may produce differences due to the varying age structure. For example, different mean errors would be achieved when assessing over a height range of 18-30 m, as opposed to say 5-30 m. Overall, there is no significant difference between applying a generic correction (based on data from all study sites) or a localised correction (based on data from a single study site and applied only to that study site); a generic correction is easier to apply as the procedure does not require localised ground data for correction. Given these results, the generic regression correction was applied to the full data set from all 4 study sites, resulting in an increased overall accuracy from 33.48% to 16.77%. For trees greater than 18m in height, the accuracy is further increased to 12.19%, with a P-value of 8.52E^{-12} , a highly significant relationship at the 95% confidence level, indicating that the retrieved heights are a very strong predictor of the measured heights. A corrected tree height map for Coed y Brenin in Wales is shown in Figure 5.23.

Table 5.9 Results of height inversion for Kielder.

H_{100}		Meas. = Retr. + 32%		Meas. = 0.88Retr. + 8.84 (Generic correction)		Meas. = 0.89Retr. + 8.65 (Site specific correction)		
Meas. m	Retr. m	Difference m	Difference %	Est. m	Difference m	Est. m	Difference %	
21.35	5.49	15.86	74.29	7.25	14.11	66.06	7.82	36.61
20.33	7.08	13.25	65.18	9.35	10.99	54.04	5.38	26.46
28.15	18.85	9.30	33.04	24.88	3.27	11.62	2.73	9.68
24.96	17.77	7.19	28.81	23.46	1.50	6.02	0.49	1.98
21.67	16.27	5.40	24.91	21.48	0.19	0.88	-1.46	6.75
18.93	14.31	4.62	24.40	18.89	0.04	0.20	-2.46	12.99
28.80	22.74	6.06	21.04	30.02	-1.22	4.23	-0.09	0.31
20.83	16.92	3.91	18.76	22.33	-1.51	7.23	-2.88	13.83
32.82	28.26	4.56	13.88	37.30	-4.49	13.67	-0.99	3.00
6.30	1.50	4.80	76.19	1.98	4.32	68.56	-3.69	58.50
4.23	0.89	3.34	78.98	1.17	3.05	72.26	-5.22	123.44
Avge.		7.12	41.77	2.75	27.71	-0.09	27.22	-0.03
SE*		± 4.20	± 24.68	± 1.63	± 16.38	± 0.05	± 16.09	± 0.02
Avge.		7.79	33.81	2.54	18.22		12.27	0.95
SE*		± 5.09	± 22.09	± 1.66	± 11.90		± 8.02	± 8.10
Without 6.30 and 4.23 above								

Meas. = Measured, Retr. = Retrieved, Est. = Estimated. * Standard error at 95% confidence interval.

Retrieved height vs Corrected height

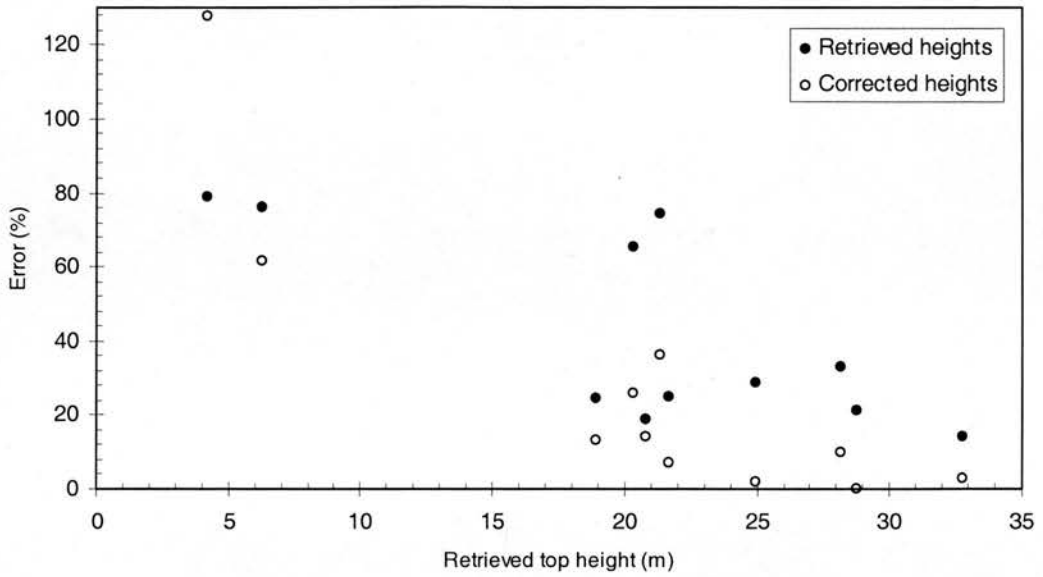


Figure 5.21 Retrieved height error vs Corrected height error, based on generic regression for Kielder. The generic equation is the inverted algorithm correction from all study sites applied to the Kielder study site ($Meas. = 0.88Retr. + 8.84$). Read in conjunction with table 5.9.

Retrieved height difference vs Corrected height difference

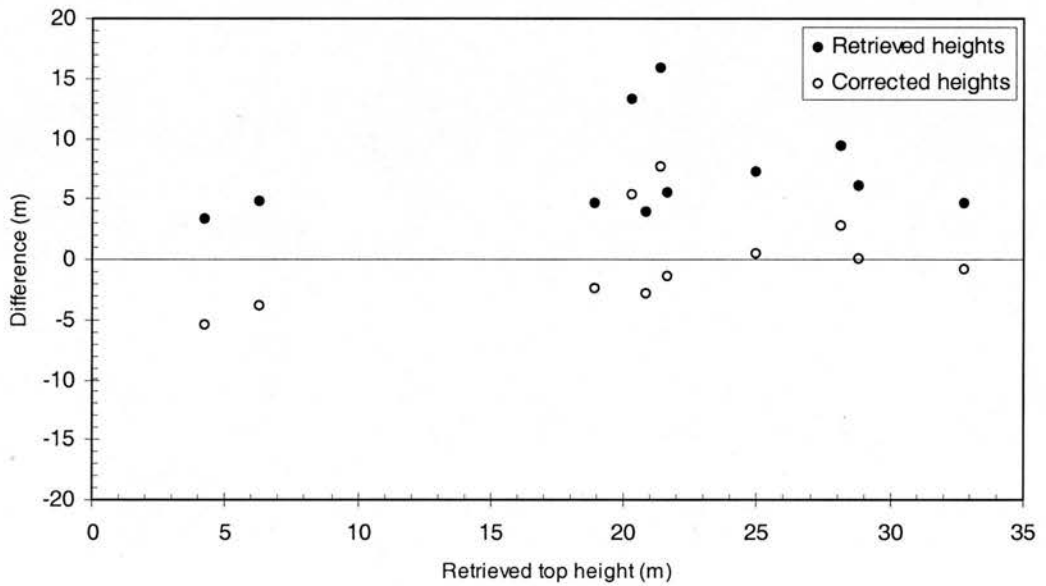


Figure 5.22 Retrieved height difference vs Corrected height difference, based on generic regression for Kielder. Zero line is shown.

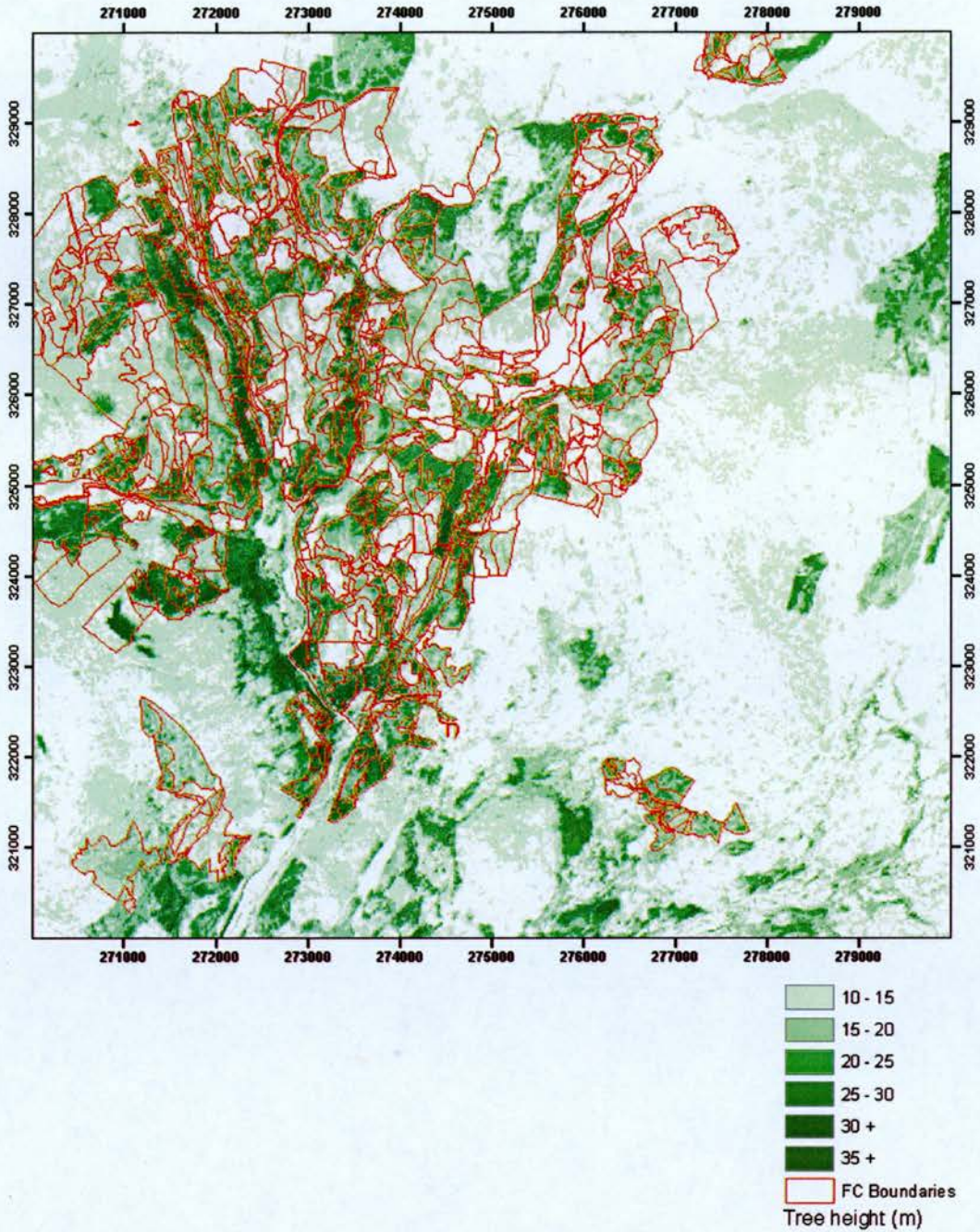


Figure 5.23 Corrected tree height map for Coed y Brenin, Wales. Based upon generic regression correction, see table 5.9. Coordinates are Ordnance Survey National Grid coordinates.

5.10 Discussion and conclusion

This chapter has assessed Intermap STAR-3i products for stand top height retrieval over 4 test sites in the UK. Height difference between a canopy surface (DSM) and a ground surface (DTM or OSDEM) was seen as being indicative of vegetation presence, and in particular forest plantation stands. Initially, the DSM-DTM procedure was performed and assessed qualitatively to see if the height difference was representative of forest stands. Although height differences were present, they were not characteristic of forest stands as indicated by Forestry Commission stand boundaries. Further, the height differences appeared to be significantly lower than the apparent visual height in aerial photographs. Quantitative assessment of a number of forest stands verified that the height difference between the DSM and the DTM was not an accurate estimate of the measured stand top heights. Average errors for top height retrieval were in the region of 90%. The explanation for this error was predominately attributed to the limitation in the DTM interpolation discussed in Chapter 5, which results in the DSM-DTM difference reducing as one goes further into a stand. As such, the DSM-DTM procedure was deemed not appropriate for tree height estimation in plantation forests.

A qualitative assessment of the height difference between the DSM and the OSDEM proved more favourable. The areas of height difference were greater in extent and height when compared to the DSM-DTM difference. Further, the height difference was more representative of stands as demarcated by the Forestry Commission boundaries. Quantitative assessment of the DSM-OSDEM procedure also produced favourable results. As expected, underestimation of top height was present, with an

average height retrieval error of 33.5%, ranging from around 19% to 42%. There are several possible reasons for the underestimation, such as penetration and attenuation of the signal, SAR geometry effects such as incidence angle, slope and edge effects, and target properties such as planting density, tree height, and canopy characteristics such as shape and density. These are further discussed in Chapter 7.

Investigation into height retrieval of single species, Sitka spruce and Scots pine, was also undertaken to see if there was an effect on height retrieval. In Sitka spruce stands, height retrieval underestimation ranged from 18-24% and for Scots pine, the underestimation was 40%. The Sitka spruce results show a marked improvement to the Scots pine results, with the improvement being primarily attributed to the difference in crown characteristics (e.g. density) of the two species. Further discussion of this is in chapter 7.

After assessing individual stand height retrievals, the DSM-DTM/OSDEM procedures were applied to the entire area of Coedy Brenin forest to produce tree height maps. As expected, given previous results, the DSM-DTM height map poorly represented the forest district when compared to the DSM-OSDEM height map, which showed a greater area of forest, corresponding to Forestry Commission boundaries, as well as displaying a more appropriate range of heights.

The heights retrieved were all underestimates, and to improve the estimates field measured tree height data was assessed to calibrate the model. Three routines were undertaken, firstly to simply adjust the retrieved heights based upon average

underestimations; as such the heights were increased by 32%. This resulted in the corrected height error being reduced to 27.7%, although an average difference of 2.75 m was still present; this was an improvement on the raw retrieval error of 7.12 m. A further routine was undertaken which involved regression of the measured heights against the retrieved heights at a generic scale (all test sites) and a localised scale (an individual test site). These routines were an improvement on the former routine, again reducing errors to less than 12.5%, with an average difference of less than 1m. There was no significant difference between the generic and localised routines, and as such it is recommended that the generic routine be used as this does not require ground data from a specific test site and can be universally applied. The generic correction was applied to the DSM-OSDEM procedure to improve the tree height map.

In conclusion, the DSM-OSDEM procedure produces height estimations with an initial underestimation error of around 33.5%, which can be significantly reduced to less than 12.5% (<1 m) when using correction routines based upon generic ground reference data. Potential reasons for underestimation are discussed further in chapter 7.

6 Results of tree height estimation over heterogeneous woodland

“There is no top. There are always further heights to reach”

Jascha Heifetz (Russian born American Violinist, 1901-1987)

6.1 Introduction, aim and objectives

This chapter discusses height retrieval over heterogeneous woodland in Glen Affric, Scottish Highlands, and in the Rio Bravo Conservation Management Area (RBCMA) in Belize. Both of these study sites are pine dominated (see chapter 3), and as such are complementary environments for assessing InSAR height retrieval. Previous chapters have demonstrated that the Intermap DTM is an inappropriate product for height retrieval (chapter 4), and that a short-wavelength InSAR DSM minus a reliable surface DEM (such as the OSDEM) procedure produces height retrieval results approaching field measured heights (chapter 5). The Belize national elevation data set has a contour interval of 20m and does not have a high enough horizontal or vertical resolution to resolve the low lying relief of the savanna region for tree height retrieval using the techniques presented in this study. Therefore, a ground survey was undertaken to produce a high resolution ground DEM (see section 3.4). The RBCMA benefits from having been mapped with two InSAR systems (see section 3.3) and the retrieved vegetation height estimates are produced by subtracting the surveyed DEM from the JPL C- and Intermap X-band InSAR DSM's. It should be noted that the X-band product used in Belize was produced using an older version of

the STAR-3i sensor, which has a lower vertical resolution than the STAR-3i used for the analyses in chapters 4 and 5 in the UK. See section 3.3 for further details.

The aim of this chapter is to assess Intermap STAR-3i X-band and JPL AIRSAR C-band InSAR products for tree height retrieval over heterogeneous woodland. The objectives to meet the aim are (i) to qualitatively assess the height retrieval produced over semi-natural woodland in Glen Affric and woody savanna in the RBCMA, and (ii) to quantitatively assess the tree height estimations from the DSM-DEM procedure with comparison to tree height data gathered in the field.

6.2 Heterogeneous tree height retrieval

Figure 6.1 summarises the procedure used to measure tree height in heterogeneous woodlands as discussed in section 3.5.3. In this chapter, tree height is defined as total height for individual tree measurements (see section 1.2.3).

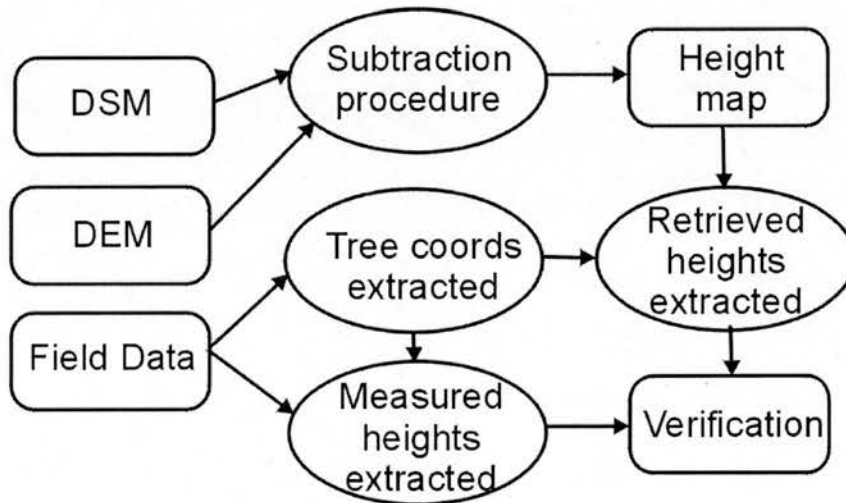


Figure 6.1 Flow chart summary of heterogeneous tree height retrieval.

6.3 Expected sources of error

Sources of error that apply to homogeneous plantations, as discussed in section 5.3, apply equally to heterogeneous woodlands. The amount of low canopy and degree of canopy openness (ground visibility), and therefore height underestimation, is expected to be higher in heterogeneous environments presented. This is primarily due to the more open nature of individual crown structure, and the combination of crowns into an open canopy. C-band (5.5 cm), being a longer wavelength than X-band (3 cm) (although still significantly longer than optical wavelengths), is expected to penetrate further into the canopy, resulting in a lower vertical location of the scattering phase centre, and subsequent estimated tree height. The tree height estimation procedure differs from that of homogenous plantation where top height was estimated by averaging retrieved heights within a stand. Here, height information is derived from locations that relate to measured trees. With this method, the effect of layover becomes more relevant; consider the situation where two trees of different heights occupy the same range resolution cell (Hoekman and Verekamp, 2001). It is expected that an individual measured ground coordinate may not be in exactly the same geographic position in the InSAR DSM. This may result in heights for different locations being compared, resulting in a discrepancy in the height retrieval which is not related to radar penetration alone (see chapter 7). The two test sites discussed consist of sparse trees and open canopies. In open woodland the returned signal is influenced by the ground and understorey which in turn influences the location of the scattering phase centre which is no longer governed primarily by the crown shape and signal extinction.

6.4 DSM-OSDEM height retrieval over heterogeneous semi-natural woodland

6.4.1 Results of qualitative assessment

Visual assessment of the DSM-OSDEM height difference map was performed in an area of semi-natural Scots pine in Glen Affric (figure 6.2). It was expected that the height difference would be indicative of tree height and location. There is a slight horizontal shift in the Forestry Commission boundaries compared to the apparent location of trees in the ORRI. This displacement does not appear to be consistent across the image, or wider area, and as such is not consistent with a data shift. It is more likely that the stand boundaries are inconsistent. Aerial photo interpretation of stand boundaries is open to interpreter bias, and as such, a boundary line is subjective. Often the 'line' is not clear and may be more 'fuzzy', and the interpreter has to decide where the boundary is to be placed. It should also be noted that there is a significant time difference between when the boundary lines were interpreted from aerial photography, and when the SAR over-flight occurred. It is possible that there have been changes in vegetation composition and location over time. The location of the boundary line compared to the ORRI has only been assessed visually, and is also open to the limitations discussed.

Figure 6.3 highlights three areas of interest in the image, the upper ellipse is the height retrieval test stand, and the other two ellipses depict Scots pine 'ridges'. These areas of interest are nicely highlighted in the height difference image (figure 6.4), and the tree heights appear to be within a reasonable range for the area (e.g. heights of individual trees in the order of 30+ m) and relate well with known field verified vegetation assemblages (figure 6.5), and correspond with Forestry

Commission boundaries (figure 6.6), although the displacement in boundaries is still evident.

Figures 6.7 and 6.8 show the location and retrieved height of a transect across the test stand. The retrieved heights (figure 6.8) indicate a good correlation to the apparent tree location evident in the ORRI (figure 6.7). The four peaks in the height retrieval transect relate to the clumps of taller trees, and the troughs relate to the subsequent areas of shadow seen in the ORRI, thus there is confidence in the ability to map the structure of the stand. The apparent retrieved heights, up to around 20 m, appear to match the measured heights, up to around 30 m (average around 17 m).

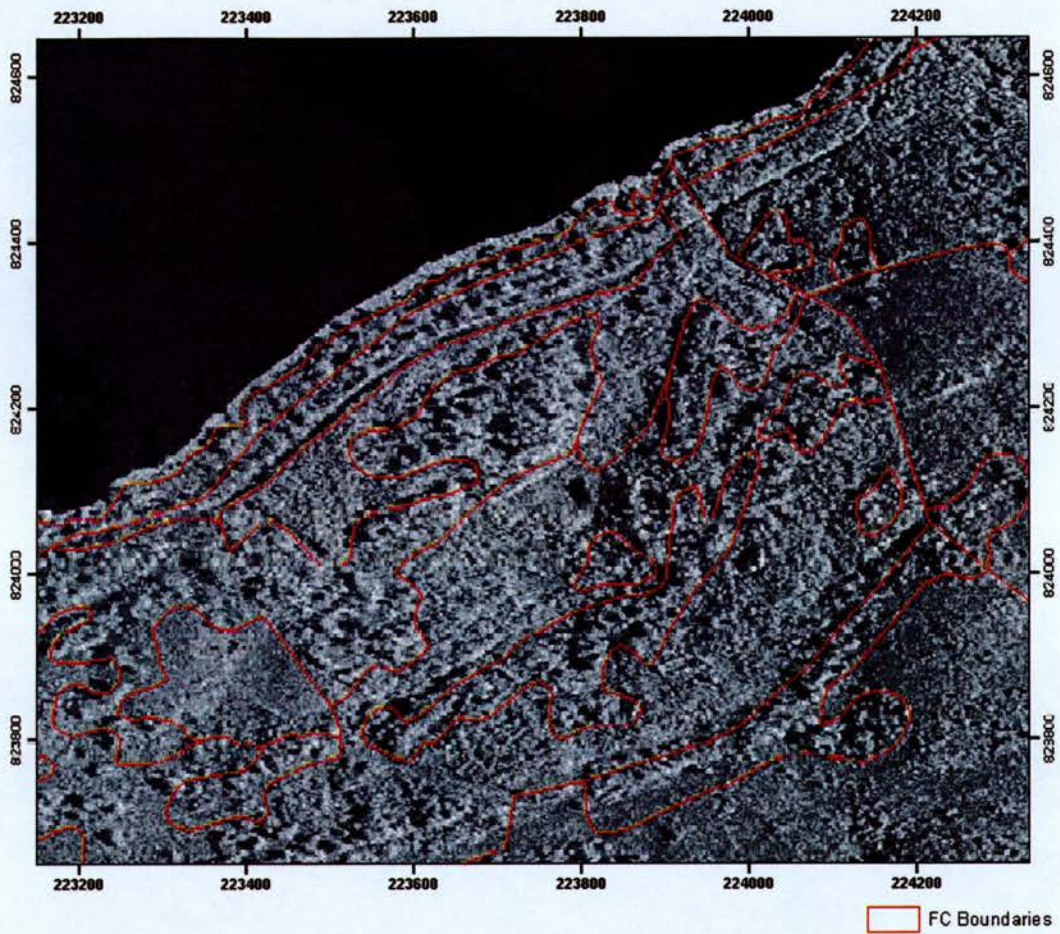


Figure 6.2 ORRI of Glen Affric test site with Forestry Commission boundaries overlain. Black area to top left is water, as is smaller black area in centre of image. Look direction is east to west. Coordinates are Ordnance Survey National Grid coordinates.

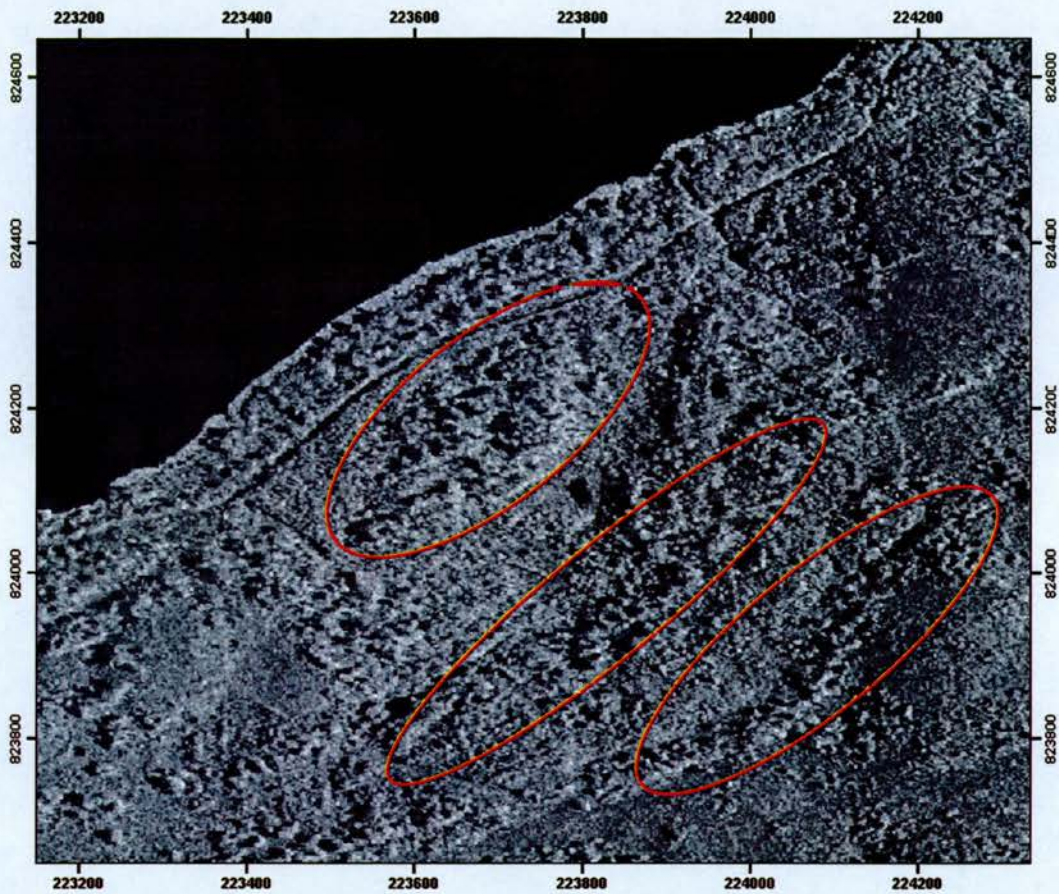


Figure 6.3 ORRI of Glen Affric semi-natural Caledonian pine woodland. Areas to note are circled in red. Height retrieval is performed in the stand within the upper ellipse. Coordinates are Ordnance Survey National Grid coordinates.

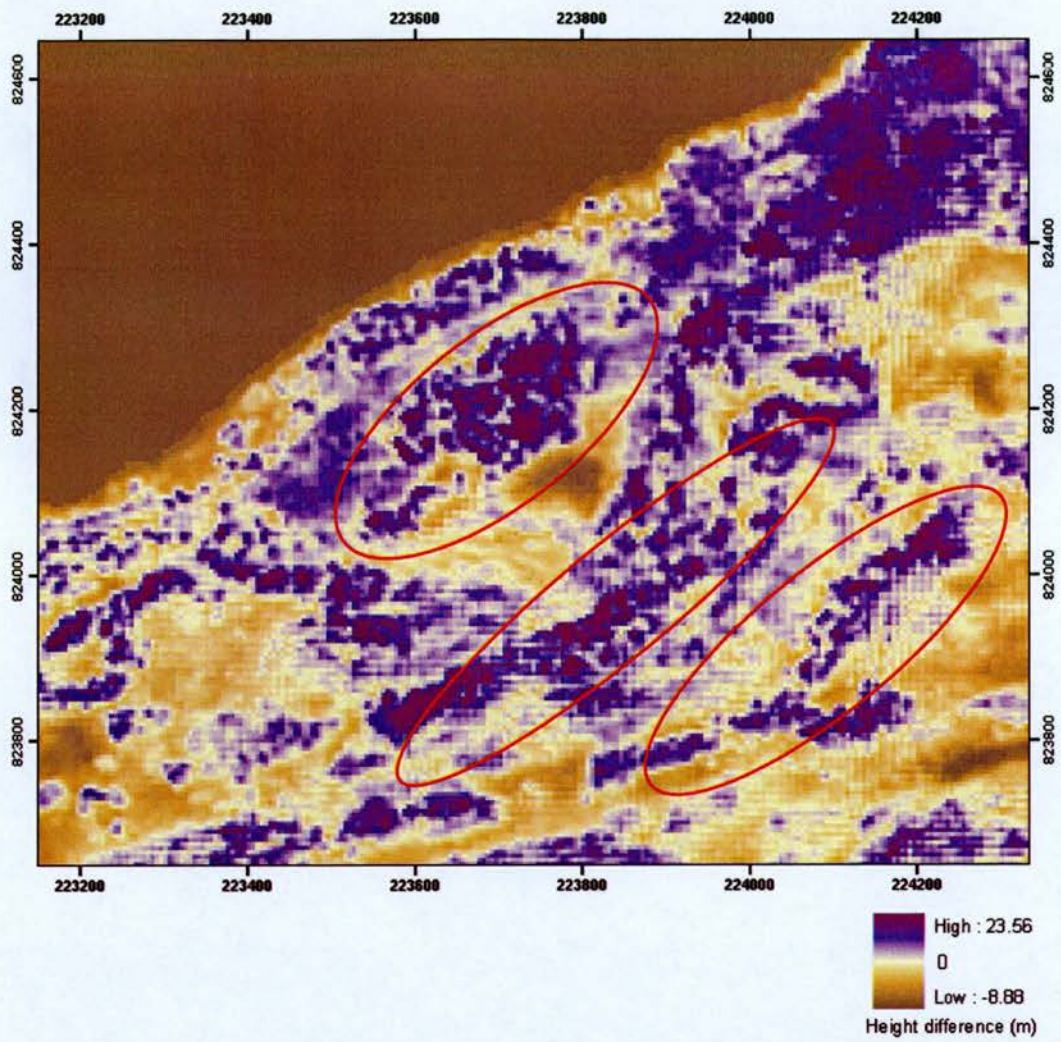


Figure 6.4 DSM-OSDEM height difference over test site in Glen Affric. Coordinates are Ordnance Survey National Grid coordinates.

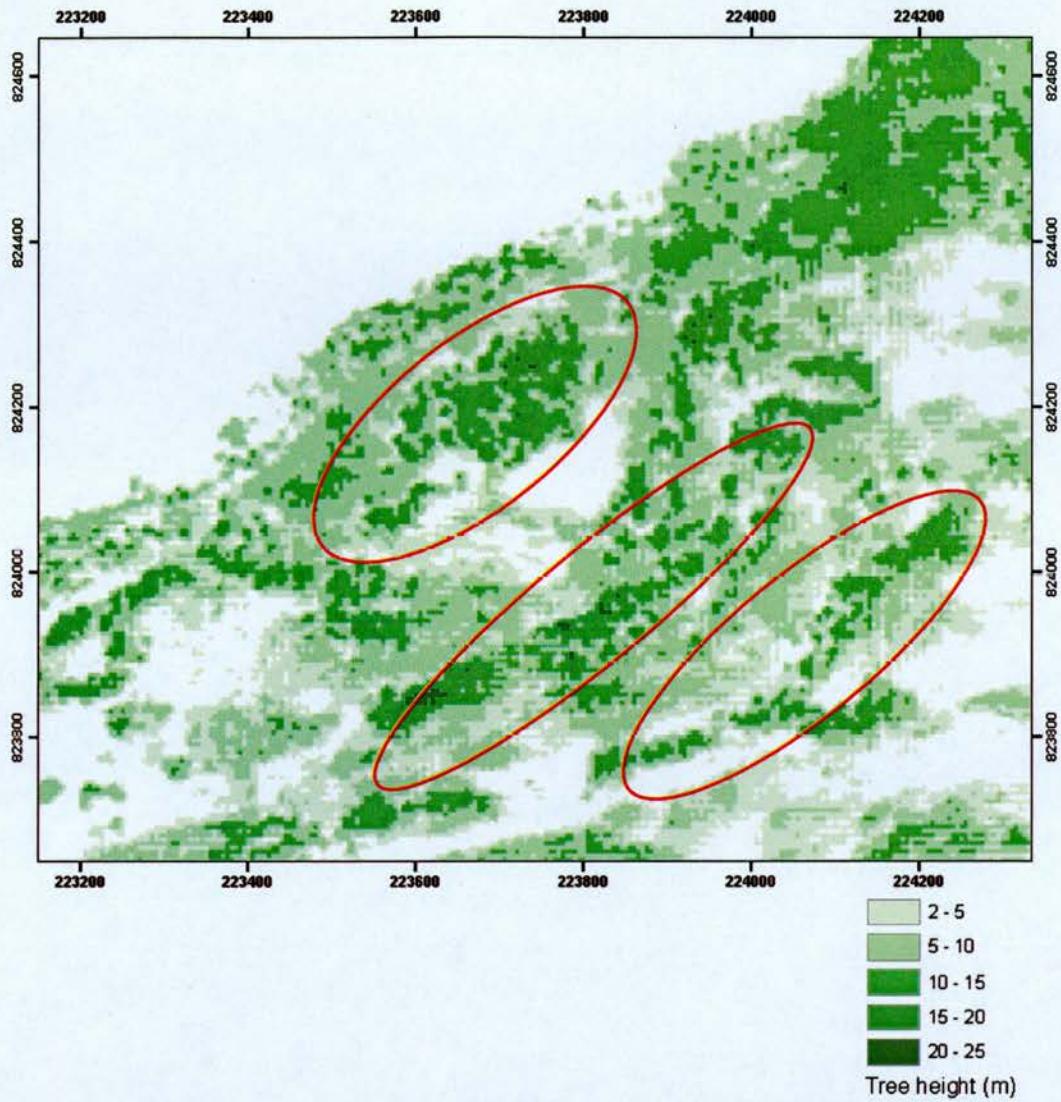


Figure 6.5 Tree height retrieval over test site, Glen Affric, indicating location of semi-natural Scots pine trees. Red ellipses are areas of interest pertaining to previous images. Coordinates are Ordnance Survey National Grid coordinates.

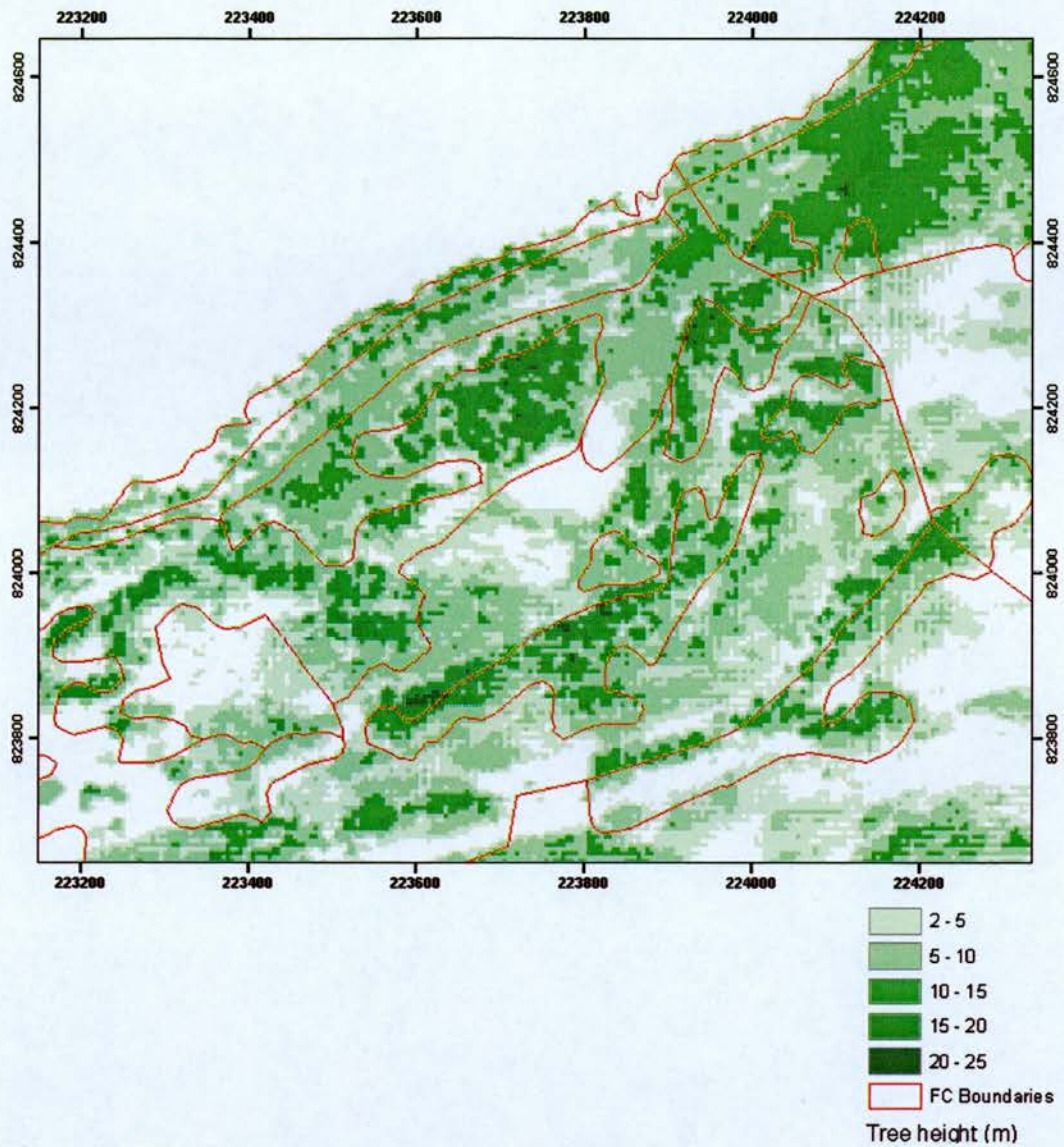


Figure 6.6 Tree height retrieval over test site, Glen Affric with Forestry Commission boundaries. Coordinates are Ordnance Survey National Grid coordinates.

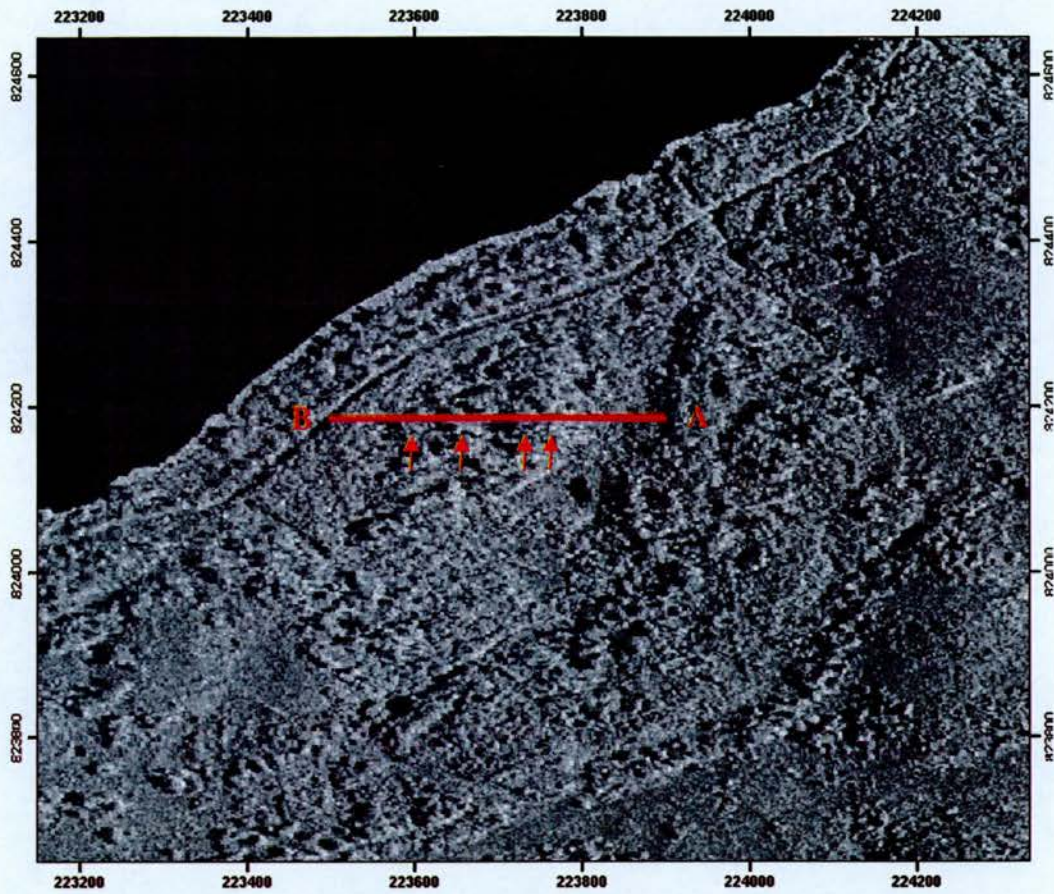


Figure 6.7 Transect line across test stand in range direction (A-B). Compare to transect in figure 6.8. Red arrows indicate approximate locations along transect of peaks in height retrieval. Coordinates are Ordnance Survey National Grid coordinates.

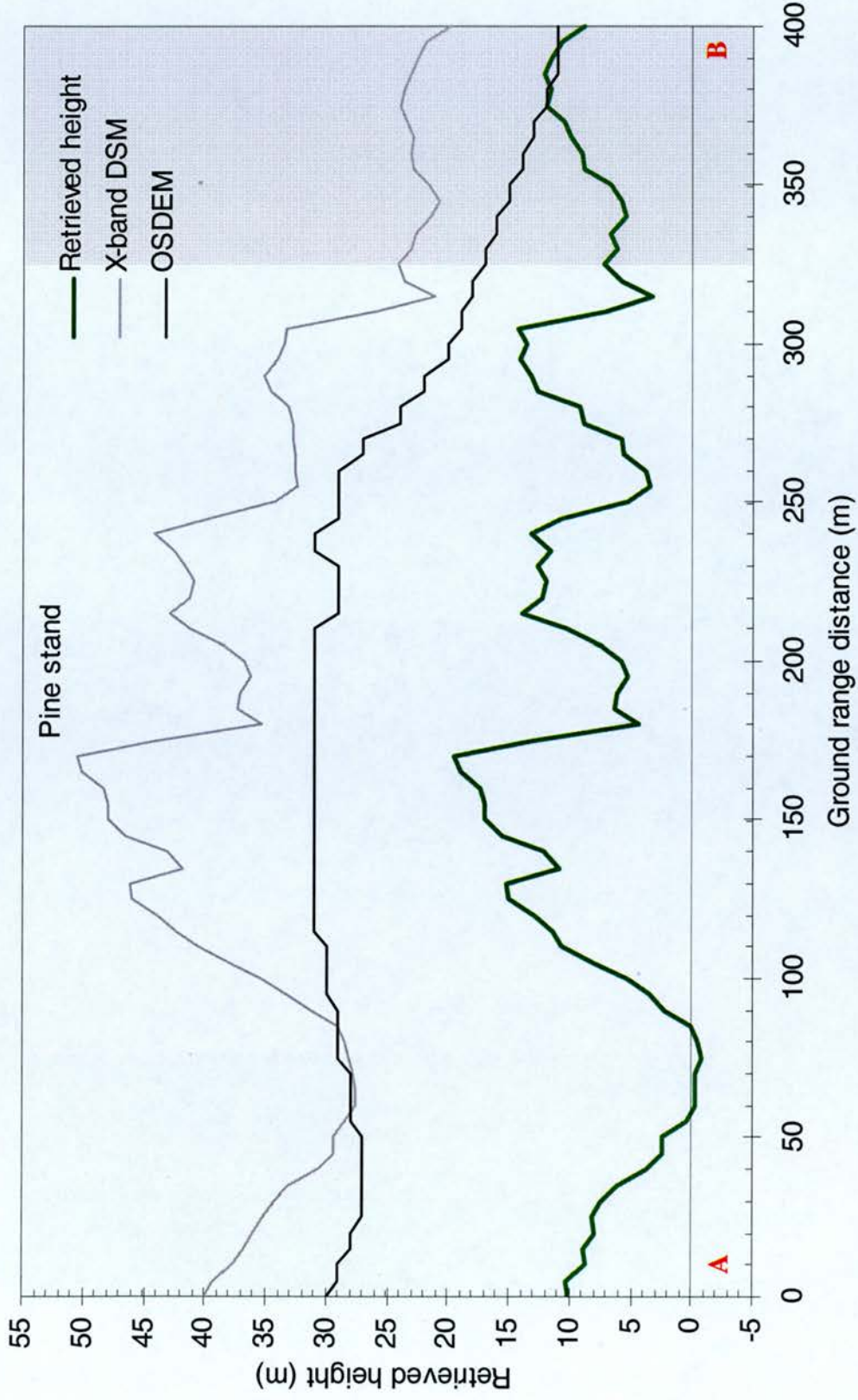


Figure 6.8 Retrieved height along transect as shown in figure 6.7. The estimated extent of the pine stand is indicated. Note that the X-band DSM and OSDEM are presented for reference and are represented 220 m below their actual elevation.

6.4.2 Results of quantitative assessment

Tree height estimates produced using the Intermap Star-3i DSM minus OSDEM were assessed and compared to measured tree heights within the test stand highlighted by the upper red ellipse in figure 6.3. Table 6.1 shows a summary of averaged results for the height retrieval.

Table 6.1 Summarised mean results of height retrieval over the Glen Affric test site.

	Measured height (m)	Retrieved height (m)	Difference (m)	Error (%)
Max	45.26	21.46	32.84	739.95
Mean	17.29	11.21 ± 1.11	6.08	94.89
Min	2.23	0.56	-17.45	2.68
SD	8.40	4.41	8.80	94.18

The retrieved heights were a mixture of over and underestimations as expected (figure 6.9), with a range of between 0.56-21.46 m and a mean of 11.21 m. Regression of the retrieved height on measured height resulted in an R^2 of 0.03 and a P -value of 0.001 (a significant relationship at the 95% confidence level, suggesting that retrieved heights were a significant predictor of measured heights). However the visual interpretation of the measured vs retrieved heights (figure 6.9) suggests little or no relationship. The difference between retrieved height and measured height ranged from a 32.84 m underestimation to an overestimation of 17.45, with the mean difference being a 6.08 m underestimation. The average height retrieval error for all trees in the stands was 94.89%, with a range of between 2.68-739.95% (figure 6.10), which in itself is not a very promising result. However, on further investigation, the influence of smaller trees on this height error is significant. The mean height retrieval error for all trees greater than 10m measured height is 58.12%

(mean 9.68m underestimate), for all trees greater than 5m measured height the mean error is 71.31% (mean 7.68m underestimate), and for trees between 2 and 5 m, the mean error is 274.06% (mean 5.97 m overestimate). The height retrieval error for small trees is therefore having a negative effect on the overall height estimation error for the stand. The mean retrieved height of 11.21 m is comparable to the mean measured height of 17.29 m (with a mean difference of 6.08 m; figure 6.11). Figure 6.12 shows the distribution of retrieved and measured heights. Measured heights are bi-modal, with small and large trees; however the retrieved heights do not reflect this, and consist of primarily medium heights. Reasons for this are discussed in chapter 7.

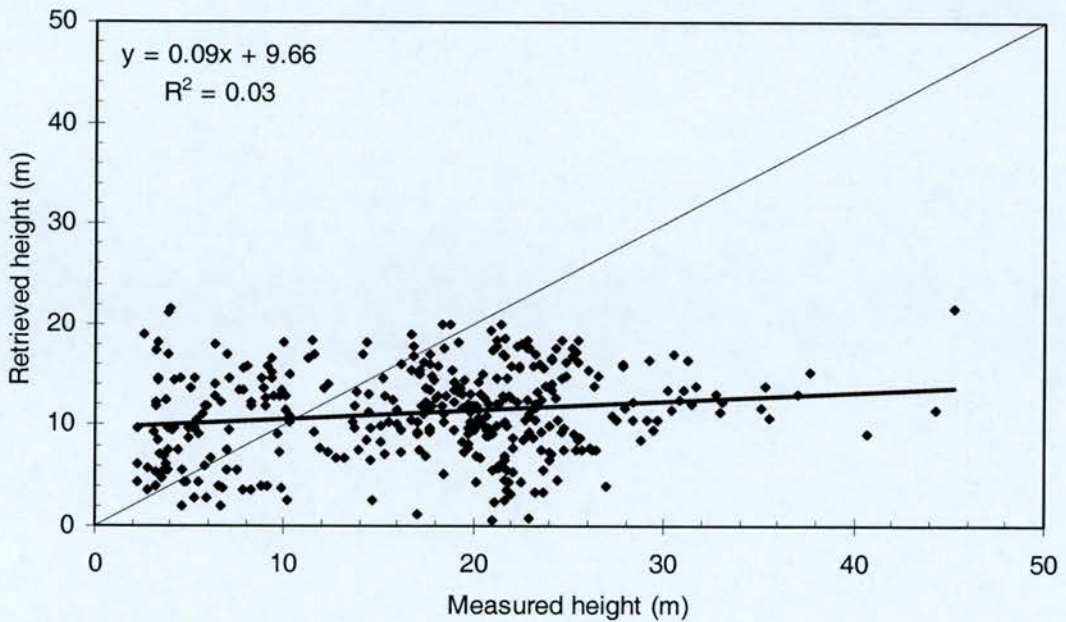


Figure 6.9 X-band retrieved height vs. measured height for semi-natural pine stand, Glen Affric. 1:1 line is shown. As mentioned in section 6.3, there is a difficulty with 1 to 1 correspondence of heights due to layover effects; as such mapped heights may not correspond to retrieved heights.

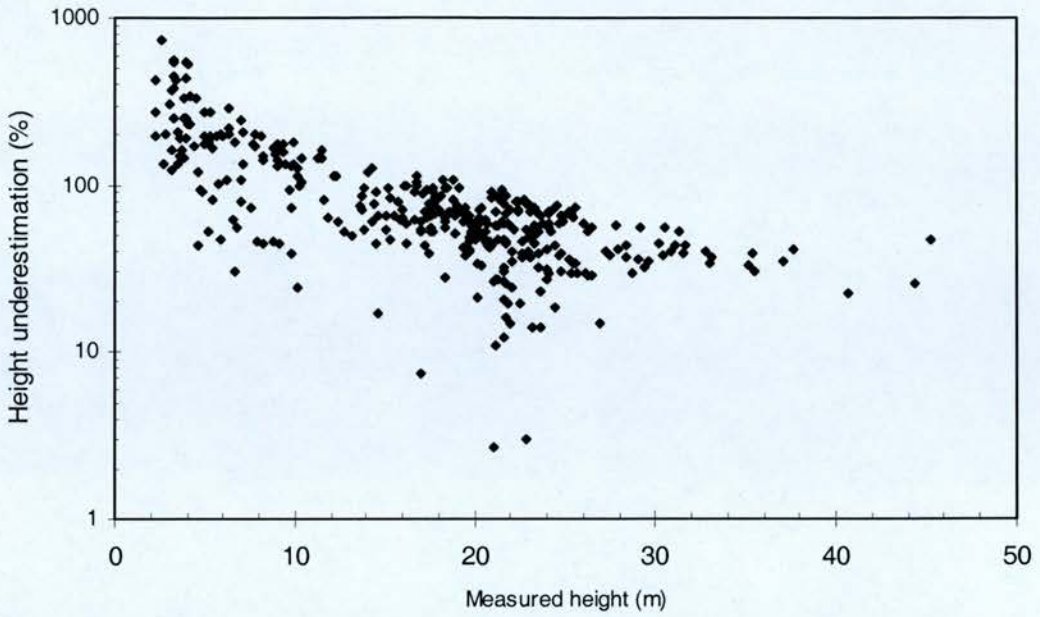


Figure 6.10 X-band height underestimation vs. measured height for semi-natural pine stand, Glen Affric.

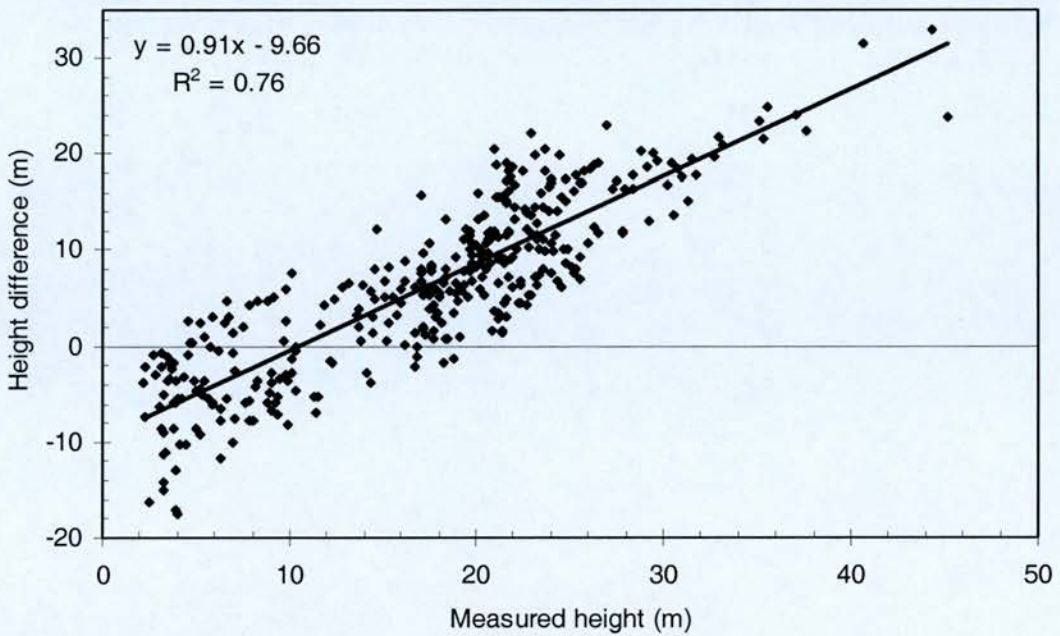


Figure 6.11 X-band height difference (DSM-OSDEM) vs. measured height for semi-natural pine stand, Glen Affric. Although the percentage underestimation decreases with height (figure 6.10), the difference between measured and retrieved heights increases. It can be seen that height retrieval is best for medium height trees, and is worse for small and large trees. Ideally, all measurements would lie along the zero line, indicating no difference.

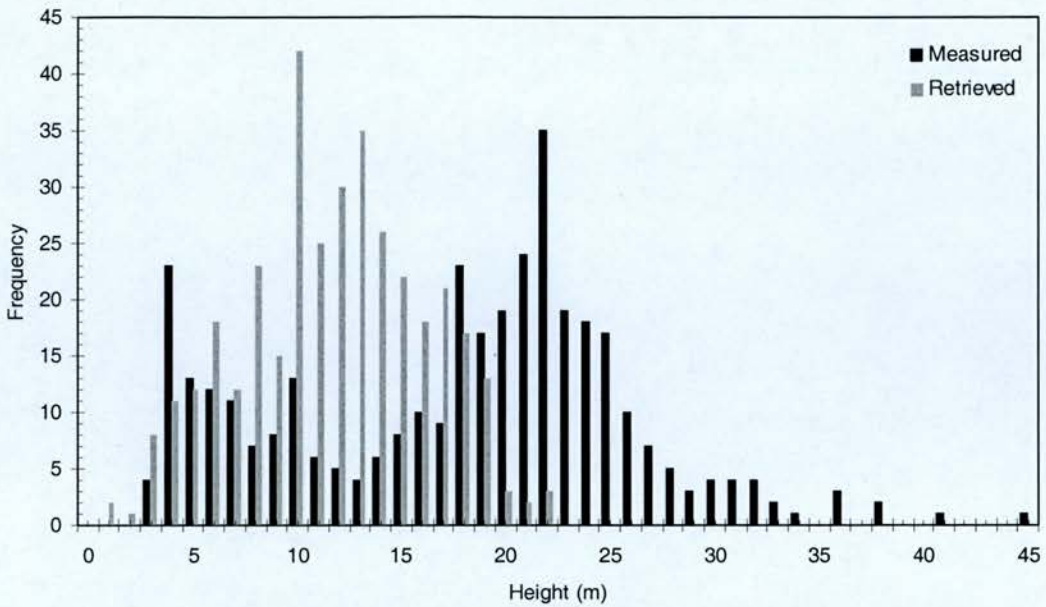


Figure 6.12 Distribution of measured and X-band retrieved heights in Glen Affric.

6.5 DSM-DEM height retrieval over heterogeneous semi-natural pine savanna

6.5.1 Results of qualitative assessment

Visual assessment of the DSM-DEM height difference map was performed in an area of semi-natural pine savanna in Belize (see section 3.2.5). There were two stages to the assessment, as well as the added benefit of being able to compare two different wavelength interferometric SAR DSM's. Following the Glen Affric method described above, the first stage was to assess the ability of X-band InSAR to estimate vegetation height in a small test site. The second stage was to assess the ability of X- and C-band InSAR for tree height retrieval over a larger area. Visual assessment performed on X-band height retrieval gave an indication that a height difference was present (figure 6.13); this related to tree heights (figure 6.14) collocated with field verification data.

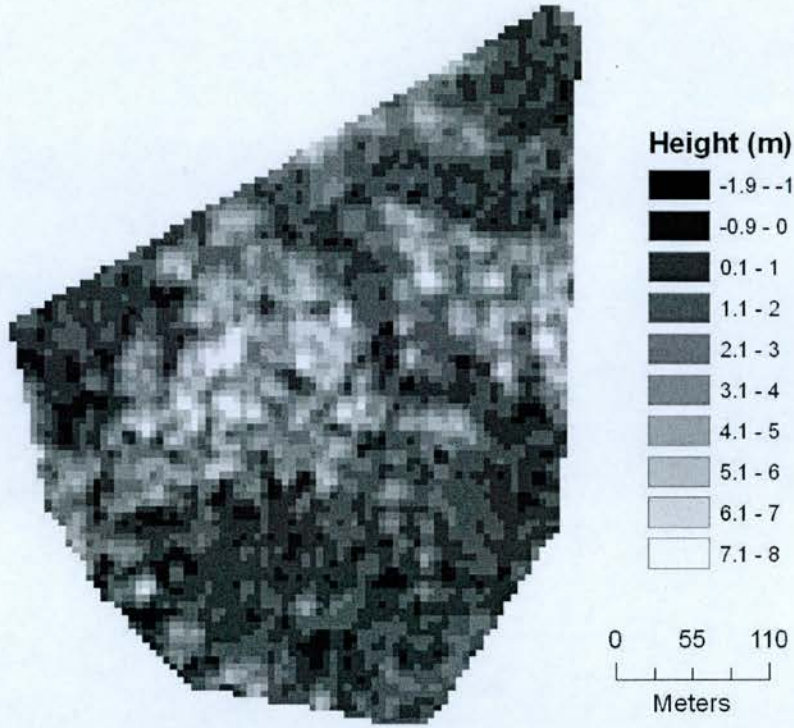


Figure 6.13 X-band DSM minus DEM height difference image over pilot test site, RBCMA, Belize. (Cameron *et al.*, 2005).

The second stage of the analysis was an assessment of height retrieval along a ~900 m transect. Figure 6.15 shows the height retrieval at X-band along the transect; higher retrieved heights were present at the location of known vegetation. A series of profiles were extracted from the height model along the height retrieval transect (figure 6.16); height differences for the X- and C-band DSM-DEM procedure were used to estimate tree height along the transect. Transect 5 is shown in figure 6.17. A clear correspondence between increased height retrieval and pine ridge location is seen. Unexpectedly, C-band retrieved heights are higher than X-band heights. It was presumed that X-band would be higher due to the reduced amount of canopy penetration expected at shorter radar wavelengths.

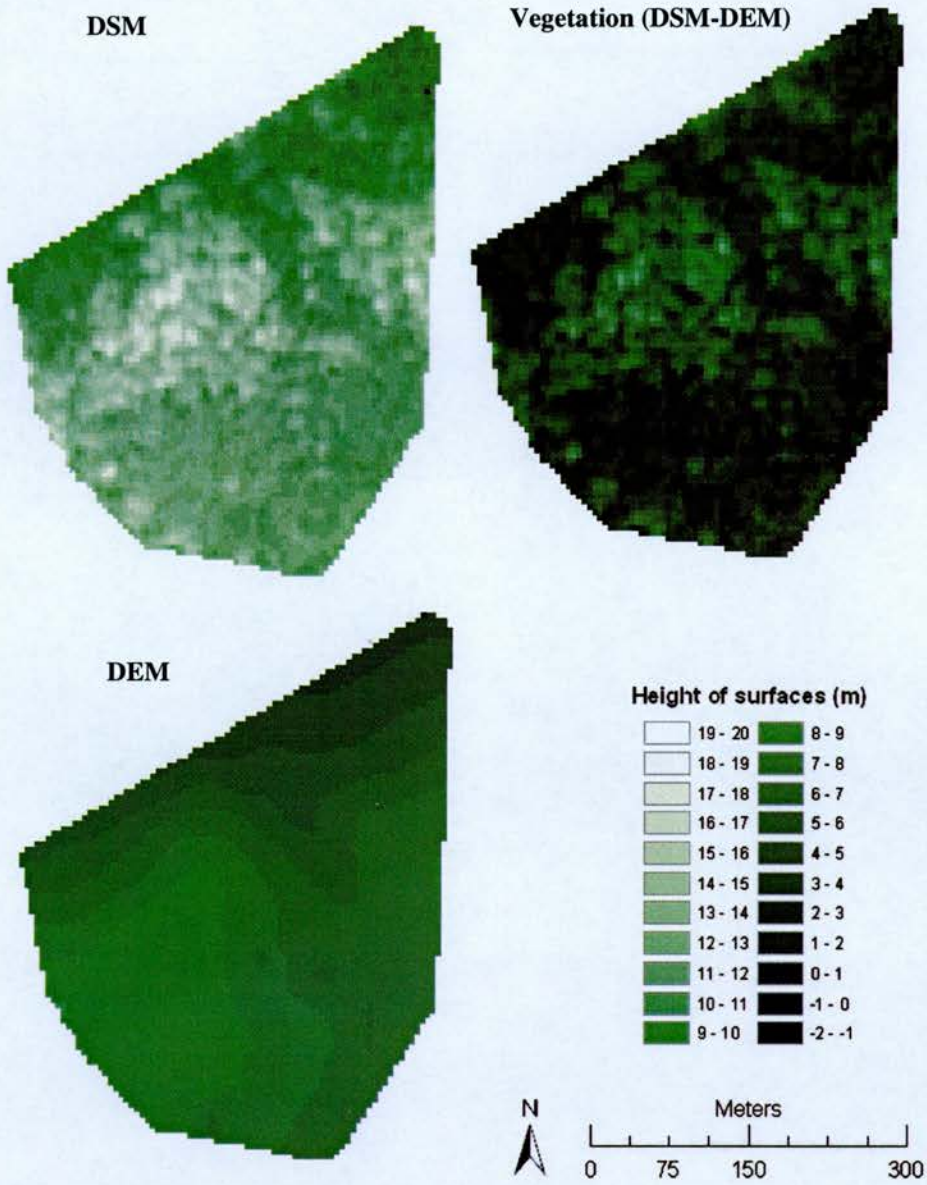


Figure 6.14 Relationship between DSM, DEM and retrieved height indicating location of vegetation. (Cameron, 2004, used with permission).

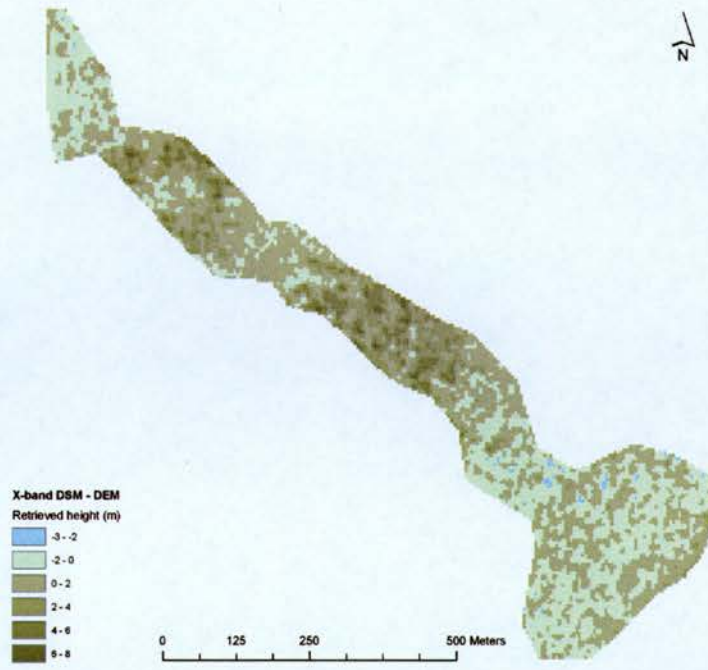


Figure 6.15 X-band retrieved height along transect in RBCMA. (Hay, 2005; used with permission).

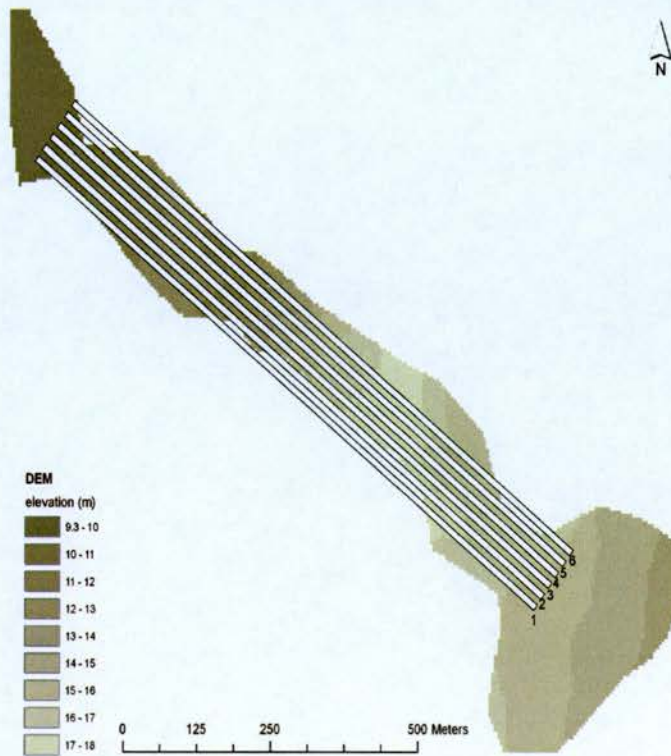


Figure 6.16 Position of transects lines along height retrieval transect (Hay, 2005; used with permission).

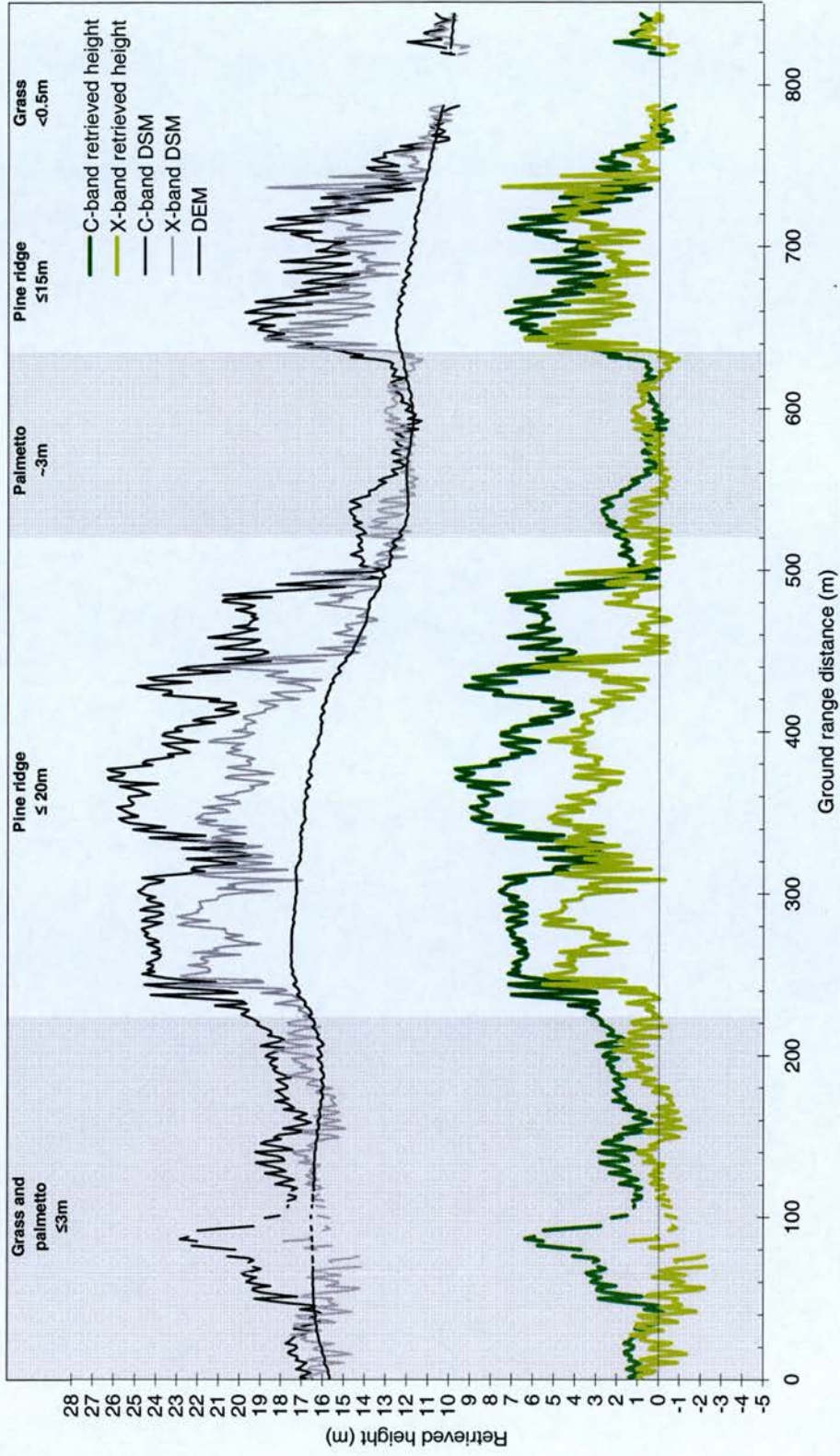


Figure 6.17 Height retrieval at X- and C-band. Heights pertain to transect 5, refer to figure 6.16. The approximate extents of different vegetation types are depicted. (After Wallington *et al.*, 2005b)

6.5.2 Results of quantitative assessment

Tree height estimates produced using the JPL AIRSAR C-band DSM and the Intermap Star-3i X-band DSM minus DEM were assessed and compared to measured tree heights within the study area (figure 6.3). Table 6.2 shows a summary of averaged results for the C-band height retrieval, and table 6.3 for X-band height retrieval.

Table 6.2 Summarised mean results of C-band height retrieval over the RBCMA test site.

	Measured height (m)	Retrieved height (m)	Difference (m)	Error (%)
Max	21.80	9.83	15.35	298.52
Mean	8.95	4.17 ± 0.21	4.79	55.97
Min	1.70	-0.69	-5.37	0.42
SD	4.75	2.49	3.59	25.68

Table 6.3 Summarised mean results of X-band height retrieval over the RBCMA test site.

	Measured height (m)	Retrieved height (m)	Difference (m)	Error (%)
Max	21.80	6.12	17.35	126.09
Mean	8.95	2.10 ± 0.12	6.85	74.71
Min	1.70	-0.81	-1.59	0.71
SD	4.75	1.45	4.05	19.02

C-band interferometry (table 6.2) resulted in height retrieval with a mean underestimation of 4.79 m (figure 6.18), with a range of between 15.35m underestimation to 5.37 m overestimation (figure 6.22). This relates to a mean error of 55.97%, with a range of 0.42-298.53% (6.20), and is not a significant relationship. X-band results were similar, with a mean height underestimation of 6.85 m (figure 6.19), ranging from a 17.35 m underestimation to a 1.59 m overestimation (figure

6.23). With a related mean error of 74.71%, with a range between 0.71-126.09% (6.21), and is not a significant relationship. These results were in-line with expectation given results in Glen Affric (section 6.4.2). However, there was no apparent effect of smaller trees representing a higher relative % error as in Glen Affric, and all ranges of heights produced similar % errors. This may be explained by fewer overestimations of the height of small trees (figures 6.18 and 6.19) than compared to the Glen Affric situation (figure 6.9). Figures 6.24 and 6.25 show the distribution of measured and retrieved heights for C- and X-band respectively. The measured heights are again bi-modal; the X-band heights are significantly underestimating measured heights, with the C-band being slightly more representative. These results are in contrast to the Glen Affric results, where medium sized tree heights were present. The differences are attributed to canopy openness and tree density, and are further discussed in chapter 7.

C-band retrieved height vs. measured height

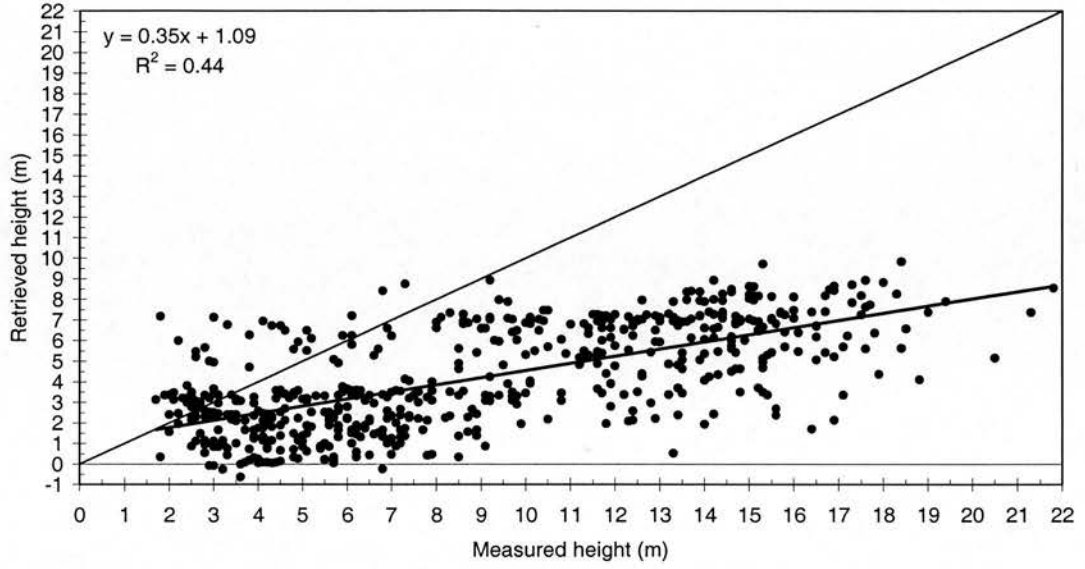


Figure 6.18 C-band height retrieval vs. measured height for the RBCMA study area. (After Hay, 2005). 1:1 line is shown.

X-band retrieved height vs. measured height

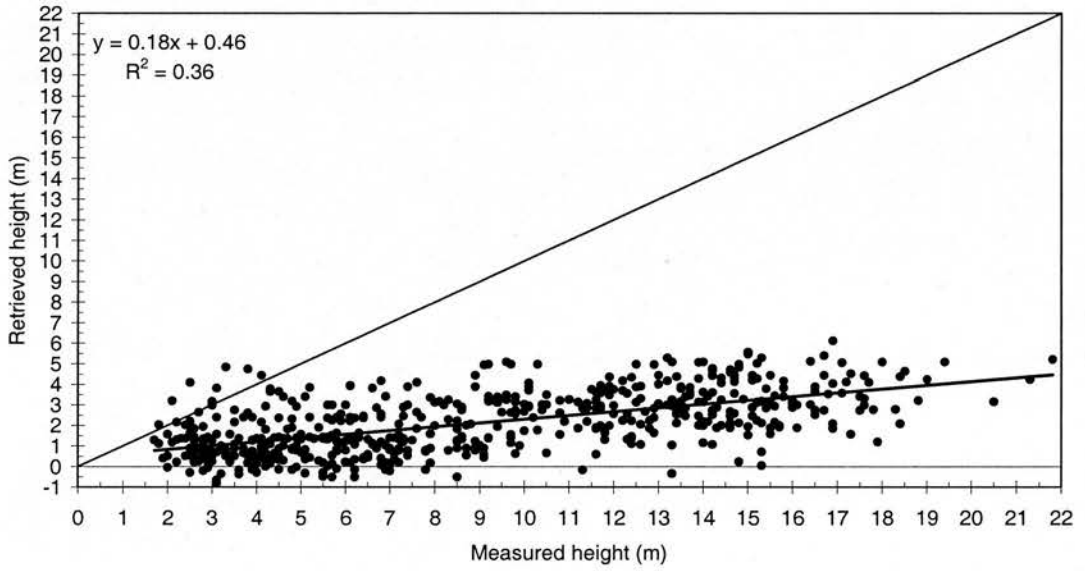


Figure 6.19 X-band height retrieval vs. measured height for the RBCMA study area. (After Hay, 2005). 1:1 line is shown.

C-band height underestimation vs. measured height

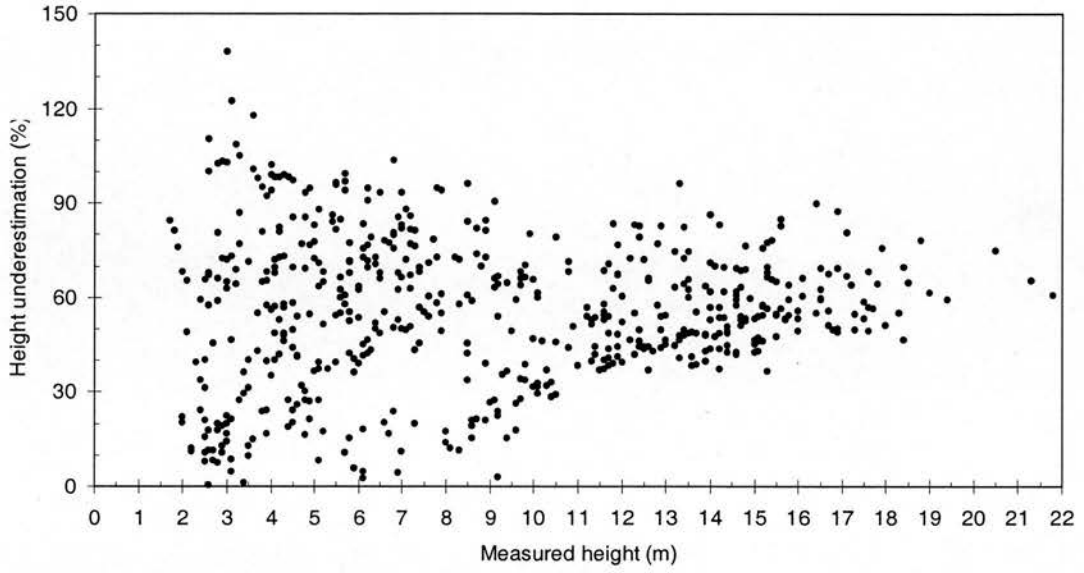


Figure 6.20 C-band height underestimation vs. measured height.

X-band height underestimation vs. measured height

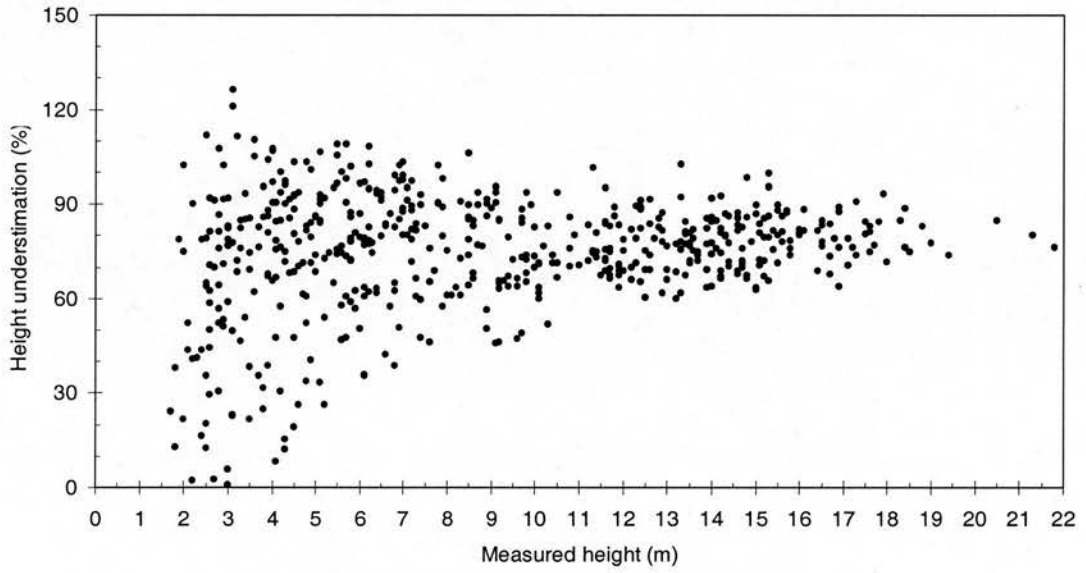


Figure 6.21 X-band height underestimation vs. measured height.

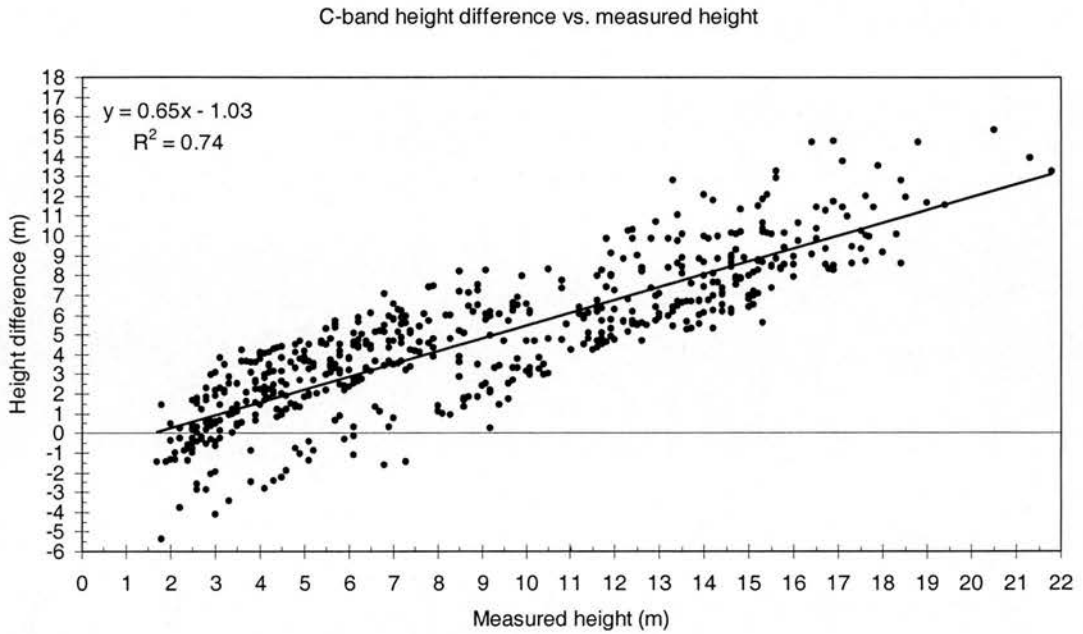


Figure 6.22 C-band height difference (DSM-DEM) vs. measured height. Although the percentage underestimation varies with height (figure 6.20), the difference between measured and retrieved heights increases with height. Ideally, all measurements would lie along the zero line, indicating no difference.

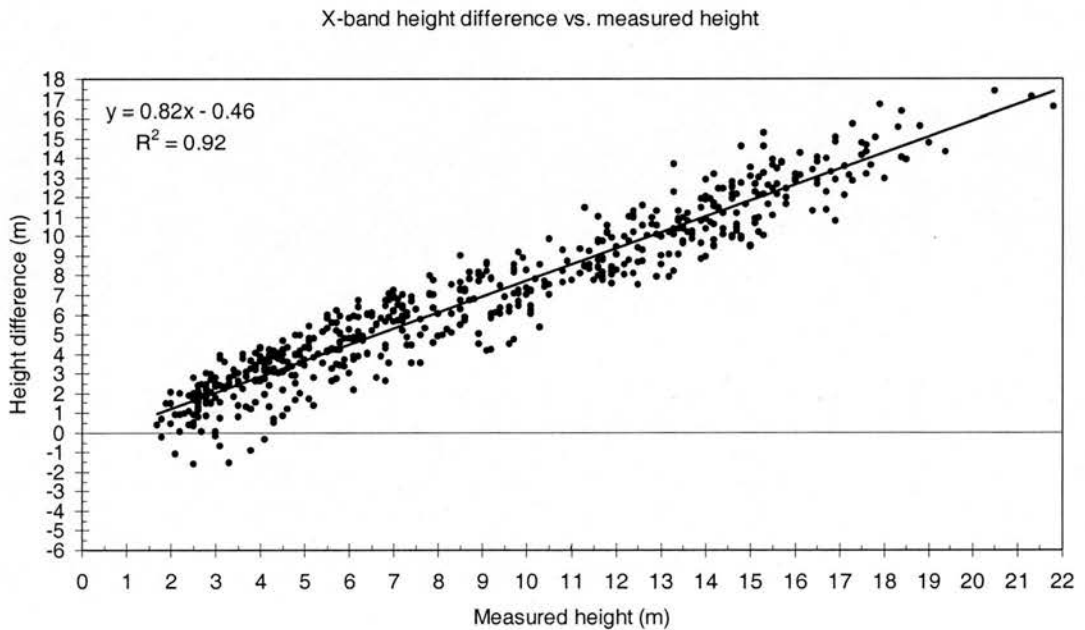


Figure 6.23 X-band height difference (DSM-DEM) vs. measured height. Although the percentage underestimation varies with height (figure 6.21), the difference between measured and retrieved heights increases with height. Ideally, all measurements would lie along the zero line, indicating no difference. Compare with figure 6.22; note the tighter correlation (larger error), indicating less influence from the canopy and a greater influence from the ground on retrieved heights.

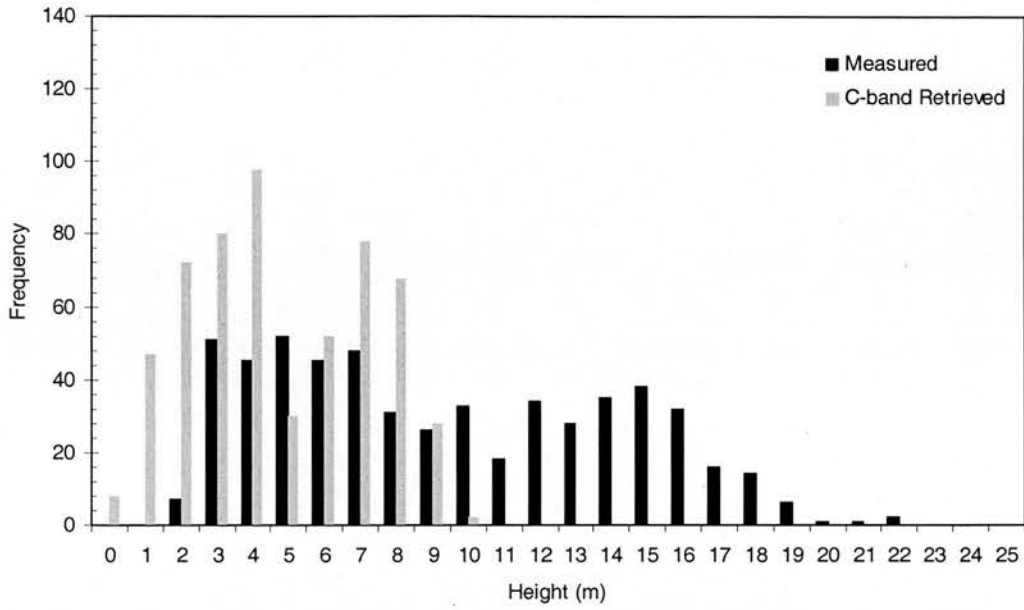


Figure 6.24 Distribution of measured and C-band retrieved heights in the RBCMA.

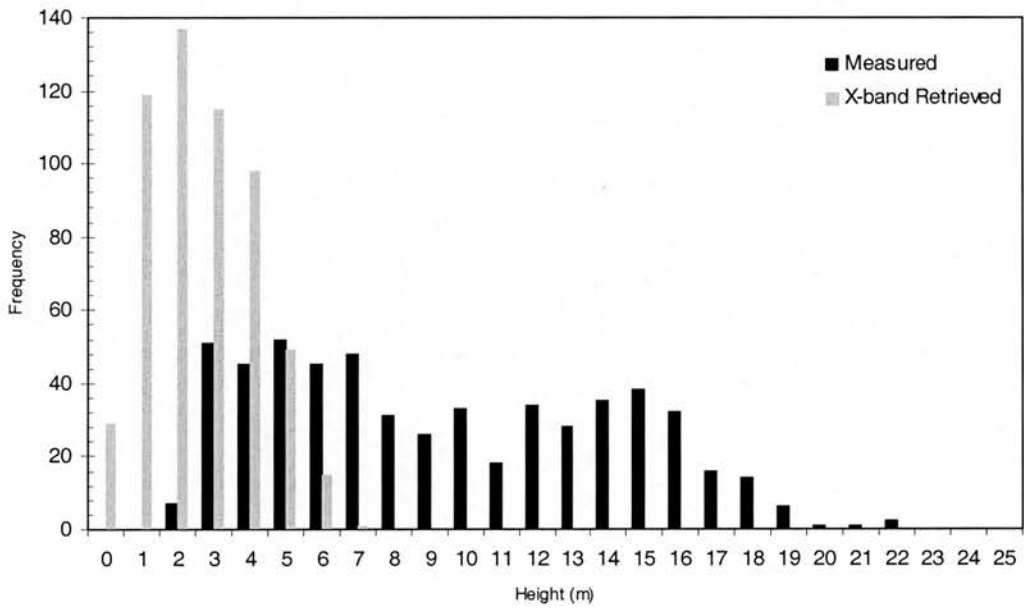


Figure 6.25 Distribution of measured and X-band retrieved heights in the RBCMA.

6.6 Discussion and Conclusion

This chapter has discussed height retrieval over heterogeneous woodland environments in the UK and Belize. In the UK, a height difference between the X-band DSM and the OSDEM was seen to be due to the presence of vegetation. This was compared to the ORRI image, as well as to Forestry Commission boundaries and field verification. For both test sites, the areas of known tree location correspond to the retrieved heights, and taller trees are represented by higher retrieved heights (figures 6.5, 6.14 and 6.15). Transects taken through the test stands to assess height retrieval were shown to be sensitive to the height structure of the stand, and identified areas of trees, whose heights were related to measured heights (figures 6.8 and 6.17). The mean error in Glen Affric was around 95%. Figure 6.9 shows that the average retrieved height was 10-11 m and the mean difference was 6.08m; the effect of this is that as trees get taller, the relative error reduces, but for shorter trees the error increases (figure 6.10). Investigation of the effect of tree height on the error revealed, that smaller trees were having an adverse effect on the retrieval error, and with these excluded, the height errors were reduced to around 58% for trees taller than 10m, and 71% for trees taller than 5m. Results in Belize were found to be similar, with a height difference between DSM and DEM being indicative of vegetation presence. Further analysis found that C-band derived heights resulted in errors of up to 299%, with a mean error of around 56%. X-band derived heights resulted in errors of up to 126%, with a mean error of around 75%.

These results are not unexpected and are consistent with height retrieval errors of up to 40% over plantation forests (Chapter 5). The nature of heterogeneous

environments presents a more challenging scenario for the use of SAR for retrieving tree heights. Penetration of the radar signal through a tree crown is likely to be greater in less dense environments due to the more open nature of the crown – due to the trees growing in a open area away from competition (as opposed to more dense crowns in plantations for example). The species of tree likely to be found are characterised by their less densely structured crown, in this case Scots pine and Caribbean pine (figure 6.26), again increasing the amount of penetration (see chapter 7). Where a slope is encountered, varying amounts of penetration can result in different heights being retrieved (see chapter 7); this is not a serious problem in Belize as the terrain is relatively flat (20 m rise over 2km). In this chapter, heights related to individual coordinates are being assessed, and as such this may result in an error due to the side-looking geometry of SAR, as the measured height related to a specific ground coordinate may not correspond to the height in a SAR image of the same coordinate. The effect of layover may result in a height being mapped to a different location in a SAR image to where it actually is on the ground (see chapter 7). Comparing heights from a single coordinate may therefore introduce errors as the heights may not be related, and this is expected to be the primary reason for high differences between measured and retrieved heights. For example, if trees of different heights both occupy the same range bin, the weighted average height will be retrieved, resulting in height underestimation for the taller tree, and over estimation for the shorter tree (see chapter 7). As such, a pixel by pixel comparison approach does not appear to be suitable in these environments. Further, if a slope is present it may be possible for the height of a small tree to be missed altogether. This

situation is more likely to occur in Glen Affric where the topography is more extreme than in the RBCMA.



Figure 6.26 Similarities in open nature of canopies in Glen Affric (left) and Belize (right).

The result of the X-band retrieved heights being lower than the C-band retrieved heights is unexpected. Reasons for this have not been fully explored. Initial thoughts are that the signal from both wavelengths is penetrating to the ground, and at X-band, the ground appears to be rougher, and so returns a larger scattering contribution than the C-band, thus resulting in a lowering of the vertical location of the scattering phase centre. A large difference in data acquisition dates is also a potential explanation for some of the differences between X- and C-band retrievals. For example, the vegetation would have grown, and it is possible that there were different surface and environmental conditions when the data were acquired.

The retrieved heights discussed in this chapter are within expected limits. As such, the ability to map heights in challenging heterogeneous forest terrain, giving a location-wise classified overview of the trees through the use of forest height maps (figures 6.6 and 6.14) is a useful contribution for management purposes. For example, an indication of the location of trees and their range of heights aids better understanding of the land to be managed (Williams, 2005). The capability to provide an indication of the height of individual trees further aids the management process. Such data would otherwise be unobtainable without lengthy, intensive and ultimately expensive field work.

7 Discussion of potential reasons for height underestimation

“The most exciting phrase to hear in science, the one that heralds new discoveries, is not Eureka! (I found it!) but rather, ‘hmm... that’s funny...’.”

Isaac Asimov (Russian born American science-fiction Writer and Biochemist. 1920-1992)

7.1 Introduction, aim and objectives

Chapters 5 and 6 presented tree height retrieval results which were underestimates of the actual measured height. This chapter investigates the possible reasons for height underestimation, and discusses the findings in the context of the SAR height retrieval. A newly developed model (section 7.2) is also presented and used in conjunction with the Intermap data to help understand the reasons for height underestimation.

The aim of this chapter is to suggest and discuss possible reasons for height underestimation. The objectives to meet the aim are (i) to introduce the Polarimetric Radar Interferometry Simulator, (ii) to discuss sources of error introduced by SAR system geometry, (iii) to discuss sources of error introduced by forest parameters variations. Discussion will refer to height retrieval using Intermap data and modelled results in the context of homogeneous and heterogeneous forest environments.

The examples given in this chapter are based primarily on homogenous plantation stands. The reasoning behind this is two fold. First, the majority of work carried out

in this study refers to plantation stands in the UK, and secondly, a plantation stand can be assumed to be reasonably uniform, and so by altering single parameters the effect of this change can be seen without further complications associated with more heterogeneous environments. Further, a number of key variables which affect SAR height retrieval are pertinent to UK plantation forestry. For example, many plantations are planted on sloped land, and the geometry of SAR systems affect the height retrieval in these areas. In the UK, most plantations are stocked with conifer species, which have a cone shaped crown, again this impacts on retrieved heights, as discussed in section 7.9. Findings are also discussed in the context of heterogeneous environments, such as those found in semi-natural pine woodlands and woody savanna, as well as applications in stands being transformed to continuous cover forest (CCF) management regimes, with particular emphasis on densities and emergent trees.

7.2 Polarimetric Radar Interferometry Simulator

The Polarimetric Radar Interferometry Simulator (PRIS) is a simple interferometric model which has been developed by Dr. Izzawati and Dr. Woodhouse at The University of Edinburgh as part of the overall larger project to which this thesis contributes.

Woodhouse *et al.* (in press) describe PRIS as a model which simulates a pair of complex backscatter images from a 3D forest canopy with variable baselines. In this study the forest is modelled as a random volume (randomly positioned and orientated scatters) but with a 3-dimensional crown shape parameterised from ground data and allometric relationships. The crown volume is modelled as comprising randomly

distributed scatterers with homogeneous number density, scattering and extinction properties. The simulated complex scattering terms are used to retrieve canopy height. This height relates to the height of the scattering phase centre (SPC), whose value depends on the following factors: i) how much signal penetrates through the forest volume, and ii) the spatial representation of the tree crowns, ground surface and gaps within the canopy. As such, the PRIS model attempts to fully describe the forest as a 3D box comprising volume element (voxels), each of which is comprised of some fraction of crown volume, gap or ground surface (Woodhouse *et al.*, in press).

The model performs three main tasks so as to calculate the retrieved height of the SPC. These are (i) to produce a 3D forest box containing a range of information for each voxel (e.g. volume fraction of the crown, trunk and ground; number density of scatterers; complex backscatter field from 2 sensors; transmitted signal; slant range) and create the backscatter images acquired by 2 sensors; (ii) calculate interferogram and complex coherence from the two complex backscatter images; (iii) perform flat earth removal and extract height from phase coherence (Izzawati, 2005). The model can be run for actual tree data (with known coordinates and parameters) or for modelled data, by entering the range of desired variables to assess (e.g. tree height, slope, crown shape, incidence angle, and stem number density). Variation of the input parameters allows assessment of the effect of change in a single variable.

In the figures showing modelled results, the look direction is from left to right, thereby the near range is to the left of the images. This study is concerned with HH polarisation (that of the Intermap Star-3i), but images also include results for HV for

comparison. It is expected that HV will produce height retrieval results nearer the true height due to the decreased contribution from the ground at HV (Woodhouse *et al.*, in press). Further details of the model and modelled results have been published in Izzawati *et al.* (2004a), Izzawati *et al.* (2004b), Izzawati *et al.* (accepted) and Woodhouse *et al.* (in press).

7.3 Edge effects

Edge effects in forestry terms relate to the different growing conditions near the physical edge of stands. The tree heights at the edge of stands are not representative of the internal height, and hence are not used for top height estimations by foresters. Edge effects, in terms of this study, are factors which significantly contribute to tree height underestimation, and are primarily driven by layover. The vertical position of the scattering phase centre (SPC), and hence retrieved height, is located relative to the scattering contribution from the canopy and the ground within a single resolution cell (figure 7.1). A higher ratio of canopy to ground contribution will result in a higher SPC, resulting in a higher retrieved height, which will be more representative of the true height (figure 7.2).

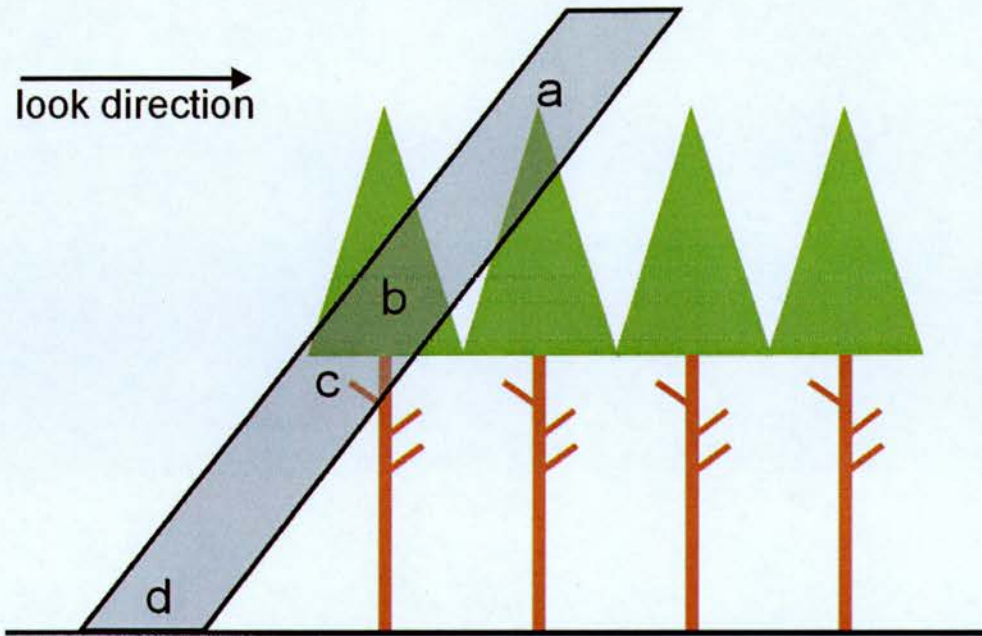


Figure 7.1 Schematic of scattering contributions resulting in edge effect. Scattering from the canopy top (a), lower canopy (b), branches and trunk (c) and ground surface (d) contribute to the vertical location of the scattering phase centre.

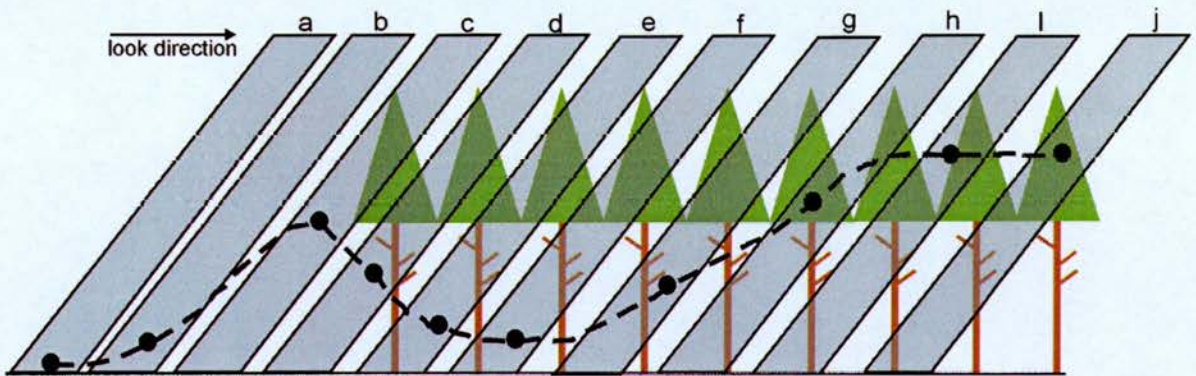


Figure 7.2 Schematic of scattering phase centre location (dots) within a resolution cell (a-j) and the resultant retrieved height surface (dashed line). The peak at the near edge of the stand is due to increased signal return due to double bounce interactions at the ground/trunk interface.

Figure 7.2 shows that as one moves further into a stand the height retrieval is more predictable, and less affected by edge effects. The reason for this is the change in relative contribution from the canopy and the ground. Over open ground, there is no canopy contribution, and all scattering is returned from the ground surface, with the retrieved height representing the ground (figure 7.2, resolution cell a). A peak in the retrieved surface (figure 7.2, resolution cell c) may occur due to increased return

caused by a double bounce at the trunk/ground interface. As height retrieval progresses further into the stand, the scattering contribution from the canopy increases, resulting in the vertical position of the scattering phase centre being located progressively nearer the actual height of the canopy (figure 7.2, resolution cells e-h). At some stage as one moves into the stand, the canopy scattering dominates over the ground scattering, resulting in a SPC location towards the top of the canopy (figure 7.2, resolution cells i-j). The remaining underestimation is due to penetration and attenuation through the canopy. The edge effect is evident in modelled results (figure 7.4) and actual height retrieval results (figure 7.5). It should also be noted that the SPC (retrieved height) horizontal location will be displaced from the actual location of the tree due to effects of layover (figure 7.3). Height retrieval is a weighted average of the location and strength of signals from all scatterers in a range bin. In figure 7.3 the scattering comes equally from the crown and the ground, and coupled with a degree of penetration, results in the retrieved height being an underestimation, and the retrieved location is displaced from the measured location (location related to incidence angle, with smaller angles resulting in a retrieved location nearer to the measured location). However, if an averaged height over a stand is taken (e.g. top height) and compared to a similarly average actual height, the horizontal shift of an individual height will not present a problem. This would potentially be an issue if attempting to compare individual coordinates such as single trees.

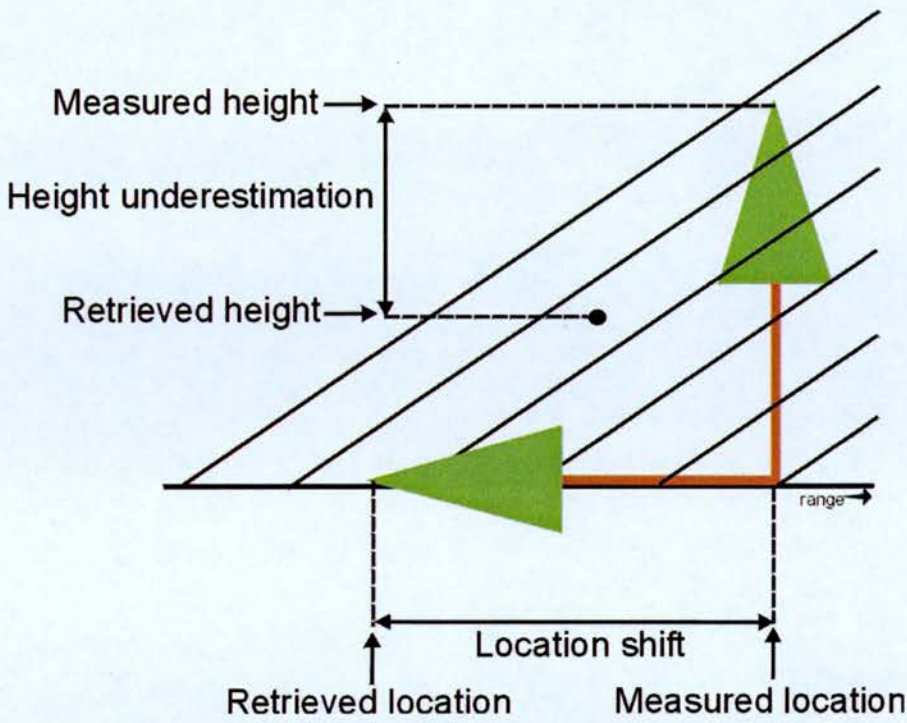


Figure 7.3 Effect of displacement. Scattering comes equally from the crown and the ground, and coupled with a degree of penetration, results in the retrieved height being an underestimation, and the retrieved location is displaced from the measured location. Diagonal lines are areas of equal range distance.

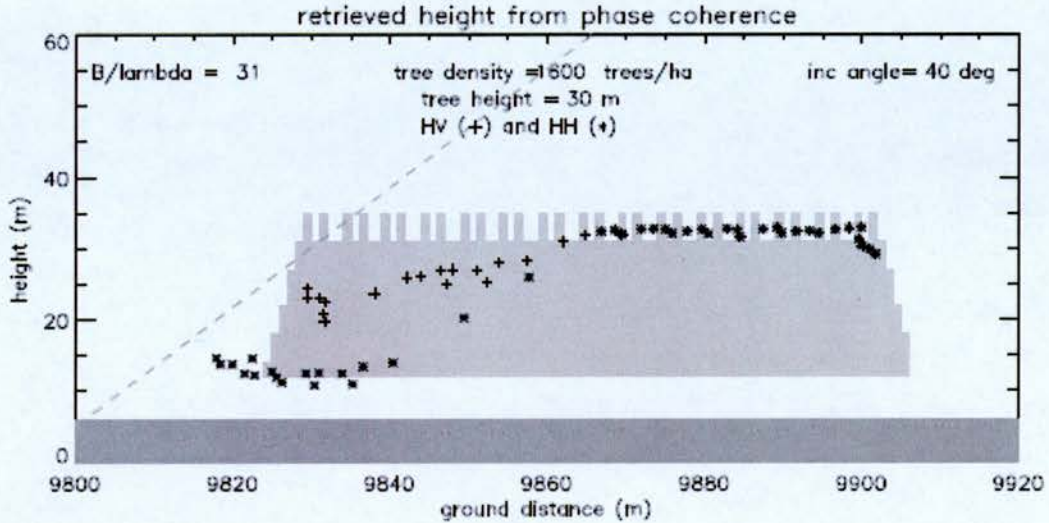


Figure 7.4 Consequence of edge effect on height retrieval seen in modelled results. Dashed line indicates line of equal slant range. Zero (0) is the height of the reference surface; the ground is at 5m; ground distance is distance from nadir.

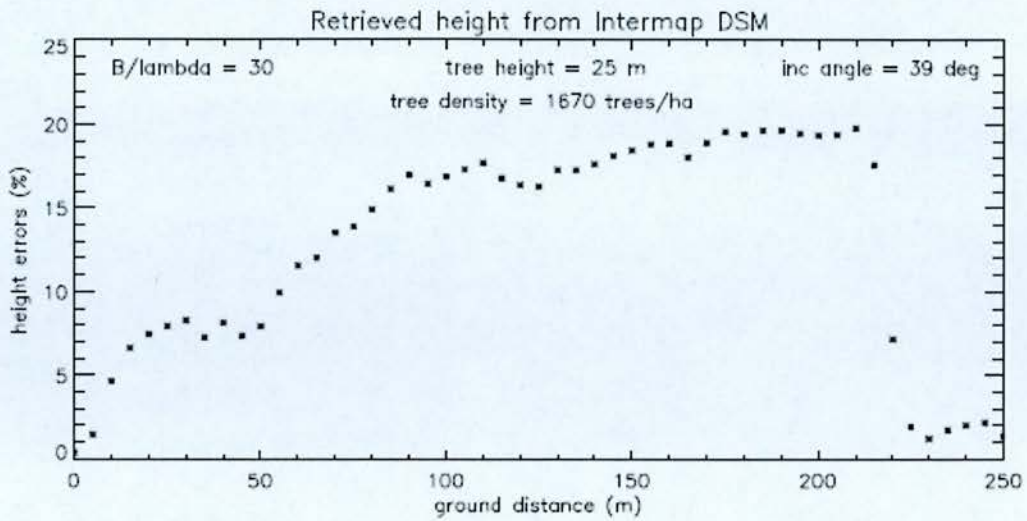


Figure 7.5 Consequence of edge effect on tree height retrieval seen in actual results.

7.4 Emergent trees

Any discontinuity within a forest will have height retrieval characteristics similar to the edge effects discussed above. The presence of emergent trees within an otherwise homogenous stand presents an edge. The SPC vertical location will be defined by the contribution of scattering from the ground surface, stand lower canopy, stand upper canopy and the canopy of the emergent tree (figure 7.6). As such, it is feasible for the retrieved height over a homogenous plantation to be higher than the actual stand height due to the scattering contribution of an emergent tree increasing the canopy scattering contribution from a higher elevation than the surrounding canopy. This effect can be seen in the modelled results (figure 7.7). The area of shadow caused by the presence of an emergent tree will result in a lack of retrieved heights in the area of shadow (figure 7.7). In a homogeneous canopy interpolation of the retrieved heights will occur across the region of shadow, thus not presenting an error source, however if the area is layover, this will result in errors. The difficulty is that it is not always possible to tell if an area is layover, a region of shadow can be

distinguished by the low backscatter intensity. This will have a consequence on the comparison of retrieved heights to actual heights within the area of potential layover, resulting in large errors. As such, it is advised to retrieve heights in areas where layover, or large areas of shadow, is not evidently a problem. This procedure was carried out in this study.

Chapter 6 discussed the difference in retrieved heights to measured heights. For example in Glen Affric, the histogram of measured heights showed a bi-modal distribution with small and large trees, whereas the retrieved heights were all medium sized trees (figure 6.12). One reason for this is explained in figure 7.6, whereby the retrieved height is a combination of a tall and short tree in the same range resolution cell, thus retrieving an average height which presents an error for both the tall and short tree, with the retrieved SPC location is displaced in the horizontal (range) direction as well as the vertical (figure 7.6). Tree height retrievals under these conditions are prone to increasingly large errors due to the height discontinuities, layover, shadowing, and multipath reflection, similar to those that have been shown to be prevalent in the use of X- and C-band interferometry for the retrieval of the top height of buildings in urban areas (Bickel *et al.*, 1997; Stilla *et al.*, 2001; Gamba *et al.*, 2001), as well as in forest environments (Hoekman and Verekamp, 2001).

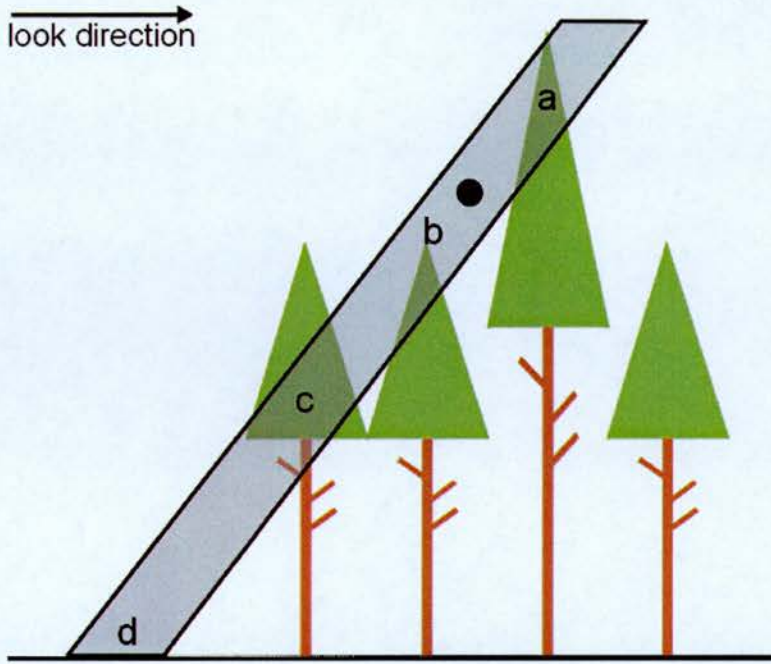


Figure 7.6 Schematic of scattering contributions effecting height retrieval when emergent trees are present. Scattering from the emergent tree canopy (a), upper stand canopy (b), lower stand canopy (c) and ground surface (d) contribute to the vertical location of the scattering phase centre. Example scattering phase centre location is shown (dot).

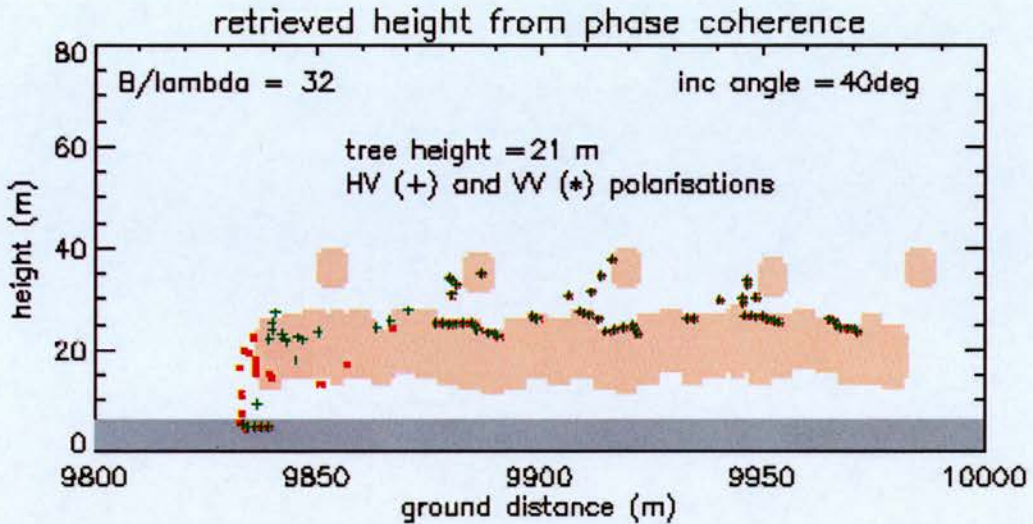


Figure 7.7 Consequence of emergent trees on height retrieval in modelled results. (Courtesy Dr. Izzawati)

7.5 Incidence angle

Incidence angle also has an impact on the extent of the area of edge effects, as well as on height retrieval in areas away from edge effects. Incidence angle has the effect

of altering the amount of canopy and ground contribution, as well as the extent to which the lower parts of the canopy are exposed to the SAR signal. The primary difference is that as incidence angle changes, the apparent angle of the trees relative to the sensor changes, although the trees themselves remain physically vertical. As incidence angle decreases (associated with an increase in depression angle and decrease in look angle), the amount of lower canopy visible is increased due to less occlusion between individual trees (figure 7.8). At higher incidence angles vertical penetration is reduced as the signal has to pass through more canopy. In low density stands, decreasing incidence angles has the effect of increasing the visibility of the ground, thus increasing the ground scattering contribution, which in turn decreases the scattering phase centre and the retrieved height.

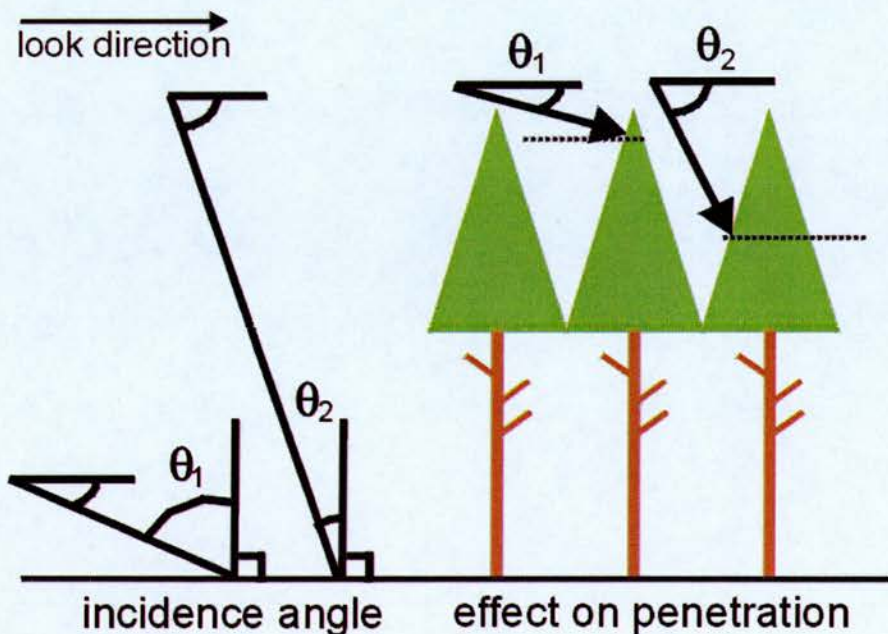


Figure 7.8 Effect of incidence angle on height retrieval. A high incidence angle (θ_1) results in less low canopy visibility due to increased occlusion compared to a low incidence angle (θ_2).

The extent of area affected by edge effects will vary depending upon incidence angle. As one would expect, the area of edge effect is reduced at higher incidence

angles (figure 7.9) due to the higher proportion of volume scattering. It would be expected that at grazing incidence angles, the area of edge effects would be minimised, tending towards no edge effect. There is no apparent change in the extent of edge effects when compared over high-density (figure 7.9) and low-density (figure 7.10) stands; this is inline with results found in section 7.7.

Height retrieval is also affected by incidence angle. As mentioned, smaller incidence angles permit more exposure of the lower canopy, thus lowering retrieved height. Modelled results showed that changes in incidence angle do not appear to have a significant effect on height underestimation in dense stands although a small increase in underestimation is apparent (figure 7.9). However, in low density stands (figure 7.10), the change in incidence angle towards larger incidence angles results in improved height retrieval. The upper part of the canopy is visible at high incidence angles (figure 7.8), but as the incidence angle decreases, the amount of lower canopy exposure increases. At low density, this may also result in significantly increased ground scattering contribution as well, further adding to the height underestimation. Retrieved heights show that as the relative incidence angle increases, there is no apparent change in height underestimation (figure 7.11); although there is a decrease in the height difference between measured and retrieved heights (figure 7.12).

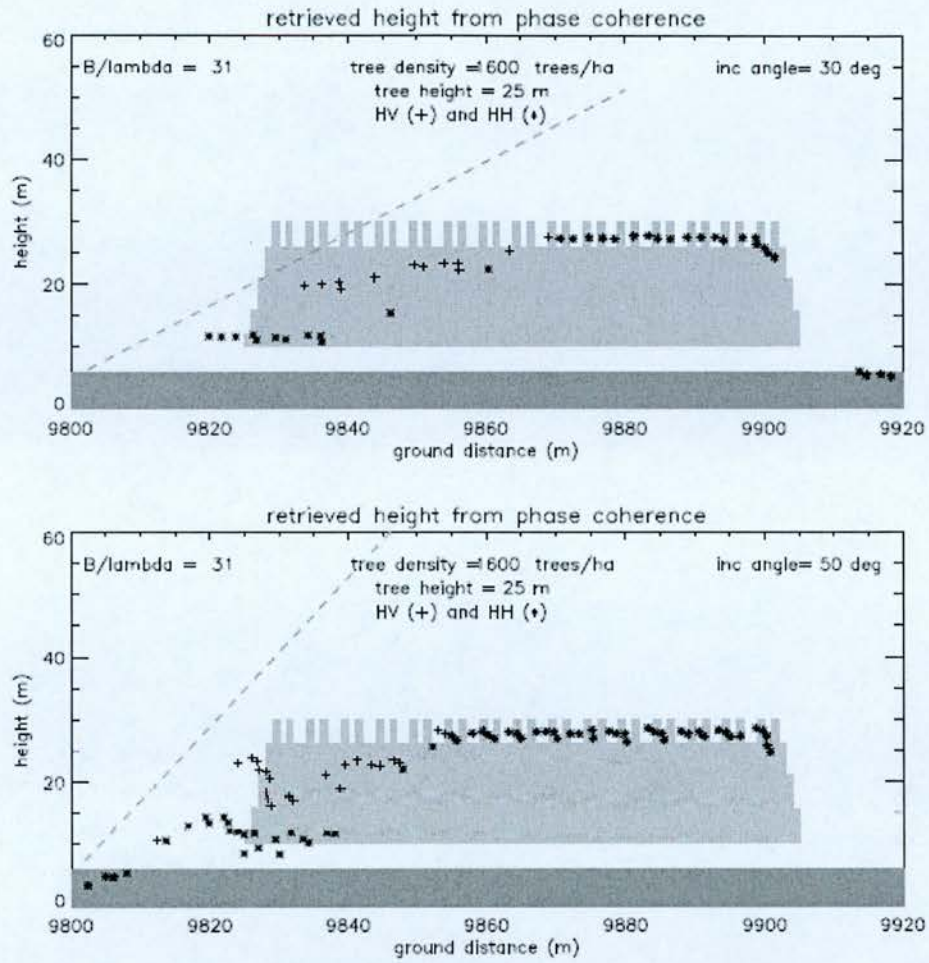


Figure 7.9 The extent of area affected by edge effects at increasing incidence angles: 30° (top) and 50° (bottom) over high-density plantations. The dashed line illustrates a line of common range for the given incidence angle. (Woodhouse et al., in press.)

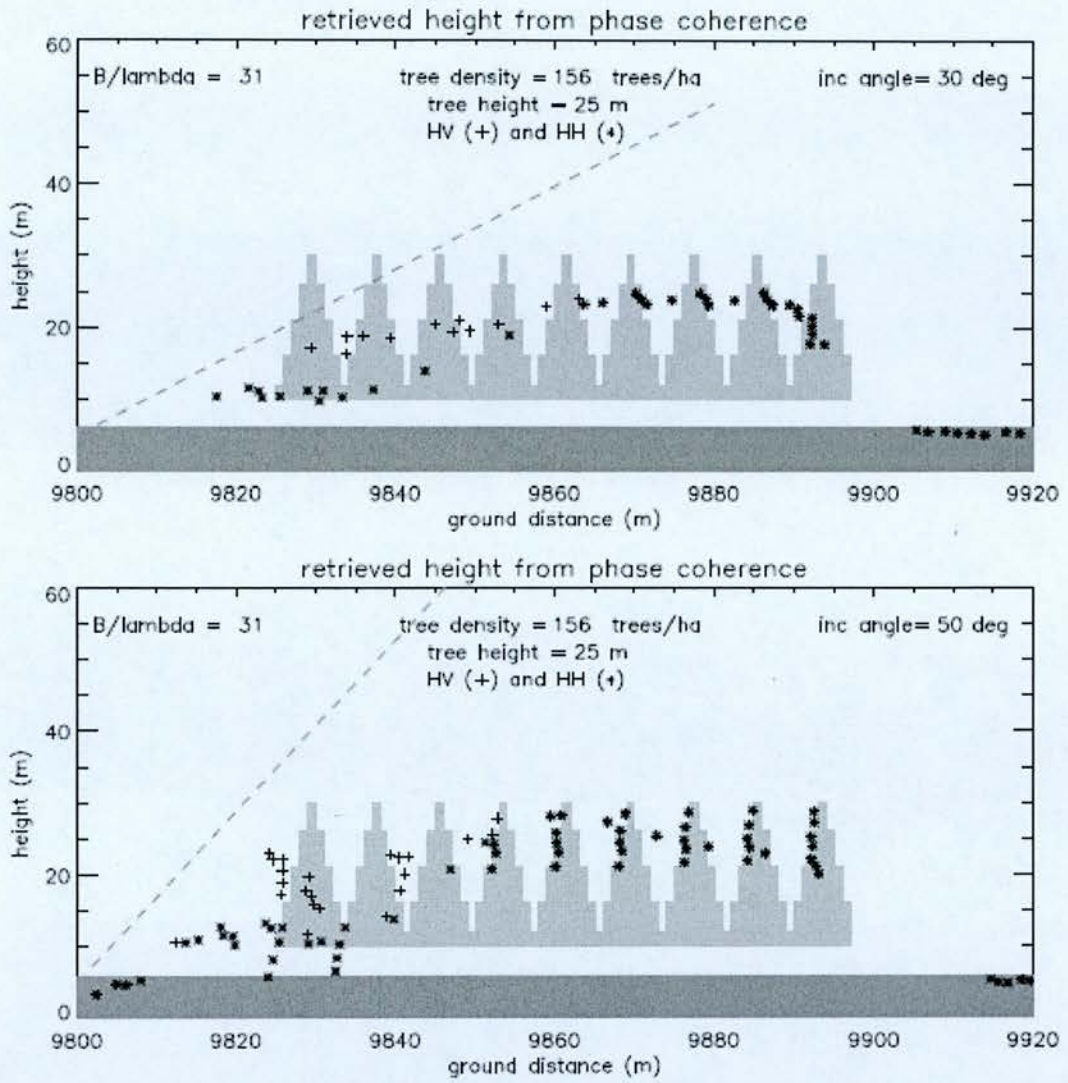


Figure 7.10 The extent of area affected by edge effects at increasing incidence angles: 30° (top) and 50° (bottom) over low-density plantations. (Woodhouse et al., in press)

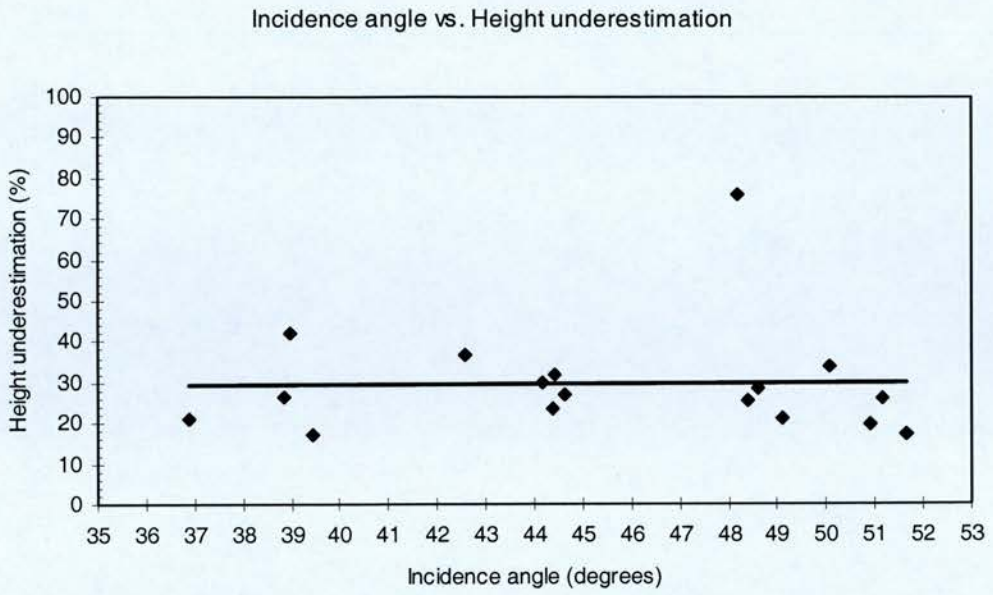


Figure 7.11 Height underestimation due to changes in incidence angle. Coed y Brenin data shown.

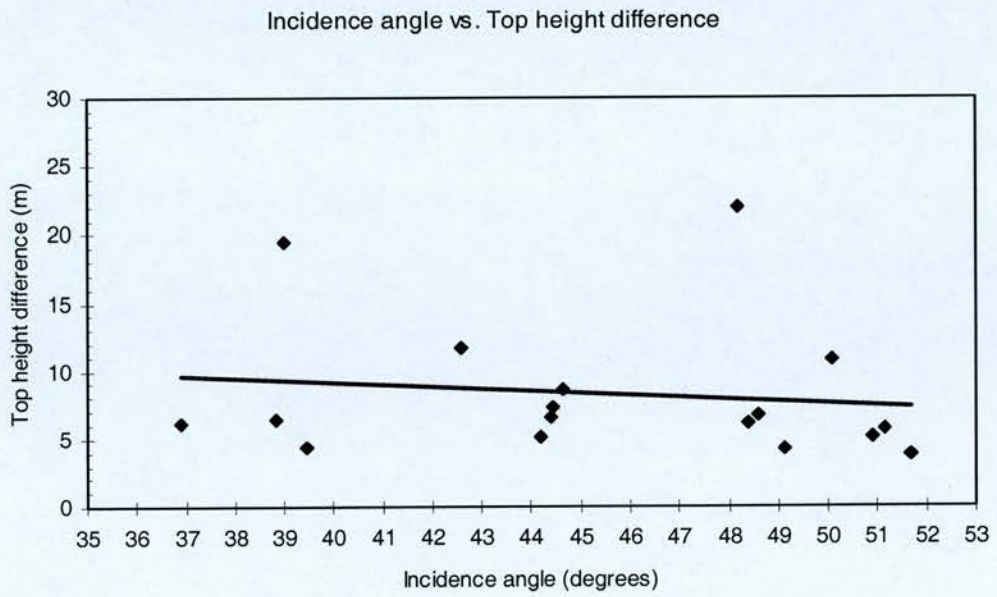


Figure 7.12 Height difference (DSM-OSDEM) due to changes in incidence angle. Coed y Brenin data shown.

7.6 Effect of slope

The effect of slope in this study is seen as having a similar but separate effect to incidence angle (section 7.5). Slope will have an effect on the location of the scattering phase centre, as it will change the visibility of parts of the crown (figure 7.13). This is in contrast to incidence angle changes, as the trees will remain vertical (due to geotropic forces acting on the tree) with respect to the signal look direction. It is anticipated that trees will always grow vertical, even on steep slopes. Figure 7.13 shows a schematic of canopy visibility changes due to slope, relative to the sensor look direction. On down slopes (negative relative to sensor) only the upper part of the crown is visible due to shadowing from trees nearer the sensor. In contrast, up slopes (positive) reduce the amount of shadowing, thus increasing exposure to lower parts of the canopy. The resultant vertical location of the scattering phase centre will therefore be higher on down slopes than up slopes, providing less underestimation when compared to measured heights.

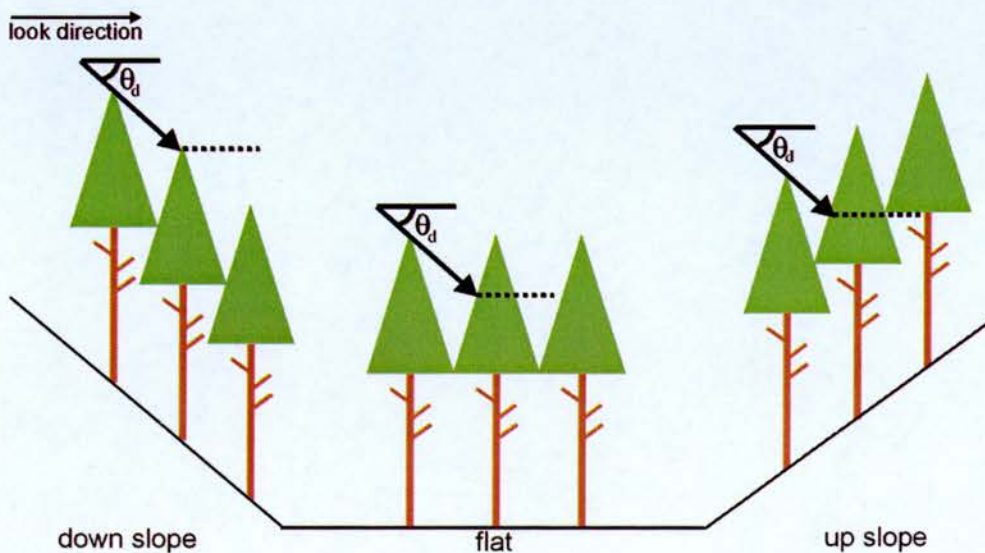


Figure 7.13 (A, above) Effect of slope on penetration depth into the canopy. Slopes are relative to line of sight from sensor. The angles shown are all of equal look angle, as represented by an equal depression angle (θ_d). (B, below) The area of edge effect is affected by slope. An increased area of scattering occurs on up slopes compared to down slopes.

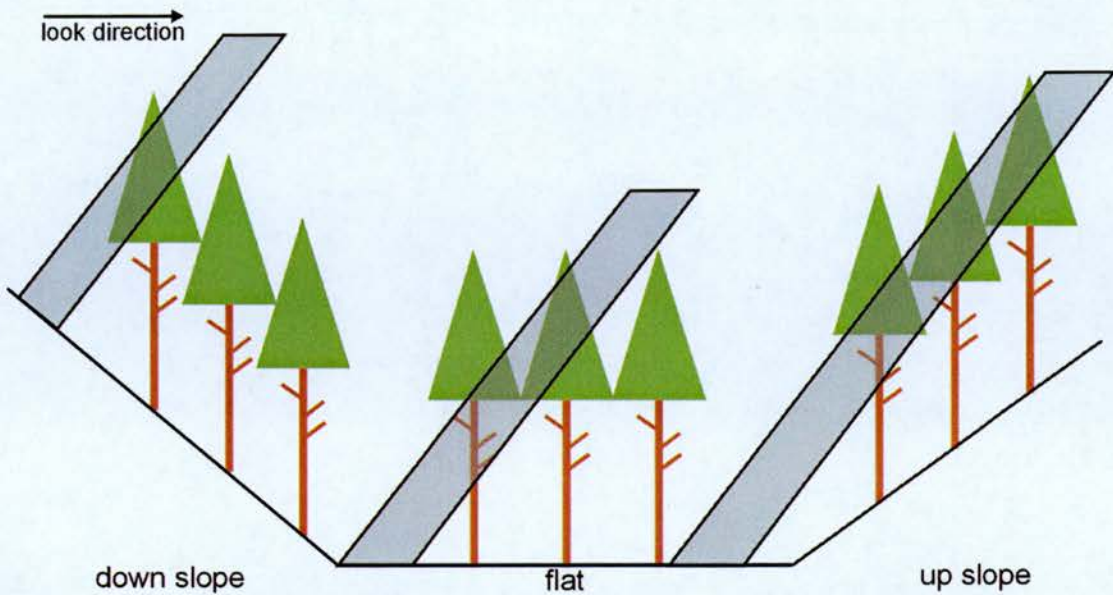


Figure 7.13 (B)

Modelling using PRIS was performed on a range of slope angles over low and high density stands. Modelled results have given an insight into two effects of slopes on height retrieval. Firstly, the extent of the area affected by edge effects is influenced by the angle of the slope (figure 7.13b). A stand on the flat has an edge effect extent of around 20m from the near edge of the stand (figure 7.28, top), however on a slope of 6 degrees upslope (relative to sensor look direction), the extent increase to around 30m (figure 7.14) and to around 40m at 24 degrees upslope (figure 7.15). On down slopes the extent is expected to be reduced, for example to around 10m at 24 degrees down slope (figure 7.16). From examining modelled results at different number densities at different slope angles, there is no apparent affect of number density changes on the area of edge effect.

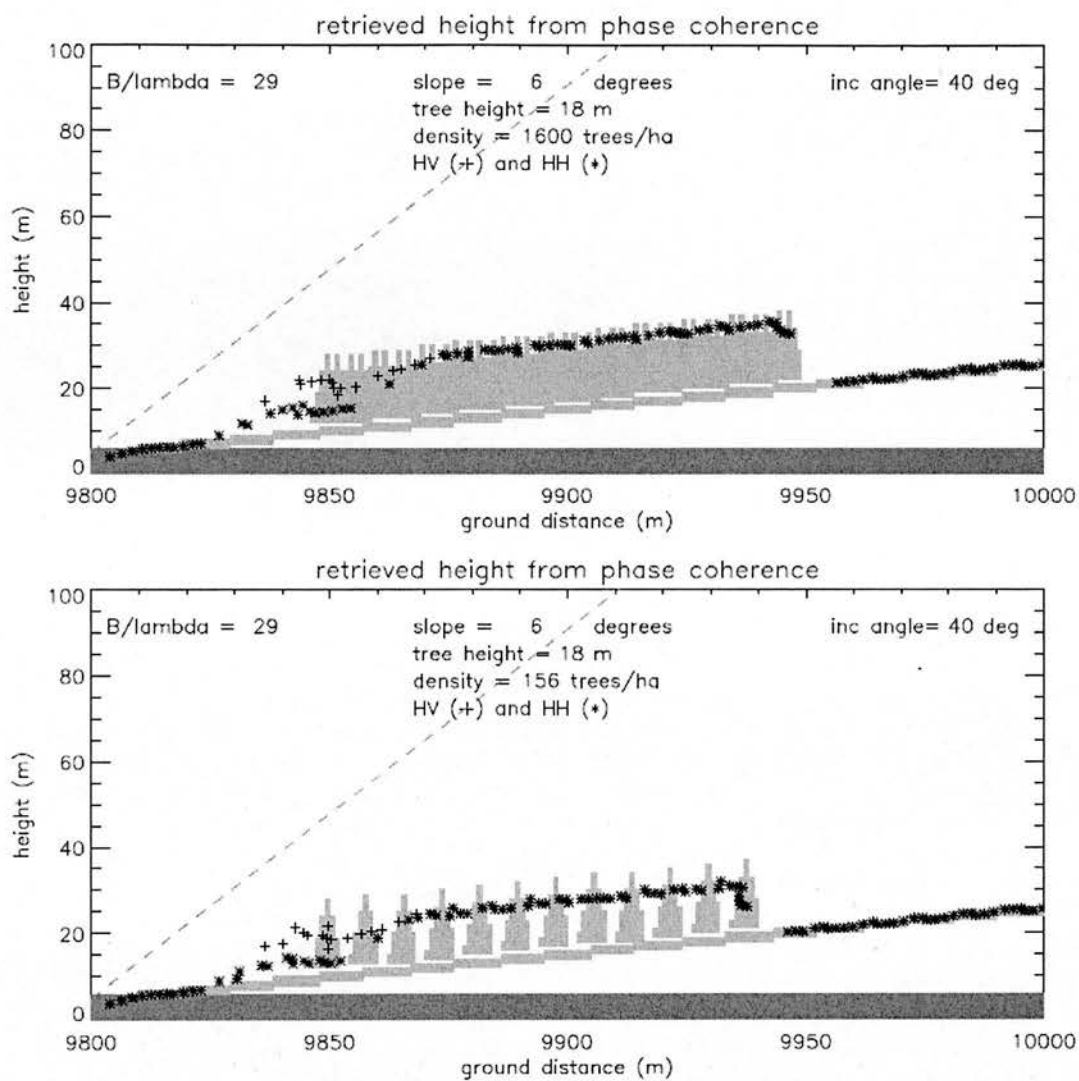


Figure 7.14 Profile of retrieved heights over high (top) and low (bottom) density stands on an upward slope of 6 degrees.

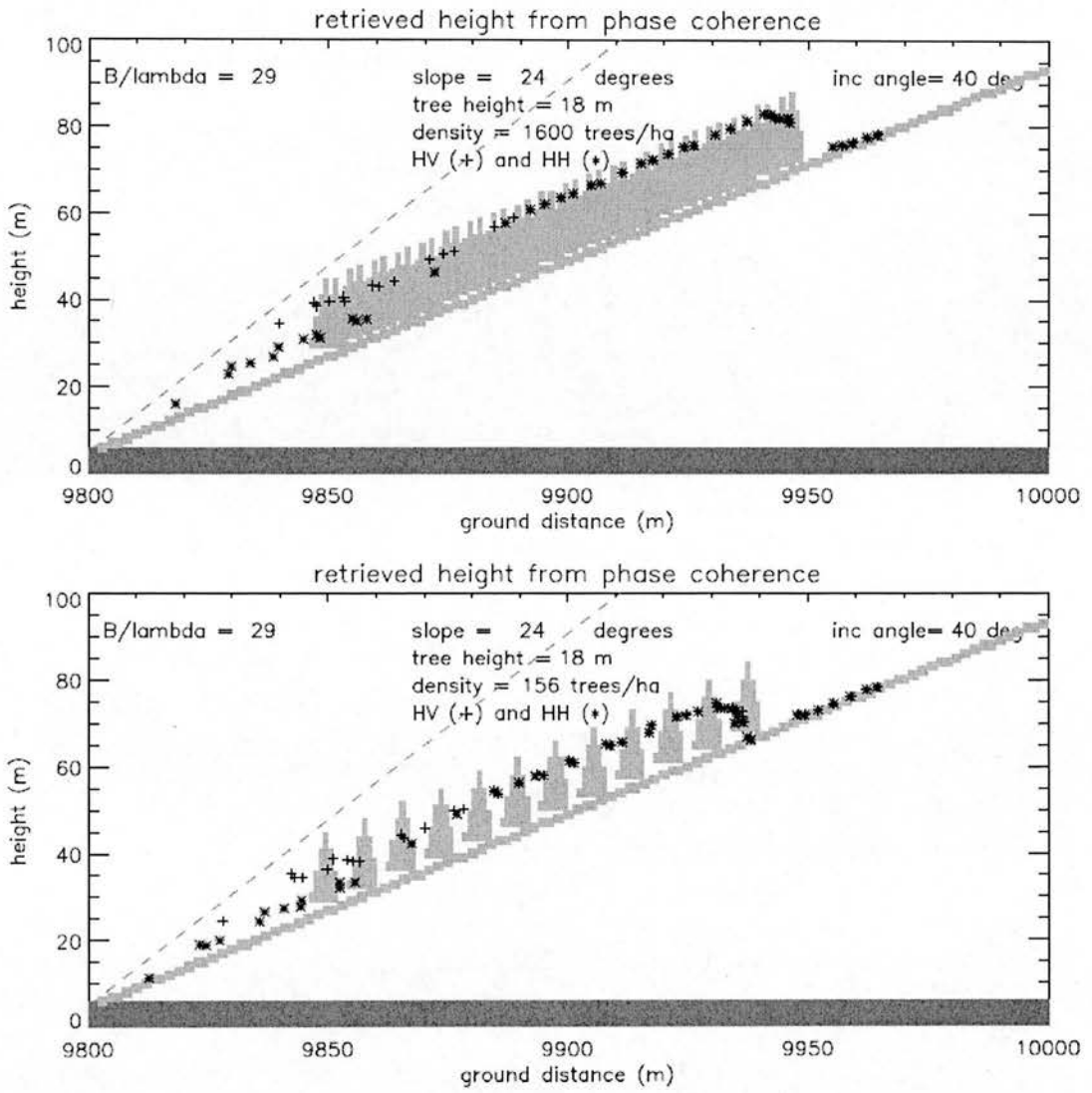


Figure 7.15 Profile of retrieved heights over high (top) and low (bottom) density stands at an upward slope of 24 degrees.

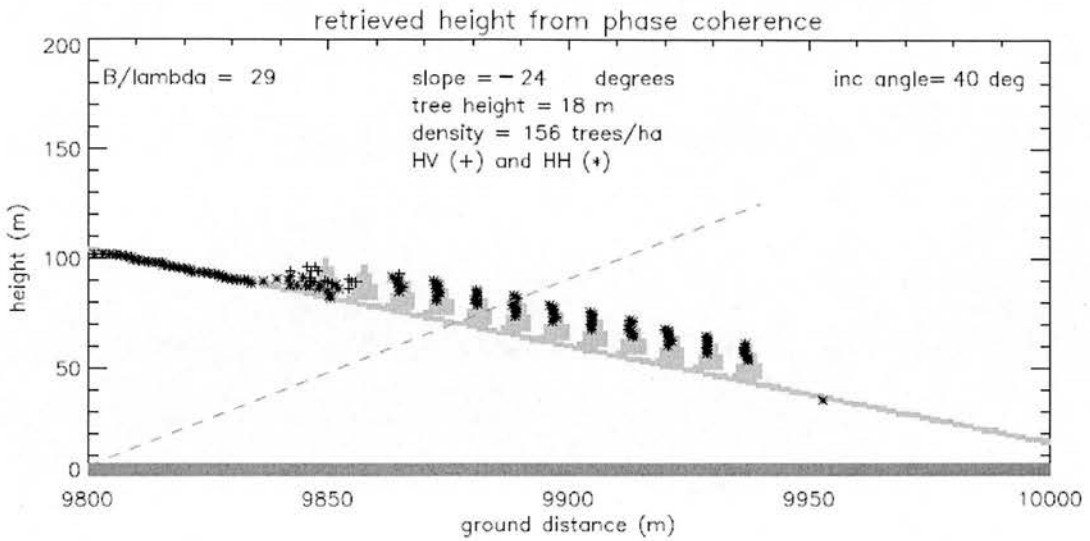


Figure 7.16 Profile of retrieved heights at low-density plantations on a down slope of -24 degrees.

The angle of the slope also has an impact on height retrieval in areas away from edge effects. For low density stands, and increase on slope angle from 0 to 20 degrees upslope has the effect of increasing underestimation from around 60% to around 70%, a similar case is seen for down slopes, although the increase is not as large as for up slopes (figure 7.17). This trend in height underestimation increase due to slope is not so apparent in high density stands.

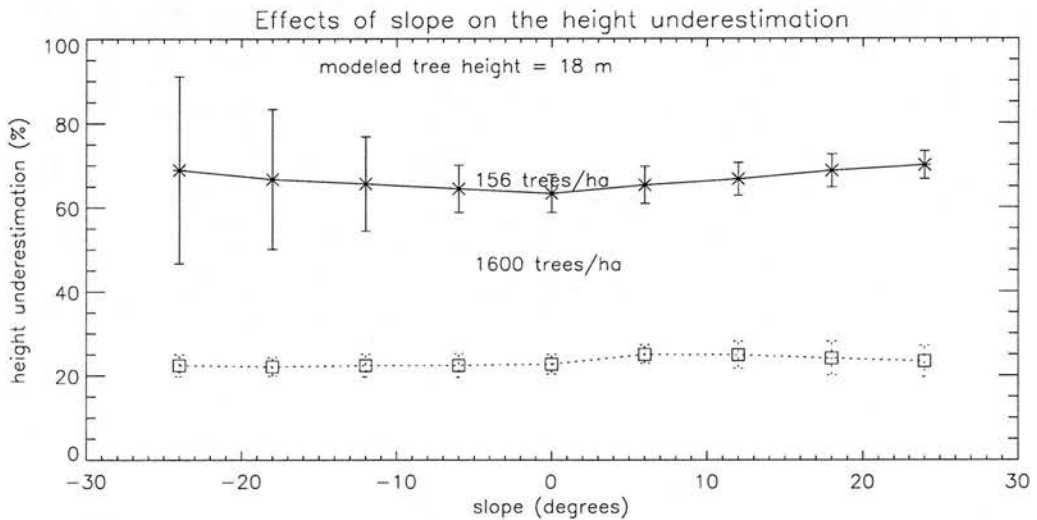


Figure 7.17 . Height underestimations due to slope variations for both low- (top) and high-density (bottom) stands on upward (positive) and downward (negative) slopes.

The general trend of increasing height underestimation at higher slope angles can be seen in the real data (figure 7.18). It is also interesting to see that up slope errors increase higher than down slopes as predicted, and that on down slopes the error decreases until extreme slopes (greater than -20 degrees) are reached. The trend is seen more clearly when analysing the height difference between the retrieved height and the measured height (figure 7.19). Second order polynomial regression lines were chosen so as to allow representation of increasing and decreasing slope angles, which would not have been shown with a linear regression.

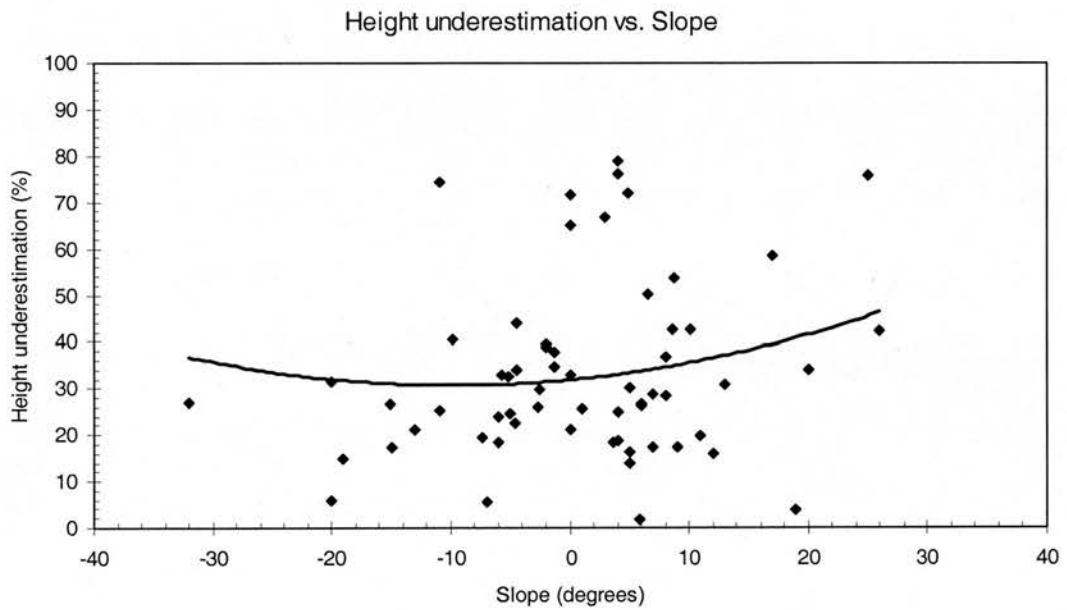


Figure 7.18 Height underestimation due to slope angle. Polynomial regression line indicates underestimation. Mean underestimation is 33.5%.

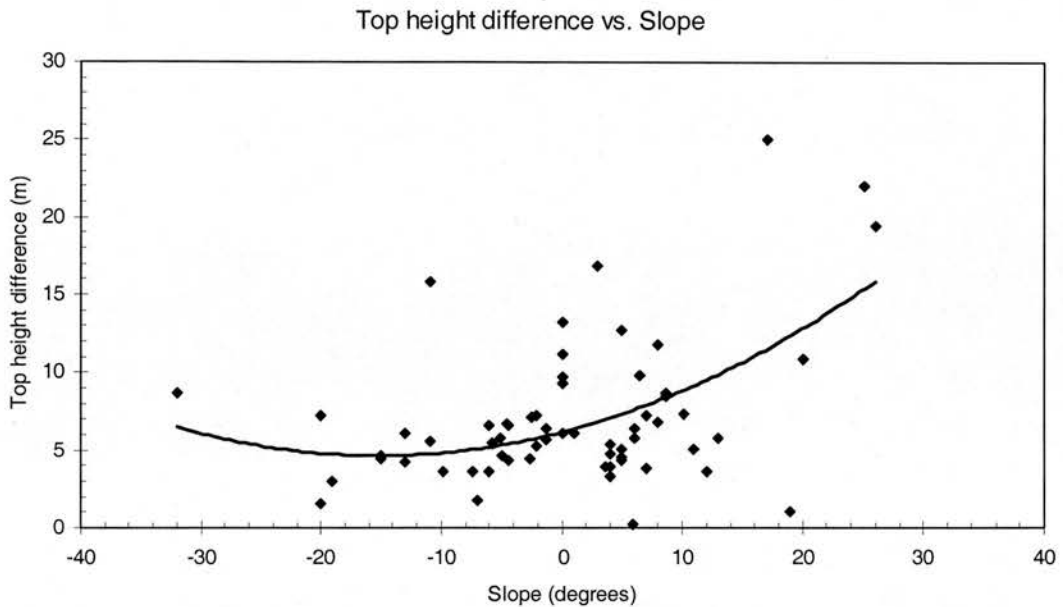


Figure 7.19 Height difference due to slope angle. Polynomial regression line indicates difference. Mean height difference is 7m.

Assessing the effects of slope on height retrieval at different number densities produces a different result than predicted by the modelling results. At low density, the height underestimation increases as the up slope angle increases, the down slope trend is a slight decrease in underestimation (figure 7.20). However the modelled errors of 60% and above are not generally apparent, with the average underestimation being 27%, although there are a few outliers. Modelled underestimations for high density stands are around 20%; however height retrieval results show an average underestimation of 42% (figure 7.20), and the trend towards increasing error at steeper slopes is more apparent than modelled results. This is not inline with the predicted modelled results, but is supported by other findings. Section 7.7 determines that as stem number density increased, height underestimation also increased, this is seen in the results presented in figure 7.20, where higher density stands produce a higher underestimation. Second order

polynomial regression lines were chosen to better represent the influence of slope angle. Section 7.8 determines that better height estimates are obtained as trees increase in height. It is assumed that as a stand of trees becomes taller, the number density decreases (through self-thinning or management intervention). As such, less dense stands can be expected to be taller, thereby with a lower underestimation, as seen in figure 7.20. This is further supported by assessing the difference between the retrieved height and the measured height (figure 7.21). In low density stands, the amount of height difference increases for steeper up slopes, this is probably due to more of the lower canopy being visible to the radar, thus lowering the retrieved height; this effect is reduced on down slopes due to less canopy visibility. For high density stands, the slope angle has less effect on canopy visibility due to the canopy being so dense that primarily only the upper part of the canopy is visible.

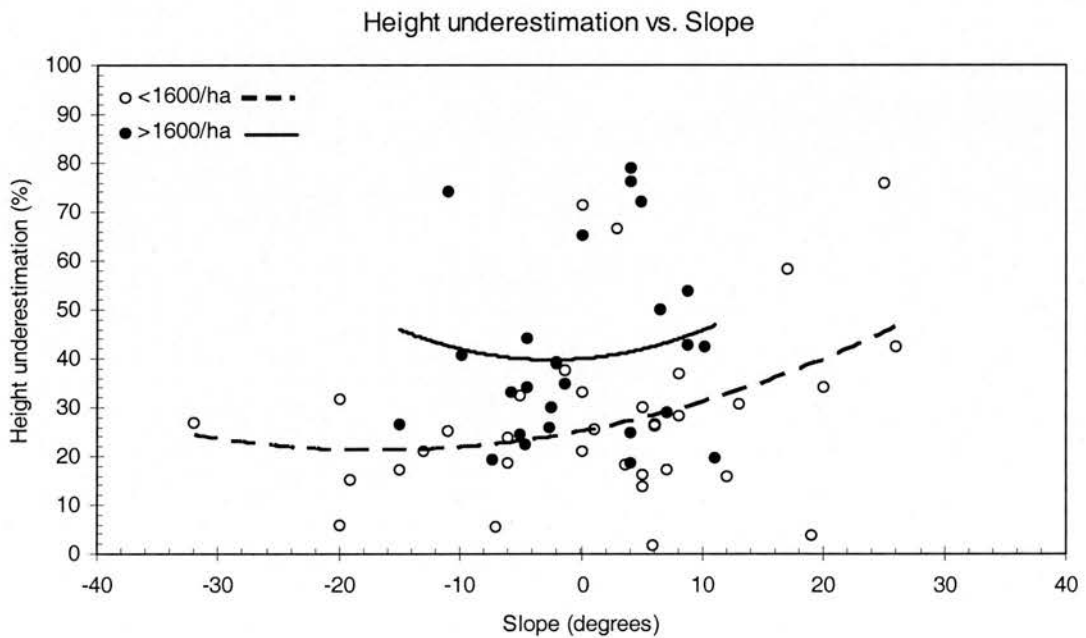


Figure 7.20 Height underestimation due to slope angle at high- and low-density stands. Polynomial regression lines indicate underestimation. Stand densities are number of stems/ha.

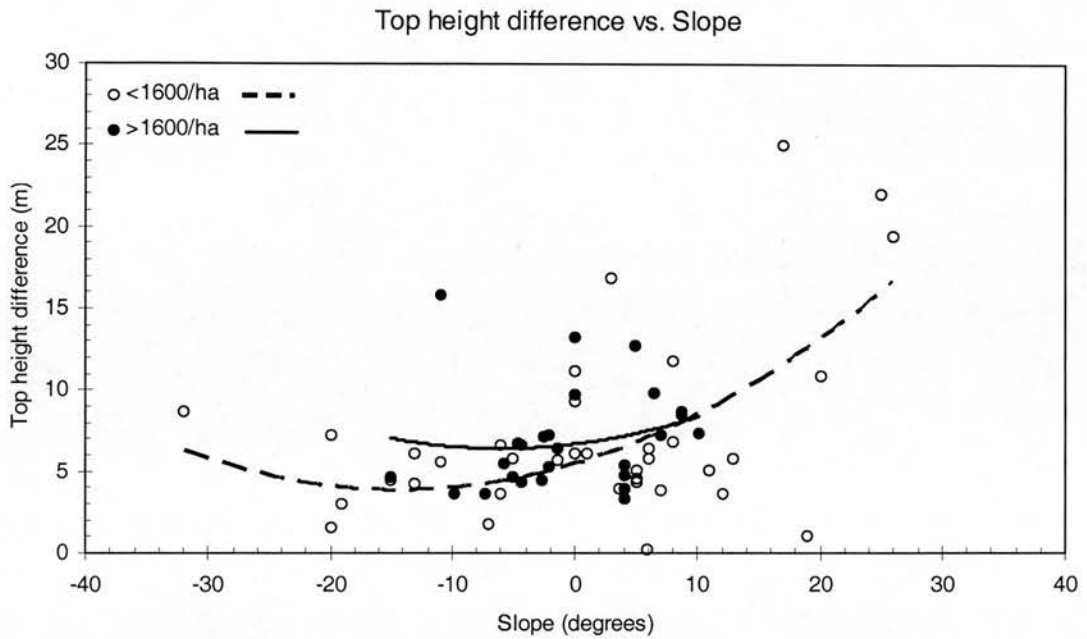


Figure 7.21 Height difference due to slope angle at high- and low-density stands. Polynomial regression lines indicates difference. Stand densities are number of stems/ha.

7.7 Effect of stem number density

The density of the stand, expressed in stems/ha, has an effect on height retrieval. The height retrieved over low density stands was anticipated to be lower than that of high density stands. A denser stand presents more canopy area (therefore fewer gaps) to the radar signal, resulting in less visibility to the lower canopy or ground (figure 7.22). The resultant SPC is therefore higher due to increased contribution from canopy scattering and less from ground scattering. In dense stands (e.g. >1500 stems/ha) it is expected that canopy scattering will dominate over ground scattering because less signal reaches the ground. In less dense stands, larger gaps allow more signal to reach the lower canopy and ground, thus lowering the SPC. Height retrieval produced by averaging retrieved heights across a dense stand will result in higher height retrieval when compared to a less dense stand of the same height (figure 7.22).

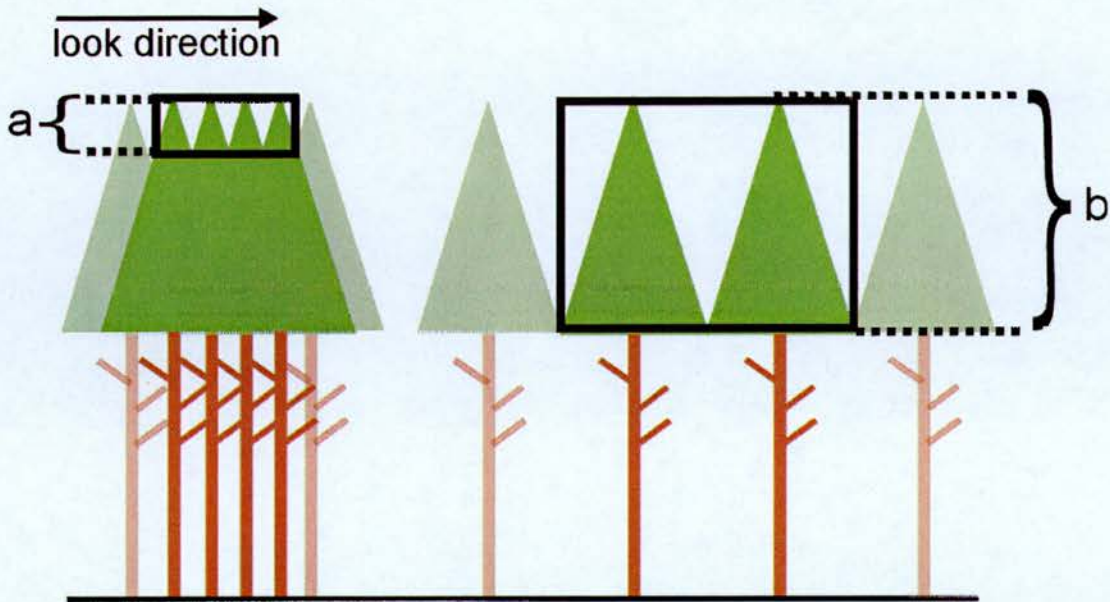


Figure 7.22 Schematic of areas of canopy scattering contributing to retrieved height within a stand (away from edges) over high (left) and low (right) density stands. Note that average retrieved height of 'a' is higher than average of 'b'.

Figure 7.23 shows the resultant trend in height underestimation (%) when compared to number density for the stands used in this study. As stand density increases, the underestimation increases. This is not in line with expectation. Comparing figure 7.23 with figure 7.24 however sheds more light on this unexpected trend. Figure 7.24 depicts a decreasing trend in height difference (between retrieved height and actual height) as density increases; this is supported by results of modelled data (figure 7.25), which shows a lower retrieved height as density decreases. In UK conifer plantations, a higher density stand is indicative of younger, shorter trees. There are also likely to be more gaps as canopy closure may not have been reached. More signal penetration to the ground increases the ground scattering contribution, resulting in a lower retrieved height. Also, a shorter canopy depth (as well as a more open canopy) may allow SAR penetration right through to the ground, resulting in increased ground scattering. The level of underestimation in smaller trees is high

(figure 7.23), but the actual difference in retrieved height is less than with taller trees (figure 7.24). A fixed/constant amount of underestimation would appear larger on a short tree relative to a taller tree. Section 7.8 further discusses the effect on height retrieval due to tree height. It should be noted that number density has no apparent impact on the area affected by edge effects (figure 7.25). When assessing effect of number density over heterogeneous environments (e.g. semi-natural and savanna), it should the low stem number density (e.g. <100 stems/ha⁻¹) presents a very open and sparse canopy, thus allowing significant signal penetration to the ground. This results in a large ground contribution to the scattering phase centre, thus reducing retrieved height, and increasing the difference between measured and retrieved height (e.g. extreme case of figure 7.24 and 7.25 bottom).

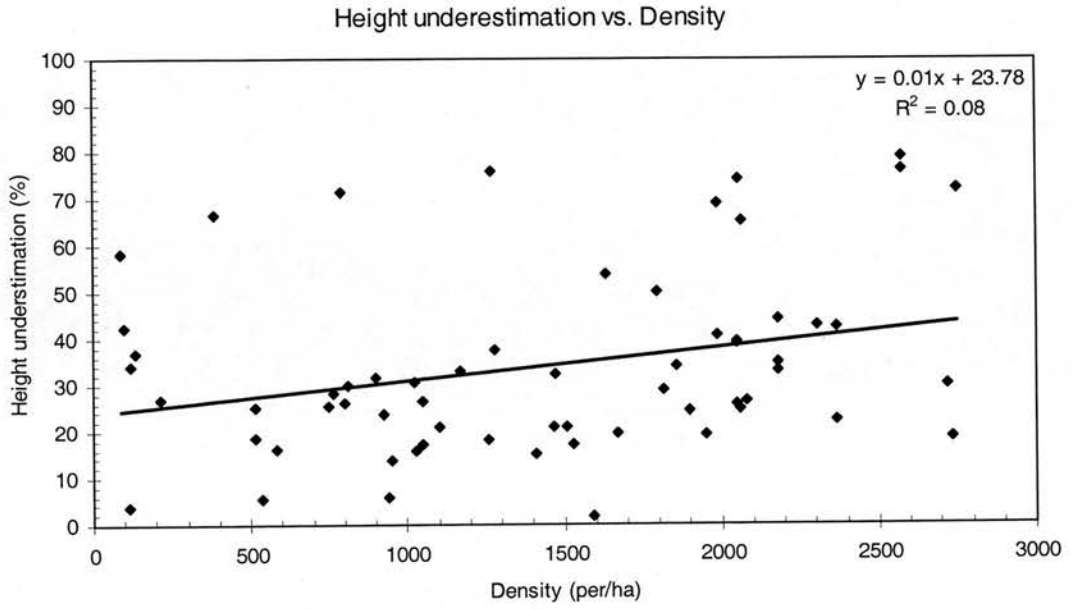


Figure 7.23 Comparison of retrieved top height underestimation to number density.

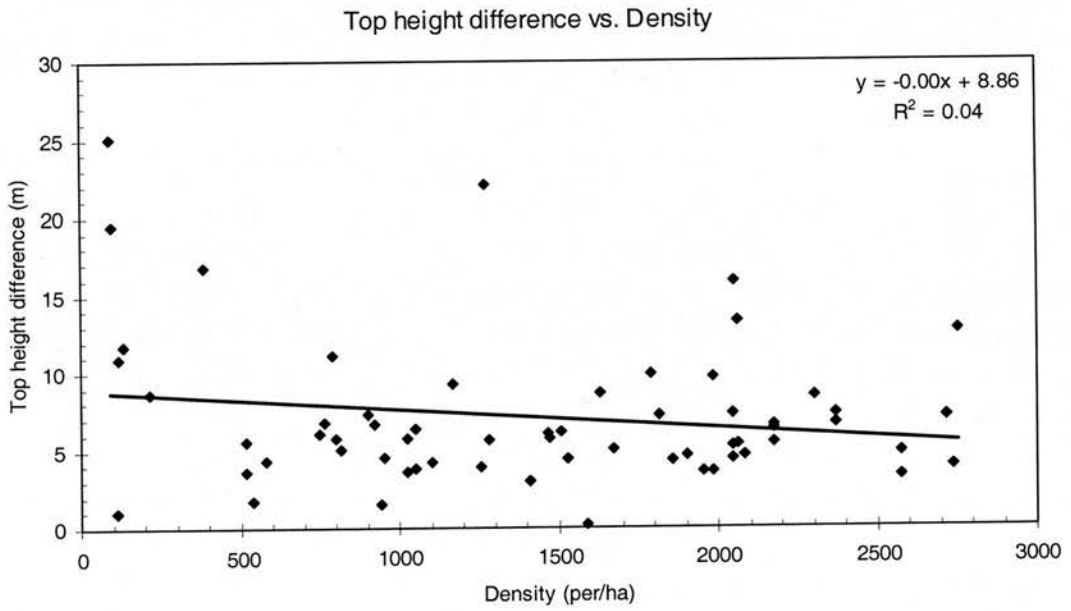


Figure 7.24 Comparison of top height difference to number density.

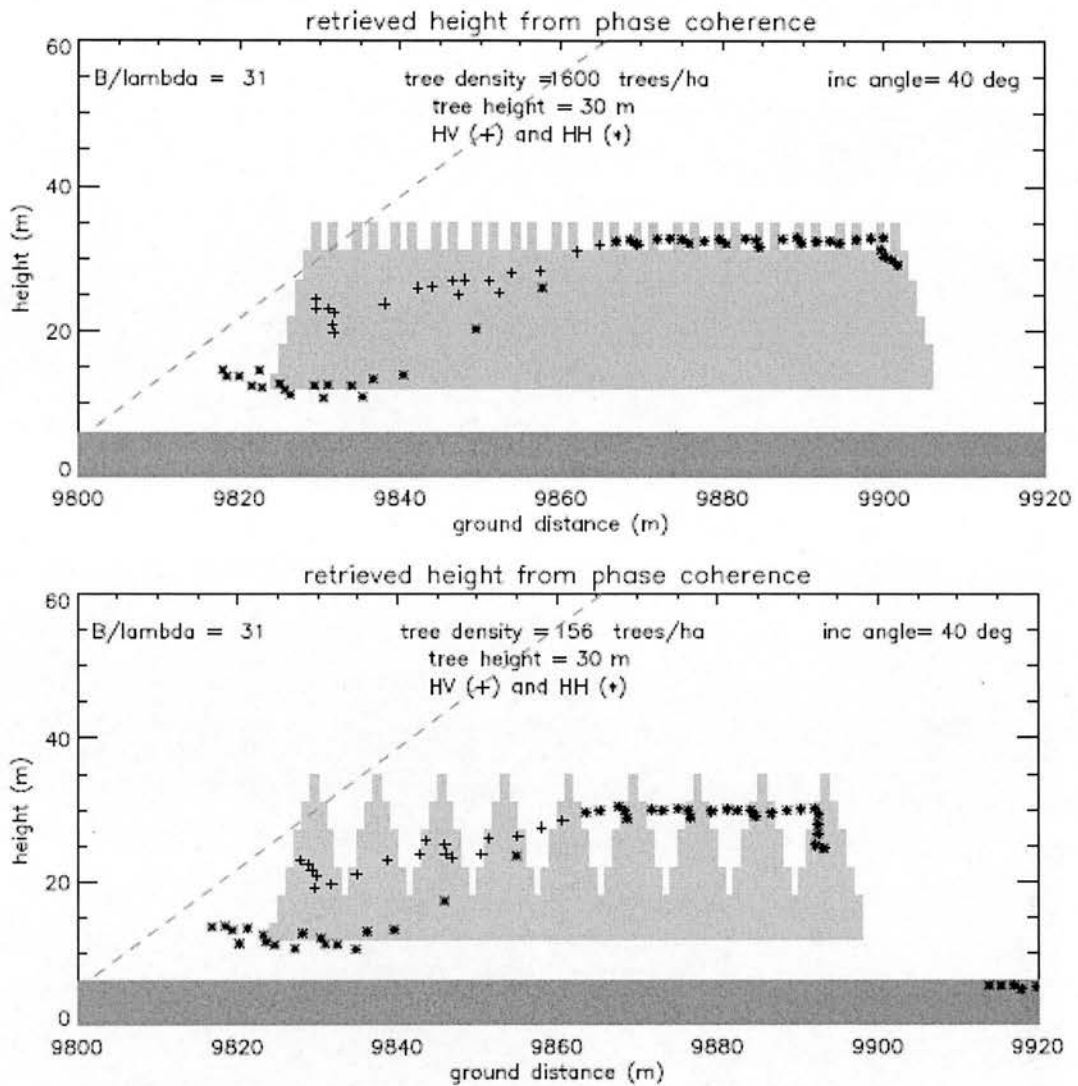


Figure 7.25 Modelled results of affect of number density on retrieved height over high density (top) and low density (bottom) stands. (Izzawati et al.; Accepted)

7.8 Effect of tree height

Following on from comments in the previous section, height retrieval accuracy is also affected by the height of the tree. A fixed amount of underestimation, e.g. 5m, would relate to 25% of a 20m tall tree, whereas the same amount would represent 50% of a 10m tall tree (figure 7.26). In a dense stand, as tree height increases, underestimation (expressed as a percentage) would be expected to decrease. Taller (older) trees generally have larger crowns thus reducing the number of gaps (canopy

closure); hence signal penetration is limited to the upper part of the canopy. The relative percentage of underestimation compared to the actual tree height therefore reduces as the tree grows taller (figures 7.27 and 7.31) although the difference increases (figure 7.28). At low density, height underestimation is expected to be worse, although as tree height increases, the amount of underestimation will become relatively smaller (figure 7.32), although low density stands will still have a greater amount of underestimation than high density stands (figure 7.33). An indication of the relationship between height underestimation/height difference, top height and number density can be seen, as discussed (figures 7.29 and 7.30). It is seen that as height increases the stem number density decreases, thus allowing more gaps (and hence signal penetration to the ground), resulting in a lowered scattering phase centre and retrieved height, and an increase in the difference between retrieved and measured height (figure 7.30).

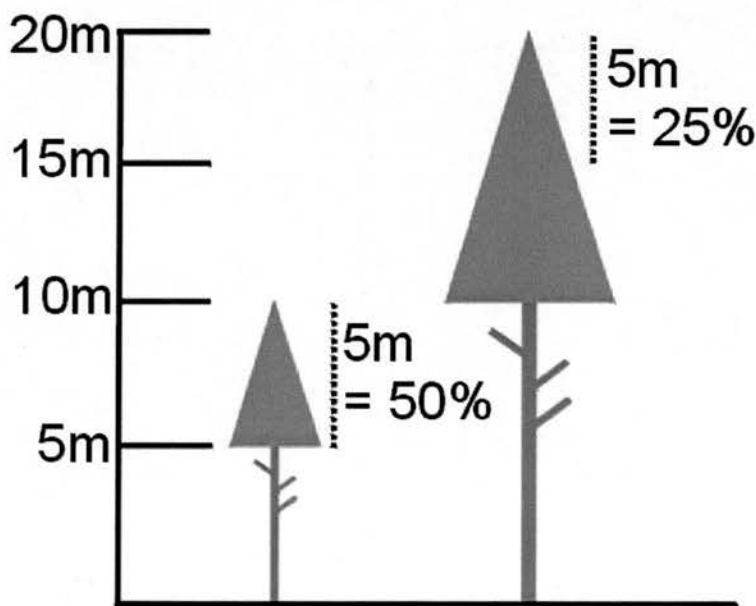


Figure 7.26 Schematic of relative height underestimation at differing tree heights.

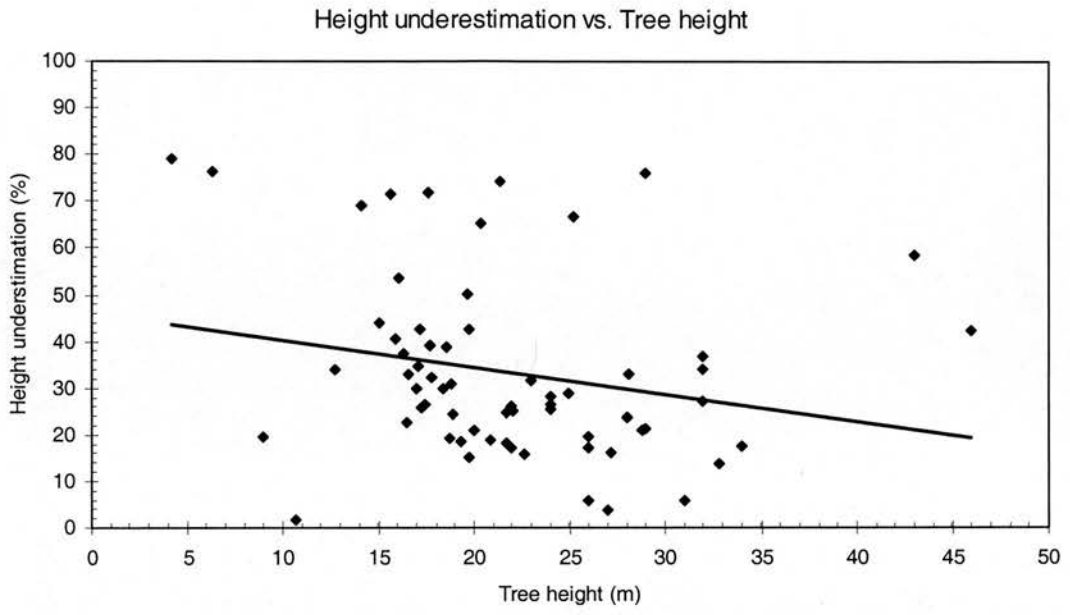


Figure 7.27 Height underestimation compared to measured top height.

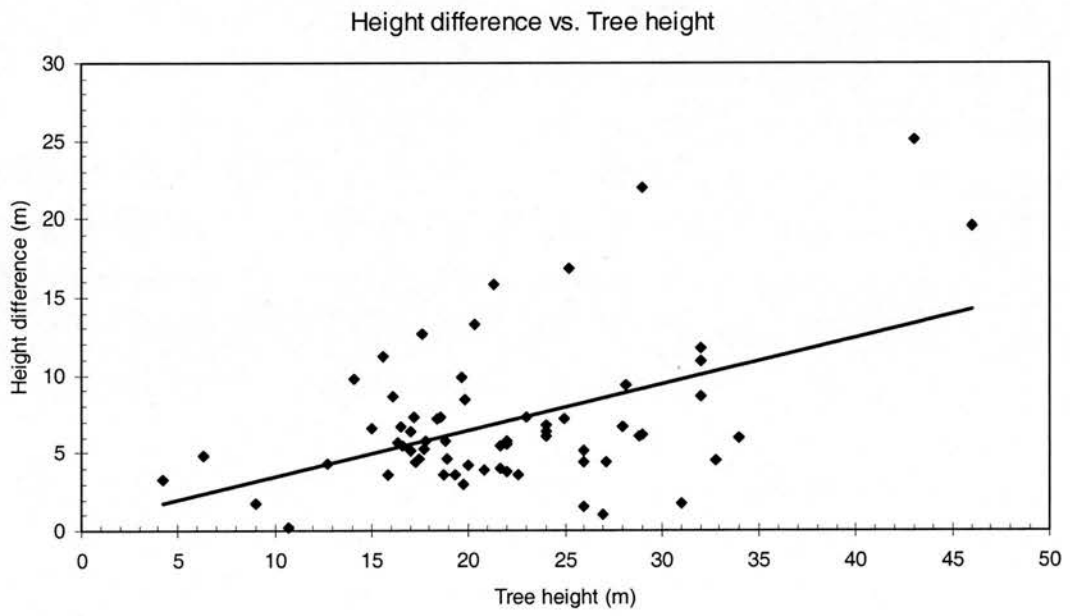


Figure 7.28 Height difference (DSM-OSDEM) vs. measured top height.

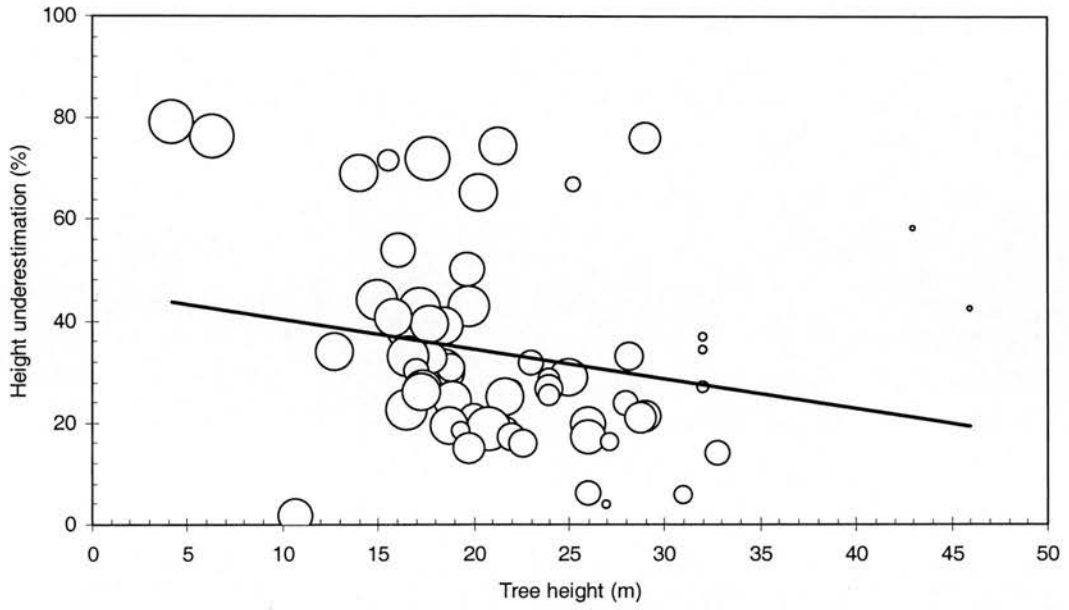


Figure 7.29 Height underestimation vs. top height and density. Larger circles represent higher number densities.

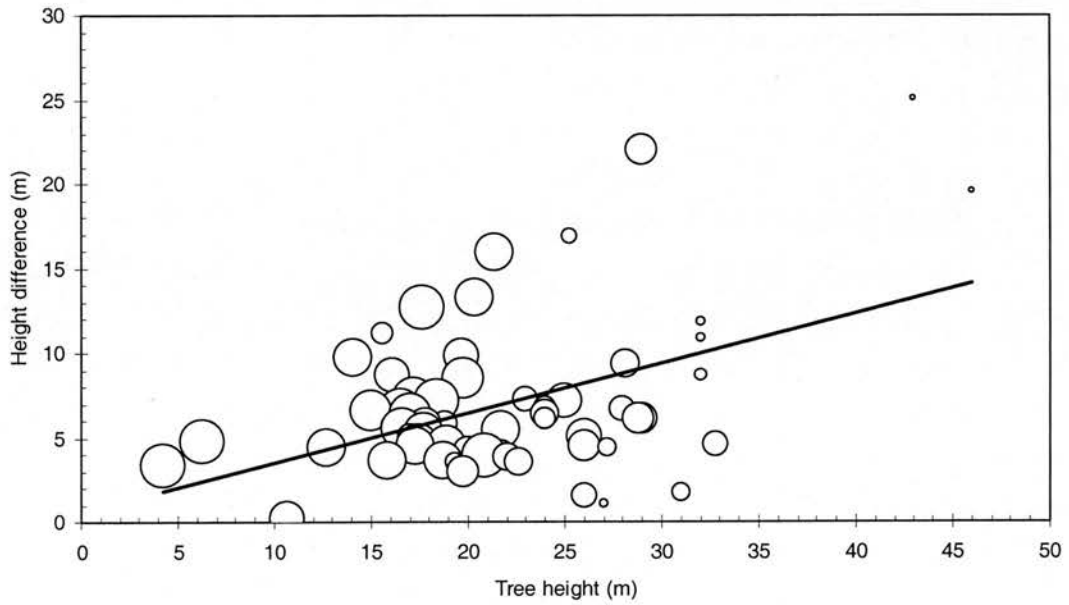


Figure 7.30 Height difference (DSM-OSDEM) vs. top height and density. Larger circles represent higher number densities.

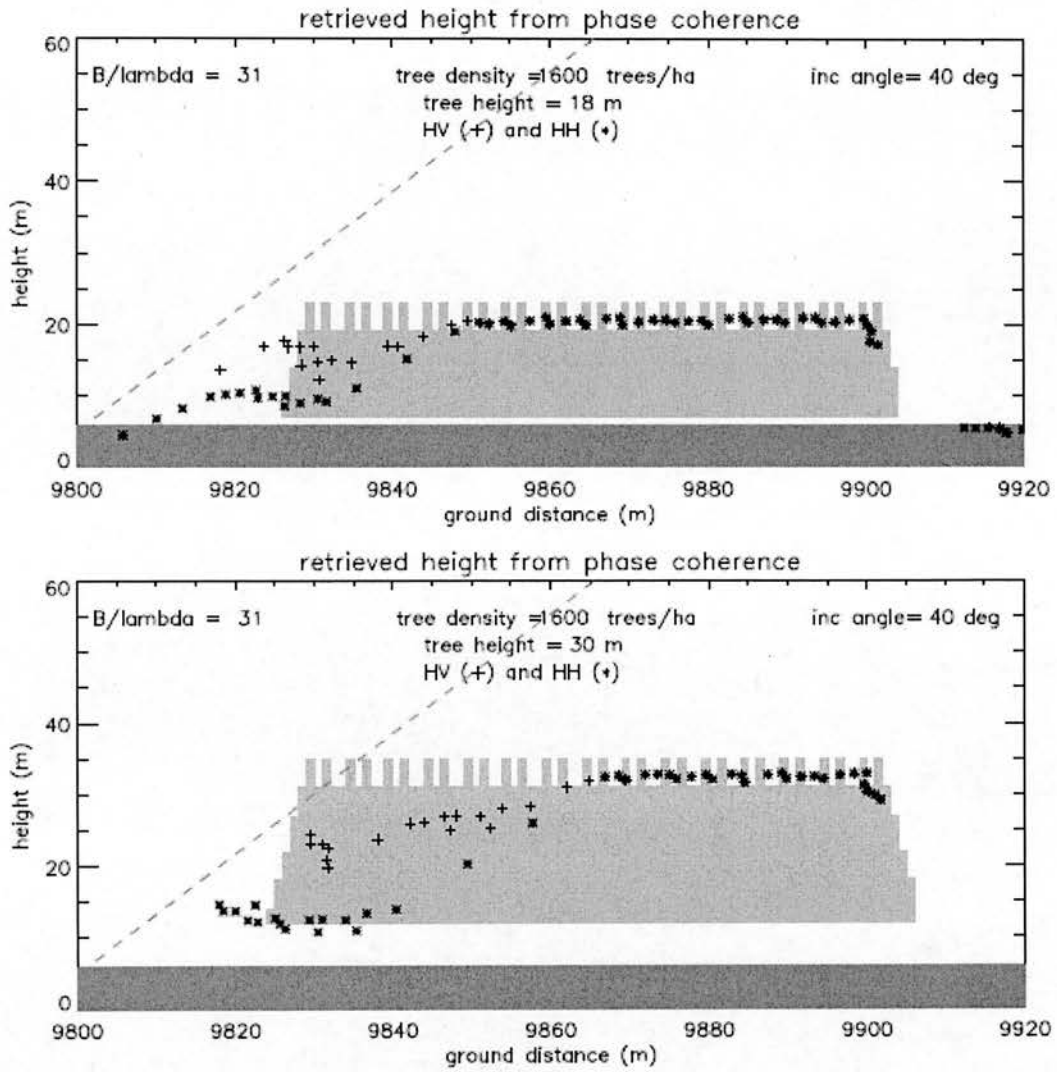


Figure 7.31 As tree height increases in a dense stand, the relative height underestimation decreases as a proportion of the tree height. Note also the increase in area affected by edge effect as tree height increases from 18m (top) to 30m (bottom). (Woodhouse *et al.*, in press).

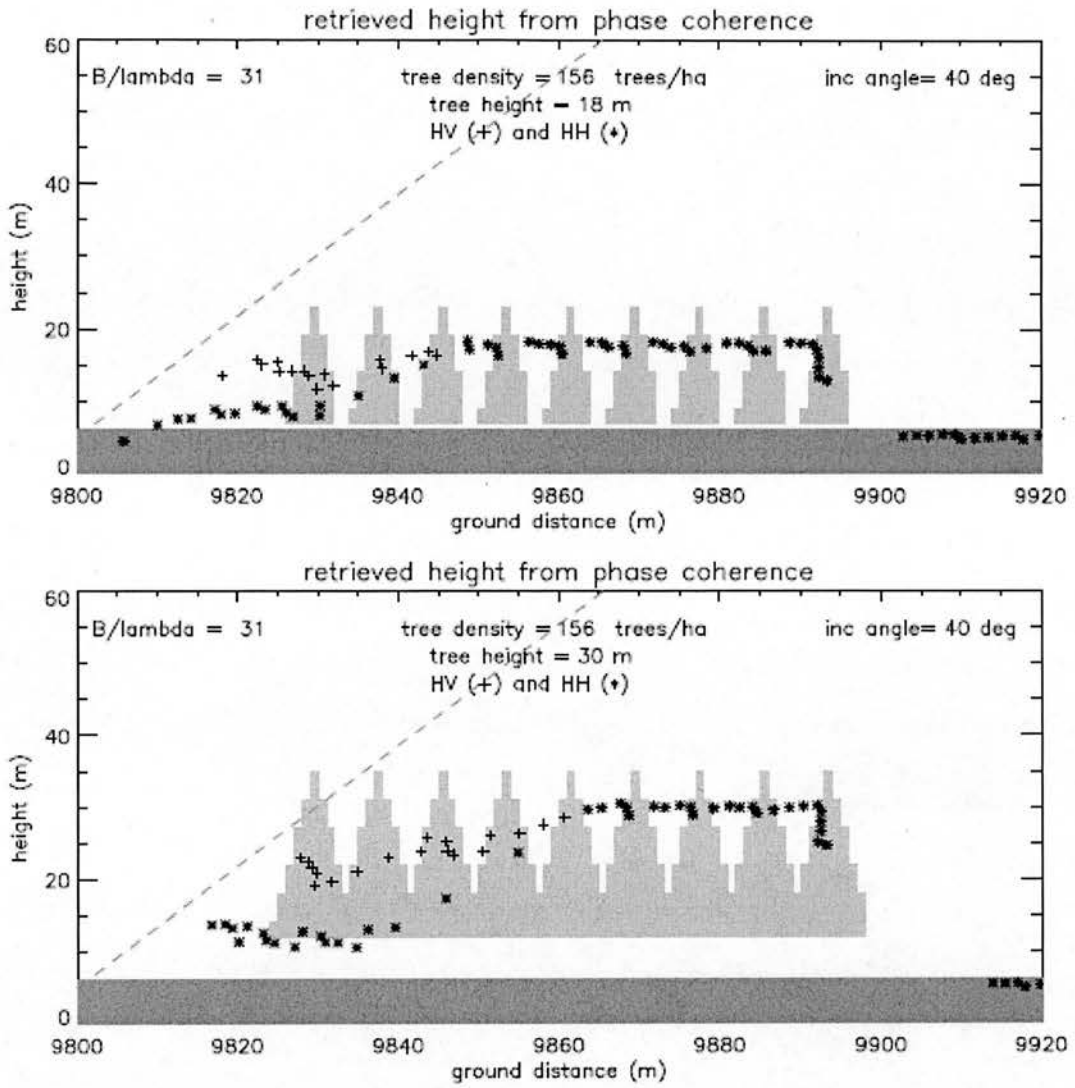


Figure 7.32 As tree height increases in a low density stand, the relative height underestimation decreases as a proportion of the tree height. Note also the increase in area affected by edge effect as tree height increases from 18m (top) to 30m (bottom). (Woodhouse *et al.*, in press).

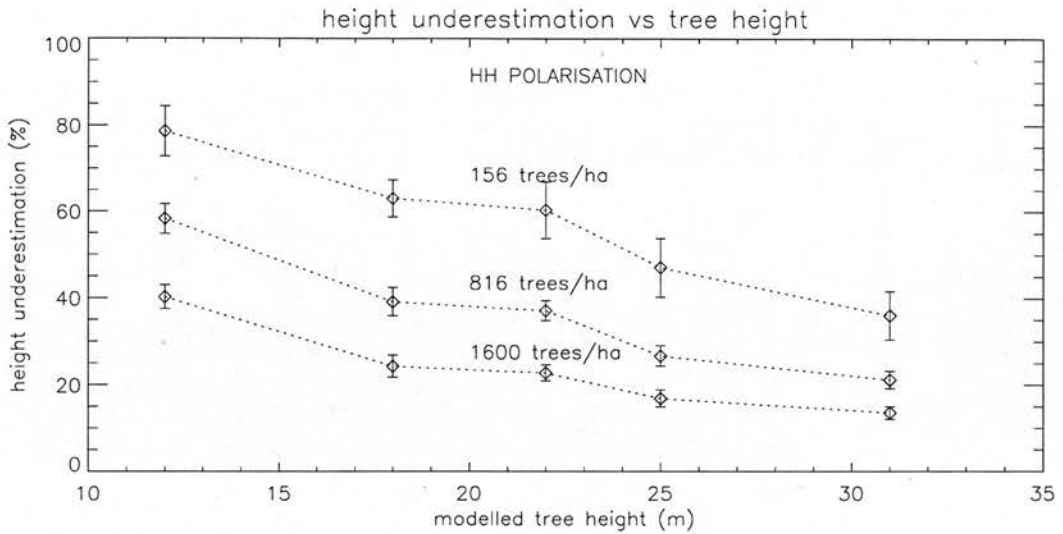


Figure 7.33 Height underestimations due to increasing tree height at varying densities (compare to figure 7.27). (Izzawati *et al.*, accepted)

The extent of the area affected by edge effects (section 7.3) is also affected by tree height. As tree height increases, the area of edge effect also increases (figures 7.31 and 7.32). The edge effects are effectively a layover effect, therefore increasing tree height results in a larger region of error. In areas away from edge effects, the actual height errors increase with increasing height (figure 7.28), but remain proportionally similar.

7.9 Effect of crown shape

The effect of crown shape on tree height retrieval is a significant one. Figure 7.34 demonstrates the areas of canopy scattering contributing to retrieved height for elliptical (broadleaf like) and conical (conifer like) shaped crowns. At X-band, the geometry of an ellipse presents more scattering area towards the upper part of a canopy, whereas a conical shape allows scattering from lower in the canopy. The resultant retrieved heights will therefore be higher for an elliptical shaped crown (figure 7.34). Figure 7.35 shows the difference in modelled retrieved height for

cone-shaped (top) and ellipse-shaped (bottom) crowns in a high density stand. Height retrieval over the ellipse-shaped crowns corresponds very well to the actual heights and gives very little underestimation. Height retrieval over the cone-shaped crowns does not provide quite so good a correspondence to the true height. Compare this result to modelled results in figure 7.36, where the two crown shapes are depicted at low number density. Again, low underestimation is achieved with the ellipse-shaped crowns, whereas poorer estimation is achieved over the conical crowns. Further modelling results (figure 7.37) show that overall, retrieved heights over ellipse-shaped crowns provide least underestimation, and as expected, the amount of underestimation decreases as number density increases. This has implications in UK forestry, as the majority of plantation forests are coniferous, which have a conical-shaped crown (FC, 2004b).

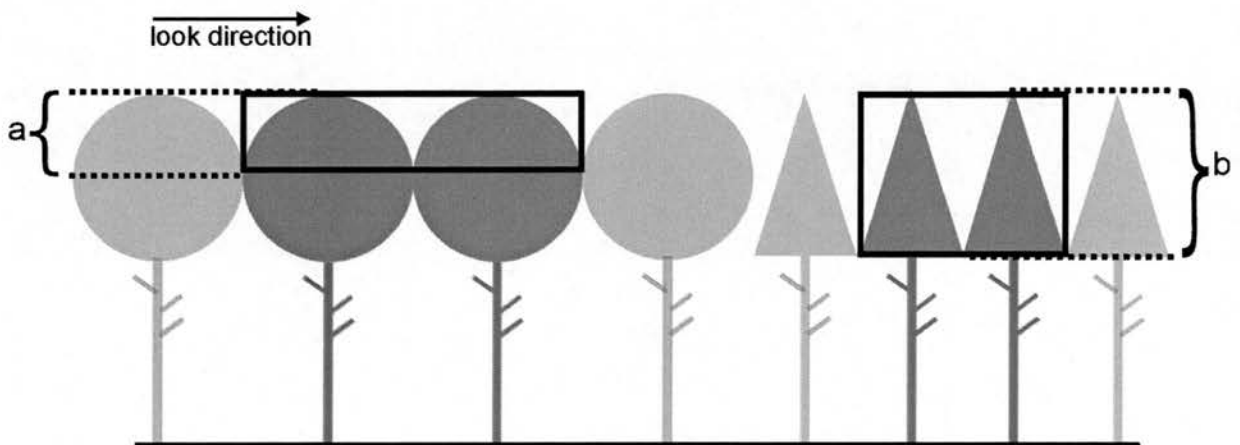


Figure 7.34 Schematic of areas of canopy scattering contributing to retrieved height within a stand (away from edges) over elliptical (left) and conical (right) shaped crowns. Note that average retrieved height of 'a' is higher than average of 'b'.

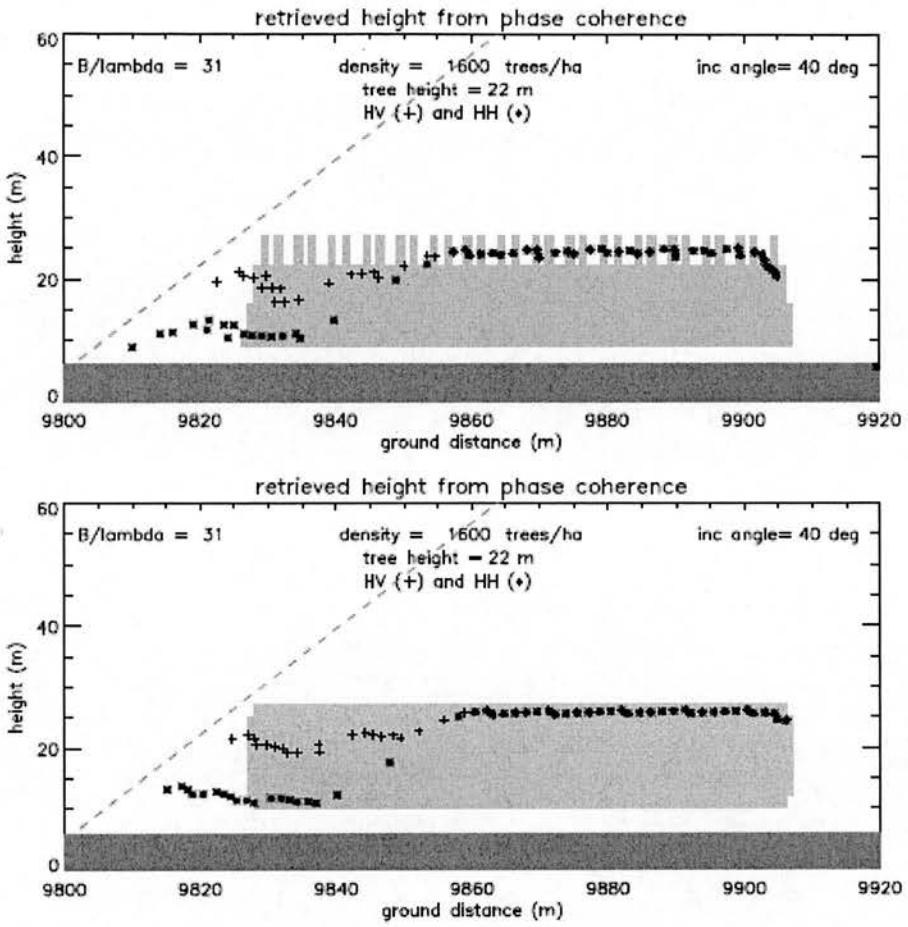


Figure 7.35 Modelled profile of the retrieved heights at high-density plantation with cone-shaped (top) and ellipse-shaped (bottom) crowns. (Izzawati *et al.*, accepted)

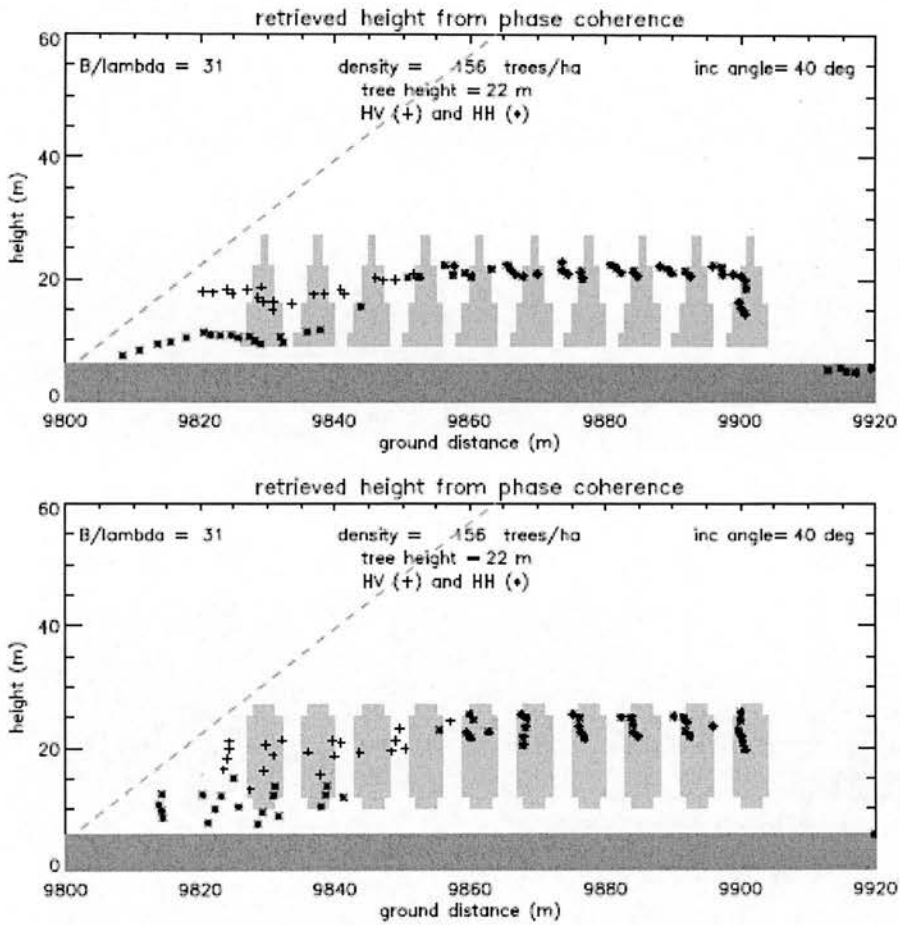


Figure 7.36 Modelled profile of the retrieved heights at low-density plantation with cone-shaped (top) and ellipse-shaped (bottom) crowns. (Izzawati *et al.*, accepted)

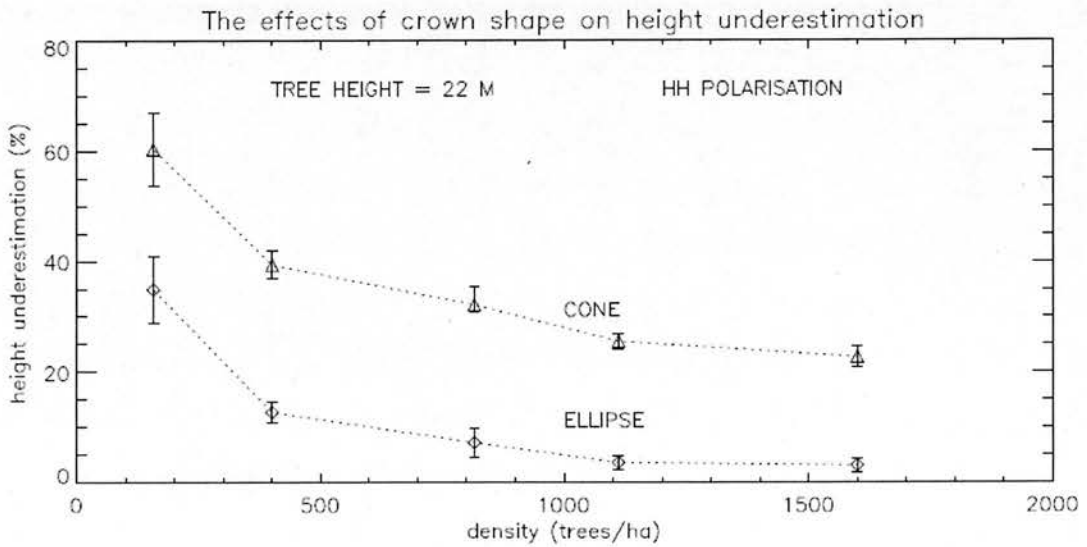


Figure 7.37 Height underestimations due to increasing plantation density for cone and ellipse shaped crowns. (Izzawati *et al.*, accepted)

7.10 Effect of crown density

Crown density has a similar effect to stem number density, whereby, the denser the crown, the higher the retrieved height (figure 7.38). Crown density in this study refers to the density of individual tree crowns, and not the overall crown density of multiple trees, whereas the latter is inferred by stem number density. At X-band, a high density crown will not permit as much signal penetration as a low density crown. The vertical location of the scattering phase centre will therefore be determined by the dominating canopy scattering from the upper part of a dense crown, whereas as the crown becomes less dense, ground scattering and scattering from lower in the crown will contribute to a lower SPC and subsequent lower retrieved height.

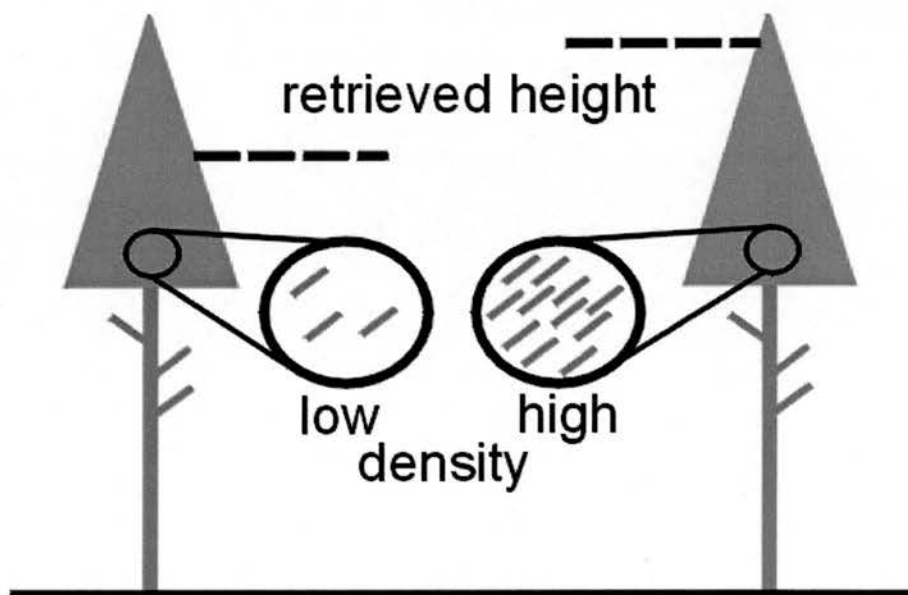


Figure 7.38 Schematic of effect of canopy density on retrieved height.

The difference in crown density can be attributed to different tree species characteristics. For example in coniferous species, a Sitka spruce canopy is denser than a Scots pine canopy – this has not been directly measured in this study, but has

been observed during field work. The difference in canopy densities is expected to result in a lower underestimation in height retrieval from Sitka spruce than from Scots pine (See section 5.7). It is also worth noting the difference in growth patterns in different species. As Sitka spruce grows, the canopy shape doesn't alter significantly, it expands to fill any gaps whilst maintaining a dense internal structure, therefore the height underestimation decreases as a stand grows taller (figure 7.39). This is an effect of tree height to underestimation ratio. Scots pine, however, has a different growth pattern, whereby young trees are conical in shape, and older trees (taller) assume an 'inverted cone' or 'V' shape canopy, which is also much more open in structure and density (figure 7.40). The open nature of the crown results in an increase in height underestimation as the stand grows taller (figure 7.39). Refer also to section 5.7 for height retrieval comparison between Sitka spruce and Scots pine.

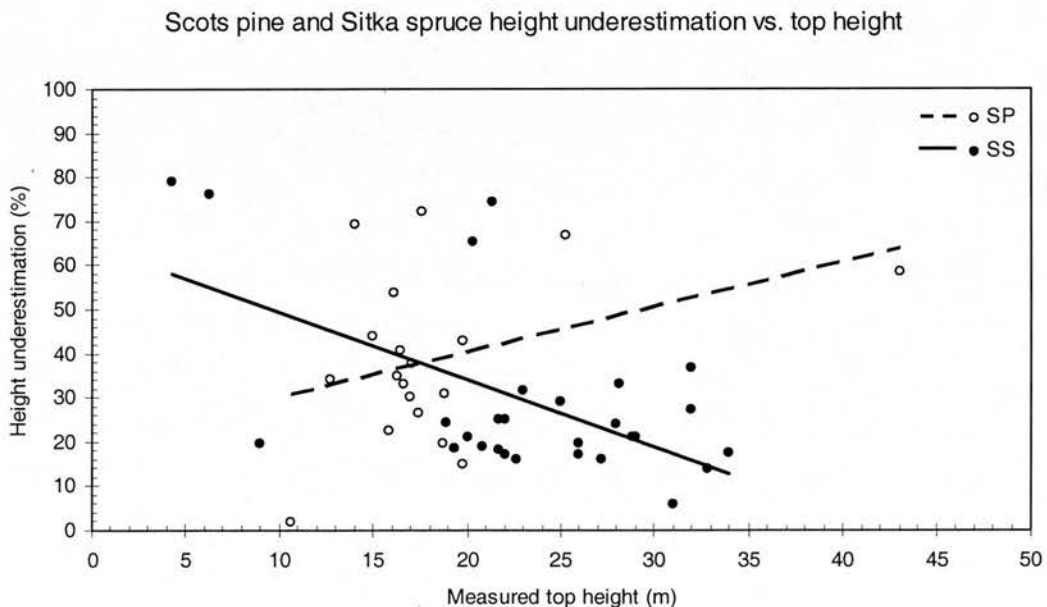


Figure 7.39 Height underestimation as top height increases for Sitka spruce (SS) and Scots pine (SP). Linear regression lines give an indication of height underestimation.

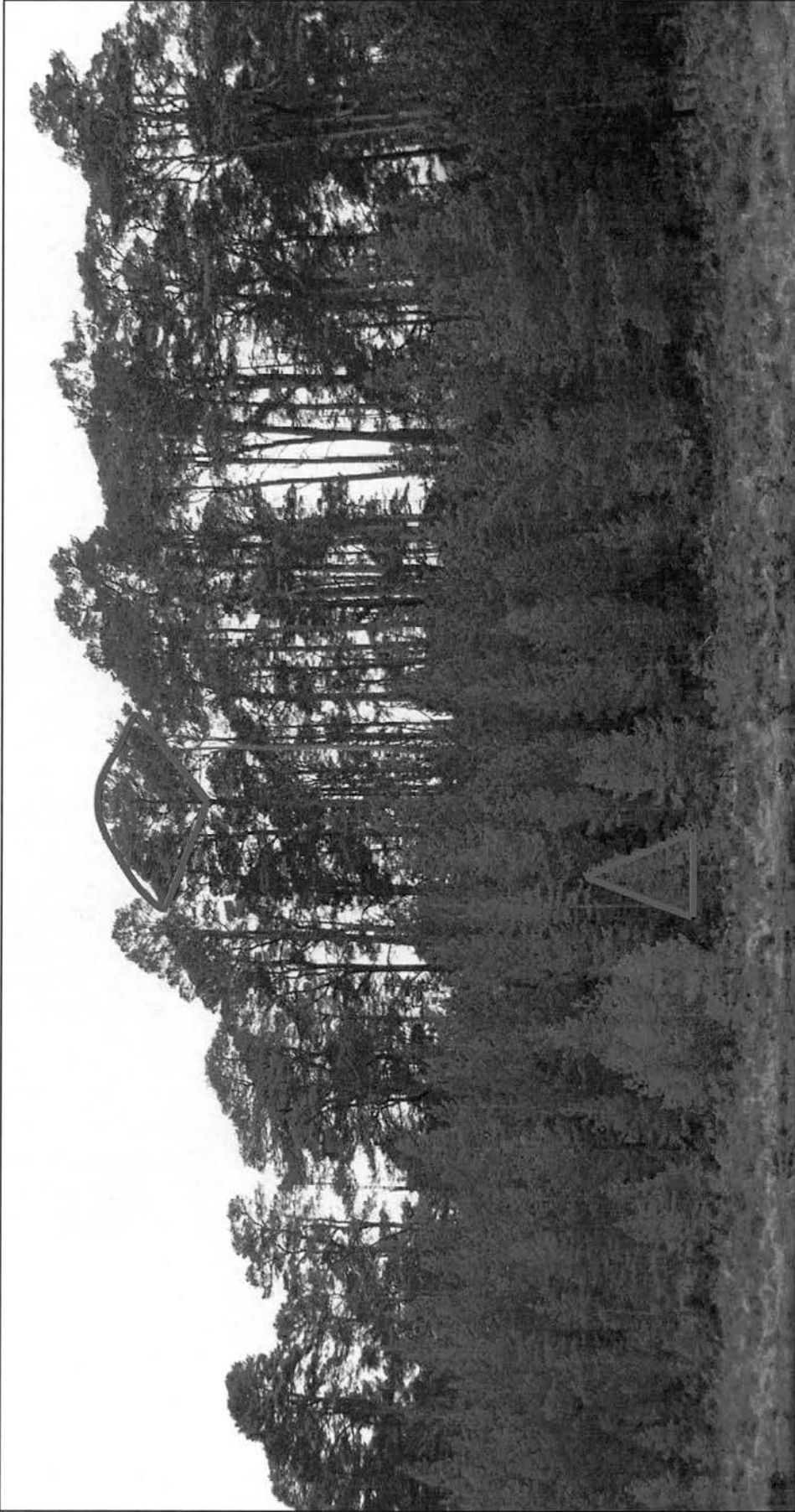


Figure 7.40 Crown shape of young (foreground) and mature (background) Scots pine.

Note also the more open structure of the mature crowns.

7.11 Discussion and conclusion

This chapter has discussed a range of system and target parameters which have an influence on height retrieval using X-band SAR. Two factors were examined, that of the extent of the area of edge effect and the effect on height underestimation in areas away from edge effects. These effects have implications for height retrieval in both homogenous and heterogeneous environments, and as such have direct applicability to the results discussed in chapters 5 and 6. It has been shown that modelled results help the interpretation of height retrieval results, although there are instances when results between the two differ. The negative effect of height estimation in areas of edge effect is a major cause of height underestimation. Small areas of edge effect within a stand caused by emergent trees or canopy gaps will nearly always be present, and care should be taken to avoid these as much as possible. Underestimation due to edge effect at major discontinuities (stands edge, ride etc) can be minimised by performing height retrieval away from areas affected by edge effect. The extent of the area of edge effect can be summarised and estimated by (Woodhouse *et al.*, in press):

$$y = \frac{h}{\tan(\theta \pm \alpha)} \quad (7.1)$$

Where y is the extent of area affected in metres, h is tree height in metres, θ is radar viewing angle and α is the slope angle.

Table 7.1 gives a summary of the edge effect modelled results for each of the parameters, and table 7.2 gives a summary of the height underestimation for modelled and retrieved data.

Table 7.1 Effect of parameters on modelled edge effect results.

Parameter	Area of edge effect
Emergent trees	Increases locally
Number density increasing	No apparent change
Tree height increasing	Increases
Crown shape	No apparent change
Crown density	-
Slope increasing upward	Increases
Slope increasing downward	Decreases
Incidence angle increasing	Decreases

Table 7.2 Effect of parameters on height underestimation.

Parameter	Effect on height underestimation	
	Modelled	Retrieved
Emergent trees	Worse	-
Number density increases	Better	Worse*
Tree height	Better	Better
Crown shape	Ellipses better than cones	-
Crown density increases	-	Better
Slope increasing upward	Worse	Worse
Slope increasing downward	Worse (lesser extent)	Worse (lesser extent)
Incidence angle	Better	No apparent change*

* The difference in height between retrieved and measured decreases. Note: These qualitative results are for indication only, and are applicable to findings in this study only.

There a number of implications of the discussed results, for both homogeneous plantation forestry, and heterogeneous forest environments (e.g. continuous cover forestry, broadleaf forests/stands and in woody savanna regions). Plantation forests

are currently important for timber production in many countries, including the UK. As such the use of SAR for mapping large areas of plantation is increasingly appealing (Smith, 2004). Many plantations are planted on sloped land, and this is one area which requires further attention, as the geometry of SAR results in an increase in underestimation as slope increases (section 7.6). Further, most plantation species are conifer, and have a cone shaped crown. This has a negative effect on height retrieval as cone shaped crowns produce poorer results than ellipse shaped crowns (section 7.9).

Broadleaf species have a more ellipse shaped crown and so will produce lesser height underestimation, but at the same time their crown structure is generally more open, resulting in a greater height underestimation (section 7.10). Likewise, the nature of a broadleaf stand will result in more variation in tree height, leading to an increase in emergent trees and shadowing between trees, resulting in height estimation error (section 7.4). This has implications for the use of radar for height estimation in continuous cover forestry (CCF) stands to varying degrees as the conversion from homogenous mono-culture plantation to mixed species heterogeneous CCF stands occurs. The diverse mixture of species will also add a further dimension of complexity (beyond defining canopy height). A number of different crown shapes and densities, as well as a mixture of tree heights and number densities will combine to give uncertainty to height estimation.

Heterogeneous areas such as semi-natural pine forests and woody savannas are characterised by open structured, low density pines (chapter 3). These areas will

have more extreme height underestimation errors. Firstly, the extremely low stem number density will result in very poor height retrievals due to the location of the scattering phase centre being dominated by ground scattering. This is enhanced by the open structure and low crown density of the pine, in both young and mature trees, furthering penetration into the lower parts of the canopy and to the ground. As the trees in these heterogeneous areas are not organised into discrete stands, the averaging process for height retrieval in plantation stands is not applicable. As such, individual tree coordinates are assessed for height and due to layover (section 7.3), the retrieved height for a specific tree coordinate may not actually pertain to that coordinate in the interferometric SAR data.

In terms of differences between the modelled height results and the retrieved height results, this is primarily explained by the complexity of the actual stands measured. The advantage of the PRIS model is the ability to alter one parameter at a time and assess the effect on retrieved height. Actual tree stands are more complex, containing a number of different variables, which can differ from one stand to the next. Therefore, the retrieved height is the result of a complex interaction of multiple parameter variations, which makes it difficult to determine exactly which one parameter is causing the underestimation - suffice to say, it is a combination of all. Therefore a difference between the modelled results and the retrieved results is to be expected. The model allows individual parameters to be isolated and tested for impact on the retrieved height, and to develop a better understanding of the SAR signal interaction with the vegetation target.

Two final contributions to height underestimation shall be briefly mentioned. Due to the nature of microwave energy, there will always be some penetration of a SAR signal into a vegetation canopy, even at short wavelengths such as X-band. There will always be penetration and therefore underestimation. The amount of penetration is determined by a number of factors including wavelength and the various parameters discussed in this chapter. Other remote sensing techniques, such as Lidar, also experience penetration, and will also underestimate tree height. A final note is that the accuracy of the height retrieval is not only determined by the interferometric digital surface model, but also by the underlying digital terrain model. Therefore, even with an optimum DSM, the height retrieval is limited by the accuracy of the ground surface model.

8 Thesis summary and conclusions

“The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them”.

Sir William Henry Bragg (Nobel Prize Winner, 1862 - 1942)

8.1 Introduction

This thesis has examined the use of synthetic aperture radar for forest height inventory, with a focus on airborne short wavelength, X- and C-band, SAR interferometry for tree and stand height estimation. The thesis aims of (i) InSAR DEM validation for tree height retrieval; (ii) tree height estimation over homogenous and heterogeneous forests; and (iii) analysis of potential reasons for height underestimation, have been achieved. Analysis focused on four study sites in the UK and one in Belize, comprising extensive fieldwork, DEM analysis, implementation of tree height retrieval algorithms, and assessment of height underestimation errors in conjunction with modelled results. This study has assessed the elevations of 29,627 points produced from Intermap products compared to elevations in the Ordnance Survey Profile DEM (Chapter 4). A total of 64 forest stands (consisting of 7525 individual retrieved heights) were measured and assessed for top height retrieval using combinations of Intermap X-band InSAR DSM minus the Intermap DTM or Ordnance Survey Profile DEM over four study sites in the UK (Chapter 5). The Intermap X-band DSM was used in combination with the Ordnance Survey DEM to retrieve heights of 395 individual trees in a homogeneous pine stand in Glen Affric,

and X- and C-band DSM's were used in combination with a ground surveyed DEM to retrieve heights of 563 trees along a 1km transect of homogeneous woody pine savanna in Belize (Chapter 6). Reasons for height underestimation were examined in conjunction with modelled results (Chapter 7) and discussed in the context of height retrieval in homogeneous and heterogeneous forest environments.

8.2 DEM comparison and validation

A comparison between the Intermap DTM and Ordnance Survey DEM (OSDEM) was undertaken in order to have confidence in the accuracy of these two data sets for use as a ground model for subtraction from the DSM to retrieve tree height. Visual assessment of the difference between the DTM and OSDEM confirmed that there were differences between the two ground data sets and that areas of significant difference coincided with known areas of vegetation – namely forest plantation. On further investigation over various ground types, it was concluded that:

- Over non-vegetated ground that the average difference between the DTM and OSDEM was 1.38m RMSE with a 1.05m Standard Deviation.
- The difference varied with land cover type, and ranged from 1.25m RMSE (1.05m SD) over soil to 1.71m RMSE (1.63 SD) over Moorland.
- Over forested ground the average difference was 13.51m RMSE (2.21m SD).

Over open ground the two ground surface models were found to be in good agreement, and within stated accuracies for both products. This gave confidence in the reliability of both products. However, on forested ground the significant

differences led to further analysis which found that the DTM gave consistently higher elevations when compared to the OSDEM, suggesting a vegetation bias in the ground elevation product. This vegetation bias was assumed to be due to the interpolation procedure used to derive the DTM assigning the canopy surface of a homogeneous plantation stand the same elevation as open ground around it, and interpolating between the two extremes. The difference was in the order of the height of the stand. Due to bias in the area of interest (forest), the DTM is not a true representation of the ground surface under forested ground and so is unsuitable for the application of height retrieval. The OSDEM has been validated for use by way of the DEM comparison, and found to be a suitable representation of the ground surface under a forested landscape, although absolute accuracy cannot be confirmed.

8.3 Tree height retrieval

Two tree height retrieval algorithms were implemented, one to derive stand top height in homogeneous plantations, and a second to retrieve single tree total height estimates in heterogeneous forest environments. Qualitative assessment of the DSM-DTM procedure gave results in-line with expectations; the height difference was greatest at stand edges, but reduced to no difference at the centre of the stand, as explained by the DTM interpolation limitation. This confirmed that the DSM-DTM was not appropriate for tree height retrieval. The DSM-OSDEM procedure produced more promising results, with the height differences being representative of forest stand locations, and being more consistent within stands, i.e. no reduction of height as one moves away from the stand edge towards the centre. Quantitative analysis concluded that:

- The DSM-DTM procedure produced height underestimation errors of 89.46% (equivalent to a mean error of 22.43m) over homogeneous plantation.
- The DSM-OSDEM procedure produced height underestimation errors of 33.48% (equivalent to a mean error of 6.99m) over homogeneous plantation.
- The DSM-OSDEM procedure when assessed with single species gave height underestimations of 18-24% for Sitka spruce and 40% for Scots pine.
- Correcting retrieved height based on regression with ground reference data was shown to improve height retrieval accuracy in Kielder from 41.77% (7.12m mean difference) to 27.22% (0.09m mean difference). It should be noted that the small mean difference is due to over compensation for some stands, and therefore negative height differences, which lower the mean difference.
- For trees greater than 18m measured height in the Kielder study site, the accuracy was increased to 12.27% (0.92m mean difference).
- Applying the generic correction, derived from regression of all retrieved data, to retrieved heights from all 4 study sites increased overall accuracy from 33.48% (6.99m) to 16.77% (3.12m).
- For trees greater than 18m in height across all 4 study sites, the accuracy is further increased to 12.19% (3.28m).

Tree height retrieval utilising the X-band DSM-OSDEM were also performed for heterogeneous forest environments in the UK, and X- and C-band DSM-DEM in Belize. Qualitative results again show that a height difference is indicative of

vegetation, and that retrieved heights were representative of measured heights.

Quantitative assessment concluded that:

- In Glen Affric, height retrieval using the X-band DSM-OSDEM procedure for individual trees produced retrieved heights with an average underestimation of 94.87% (6.08m average difference).
- In Belize, height retrieval using the X-band DSM-DEM procedure for individual trees produced retrieved heights with an average underestimation of 74.71% (6.85m average difference).
- In Belize, height retrieval using the C-band DSM-DEM procedure for individual trees produced retrieved heights with an average underestimation of 55.97% (4.79m average difference).

These results are not unexpected and are consistent with height retrieval errors of up to 40% over plantation forests; it was unexpected that the C-band performed better than the X-band. The more open crown structure of individual trees, and the combined canopy being more open as well, allows increased penetration of the radar signal into the lower parts of the canopy and the ground, resulting in lower retrieved heights. Further, due to layover effects due to SAR geometry, a measured height related to a specific ground coordinate may not correspond to the height in a SAR image of the same coordinate. Increased occurrences of edge effects through the heterogeneous environment contribute to increased errors in height retrieval for a specific coordinate when compared to ground reference data. It was interesting to discover that C-band appears to retrieve a more accurate height, even given the

longer wavelength (more penetration). This was primarily attributed to the fact that both X- and C-band signals are reaching the ground, that the surface appears rougher in X-band and hence returns a greater backscatter, thus reducing the retrieved height of the scattering phase centre.

8.4 Reasons for height underestimation

Reasons for height underestimation were investigated, with results from height retrieval over measured forests coupled with modelled results to formulate explanations for height retrieval errors. The Polarimetric Radar Interferometry Simulator (PRIS) developed at The University of Edinburgh was used to investigate the effect on height retrieval of a number of forest and sensor parameters, and these results were compared to height retrieval results. Two factors were investigated: firstly, the extent of the area affected by edge effects as parameters were varied; and secondly, parameters affecting height retrieval in areas away from edge effects. Conclusions of this work are that:

- The extent of the area affected by edge effect increases as tree height increases, or as the angle of an upward slope increases.
- The extent of the area affected by edge effect decreases as the angle of a down slope increases, or the sensor incidence angle increases.
- The above can be estimated by implementing equation 7.1: $y = \frac{h}{\tan(\theta \pm \alpha)}$
- Height underestimation increases as the angle of an upward or downward slope increases or as a stand becomes more heterogeneous.

- Cone-shaped crowns (e.g. conifer) result in greater underestimation when compared to ellipse-shaped crowns (e.g. broadleaf).

Differences between modelled and retrieved heights were observed, and these were explained in chapter 7. Modelled results were produced by varying one variable at a time; this is not the case in a complex forest stand, and as such retrieved height is likely to be affected by a number of parameters simultaneously.

8.5 Implications for InSAR forest height retrieval

This study has highlighted a number of key findings for the use of airborne short wavelength synthetic aperture radar for forest height inventory. Commercially available X-band InSAR products are able to retrieve top height in homogeneous plantation forests with underestimations of 16.8% (e.g. 3.4m for a 20m tree) when trees of all sizes are considered. Underestimations reduce to 13.37% when considering trees over 10m (2.7m for a 20m tree) and to 12.6% considering trees over 20m (2.5m for a 20m tree). These accuracies are approaching the accuracies obtainable from traditional field survey, which are expected to be around 10% (Barron, 2001; Meir, 2005), and are quantifiable over large areas, as opposed to accuracies of ground based measurements varying per surveyor. Further, height retrieval is performed for an entire stand, as opposed to dispersed sampling strategies employed during traditional inventory. These accuracies are obtainable with simple correction to the retrieved height based on linear regression with a sample of measured ground reference data. The factors influencing height underestimation (as discussed in chapter 7) are not accounted for. With further research on the combined

effect of these factors, and accounting for these within height retrieval algorithms, more accurate height estimations can be expected. Further, the accuracies obtainable are relatively consistent throughout a range of study sites, and as such the techniques presented appear appropriate for height retrieval of homogeneous forest plantations.

When compared to other commercially available remote sensing systems, the underestimations presented in this study over plantation forest with airborne X-band InSAR are comparable or better than many (Hyypä *et al.*, 2000). For example, SRTM-X has been demonstrated to have errors of up to 50% (Kellndorfer *et al.*, 2004) and 33.1% (Brown and Sarabandi, 2003). LiDAR has been shown to have tree height underestimations in the region of 7% (Suárez and Wallington, 2005), 13% (Lefsky *et al.*, 2002), 15% (Næsset and Bjerknes, 2001), 6% (Næsset, 2002), 7.6-17.6% (Næsset and Økland, 2002) and 22% (Zimble *et al.*, 2003). Traditional aerial photogrammetry has demonstrated accuracies of around 10% (Paine and Kiser, 2003). Accuracies with LiDAR and aerial photogrammetry may have the potential to retrieve more accurate heights, but the smaller areas observed add to the cost, and reduce the repeatability, of the data collection.

Reduced accuracies in heterogeneous forest environments are largely attributed to layover effects, and the comparison of heights which are not necessarily related. The techniques described in this study, i.e. pixel correlations, may not be appropriate for height retrieval in areas other than plantation forest. Further research is required to obtain a suitable height representation method. This may involve 'height matching'; whereby profiles of retrieved heights and ground measured heights are 'matched'. It

is expected that the correct tree height pattern is present in the SAR data, but is shifted from its true geographic location due to layover. By shifting the retrieved heights horizontally, it may be possible to match retrieved heights to measured heights more accurately, thus improving height comparison.

8.6 Operational status and future uptake for forest height inventory

The use of short wavelength InSAR for height retrieval over plantation forests is nearing operational status. The availability of commercially available datasets (e.g. Intermap and SRTM) over the past couple of years has provided research opportunity to demonstrate the capabilities of the techniques. This research is now nearing a point where the techniques can be offered as operational products, either as an off-the shelf product (e.g. vegetation height maps) or as a number of elevation datasets for integration of added value products into GIS management and decision systems (figure 8.1) such as the Forester extension used by the UK Forestry Commission. The ability to retrieve height also lends itself to other applications, such as sub-stand analysis for uses such as damage assessment, growth, and planting compliance (figure 8.2) and forest/non-forest classifications (figure 8.3) for improvement of national woodland inventories (e.g. Suárez *et al.*, 2005). Issues of repeatability present a possible limitation for operational use, however this depends on usage. For example, Intermap intend to re-fly the UK at a rate of 10% a year (Shepherd, 2004), this would present a complete coverage every 10 years, a similar timescale to the UK NIWT; satellite systems would offer higher repeatability times.

One current constraint of SAR for forest height inventory is the number of commercially available systems and data providers – these are currently limited. For a technique to be used operationally there is a commercial need not to be reliant on one system, and for there to be a guaranteed future continuity and availability of data (Knox, 2005). The future increase in satellite borne short wavelength SAR systems, from 2006 onwards (e.g. TerraSAR-X), alongside the supplementary use of airborne systems (e.g. Intermap STAR-3i, JPL AIRSAR, CCRS C/X-Band SAR, and Astrium MicroSAR), as well as UAV based systems (e.g. Astriums QUASAR), may provide the data continuity required for operational InSAR in forestry, as well as increased cost effectiveness due to large area coverage. There are issues of temporal decorrelation on satellite platforms, however these effects can be limited by using tandem missions, such as the proposed TanDEM-X for launch in 2008 (Infoterra, 2005).

The techniques described in this study have utilised a ground DEM and a canopy DSM to provide height estimations. This method does not rely only on a continued availability of DSM data, but also of ground DEMs at a high enough resolution and accuracy. As such, the continued use of nationally available DEM datasets is encouraged where available, although as discussed the accuracy of such data may be questionable. A consideration of the use of national datasets is the strict licensing arrangements, which may affect the viability of their cost-effective use; this would need to be assessed at an organisational level. Alternative methods for tree height estimation have been discussed in chapter 2. This study supports the use of two elevation datasets for tree height estimation, as such, with the use of short

wavelength SAR to map the canopy surface; an alternative method for ground elevation data is required. It is suggested, that this could be obtained through the use of long wavelength SAR (P-band or VHF) or LiDAR. These systems are potentially more expensive to operate, especially given satellite platform constraints, and as such are currently limited to airborne systems, which themselves are limited due to licensing of transmissions (in particular long-wavelength SAR). However, the ground surface does not change on a frequent basis, particularly below forest cover, as such it is suggested that the ground elevation could be mapped on a significantly less frequent basis than the canopy surface, thus maintaining cost effectiveness in the long term. A more accurate ground surface coupled with a canopy surface model will contribute towards more accurate tree height estimation.

SAR has the advantage over optical systems of being able to operate independently of weather or lighting conditions, as well as capturing a wider area than LiDAR systems. Optical systems will be operationally hindered by cloud, where many scenes may be required to obtain sufficient coverage, thus adding to time and cost of inventory. These factors, coupled with the commercial realisation of SAR, allow SAR data to be cost effective, as well as having the ability to acquire direct height measurements, as opposed to correlations achieved with optical systems.

This study has assessed commercial InSAR data for operational tree height retrieval. There is a research need to further validate the procedures suggested and performed in this study before operational status can be considered or implemented. Correlations of around 60% between retrieved height and ground measured height in

homogenous plantations can be partly explained by variation in stem number densities, slopes and crown structure, but these need to be further quantified. A number of research topics are suggested below to help further understand and correct for underestimation. A SAR data set with higher spatial resolution may allow for number density estimations (e.g. tree counting), and hence provide a way to correct for some of the height underestimation, systems such as Intermap's Star-4i may provide such data. Fusing of optical and SAR data may provide a way to classify species, and hence allow underestimation correction on that basis. A DTM with a higher resolution and accuracy than the OSDEM could also be used, e.g. obtained from Lidar, and reduce potential underestimations this way. As mentioned PolInSAR is an alternative method for tree height retrieval, satellites carrying sensors such as ALOS-PALSAR will provide opportunities to obtain suitable data, however there is a further need to assess height retrieval in a number of forest environments, as well as for direct comparison to InSAR techniques. Similarly, this study has mentioned that InSAR is capable of achieving similar accuracies to Lidar (e.g. Wallington and Suárez, 2005); however these comparisons require expanding to different forest environments and test site conditions.

This thesis has demonstrated that large area forest height retrieval is possible to a level of accuracy approaching that of traditional ground-based forest height inventory. The ability of remote sensing to rapidly, and repeatedly capture countrywide forest height information, with simple integration with GIS forest management systems, would be otherwise unobtainable without lengthy, intensive and ultimately expensive field work. Forest remote sensing has reached the stage of

operationality, what is now required is the transfer of technology, understanding and useful products to the people that need it the most, the foresters. The use of remote sensing in forest management and associated applications enables a timely alternative and complimentary perspective to traditional forest management practices. No one single approach is valid for all situations and requirements, and as such, a data fusion approach is required which benefits through combined input from a range of ground, air, satellite and unmanned systems. There is a requirement for a forest manager to weigh up ratios of requirement, availability, cost, accuracy, area coverage and repeatability when deciding which technique is the most suitable for height estimation for a particular application. As such, remote sensing is another tool in the forester's belt for mapping, measuring, monitoring and assessing the forest resource at a range of scales.

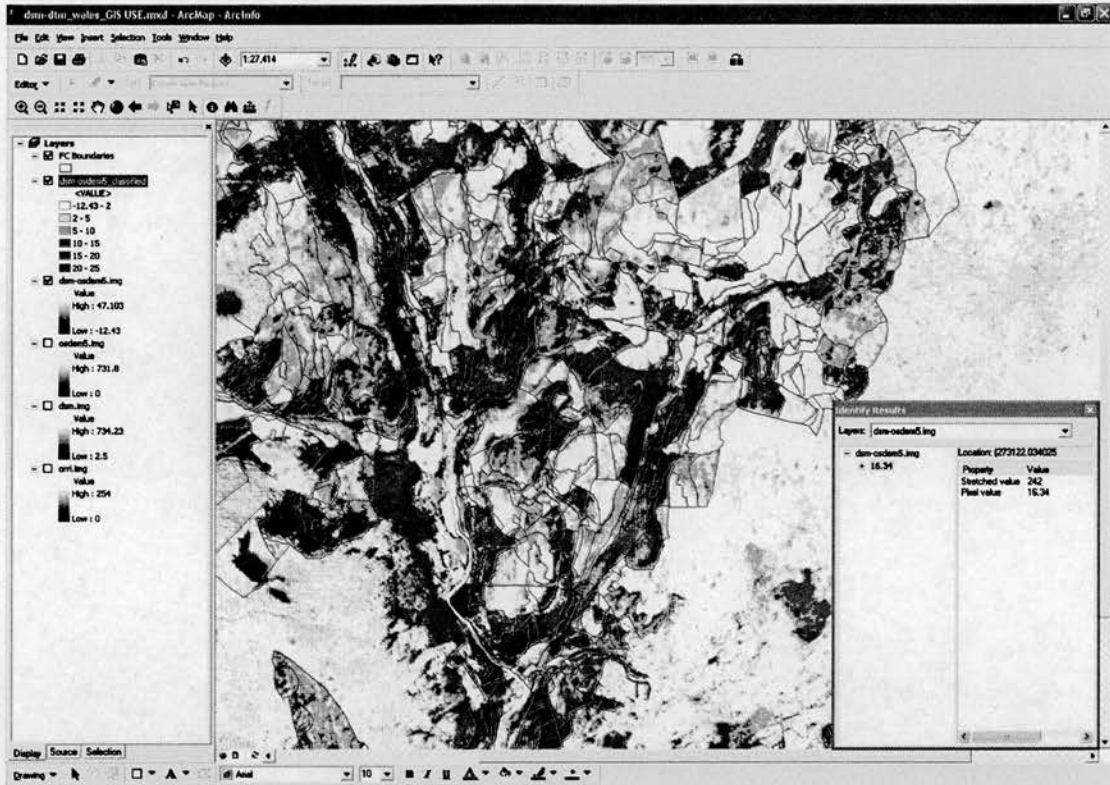


Figure 8.1 Large area tree height estimates incorporated into a GIS management system.

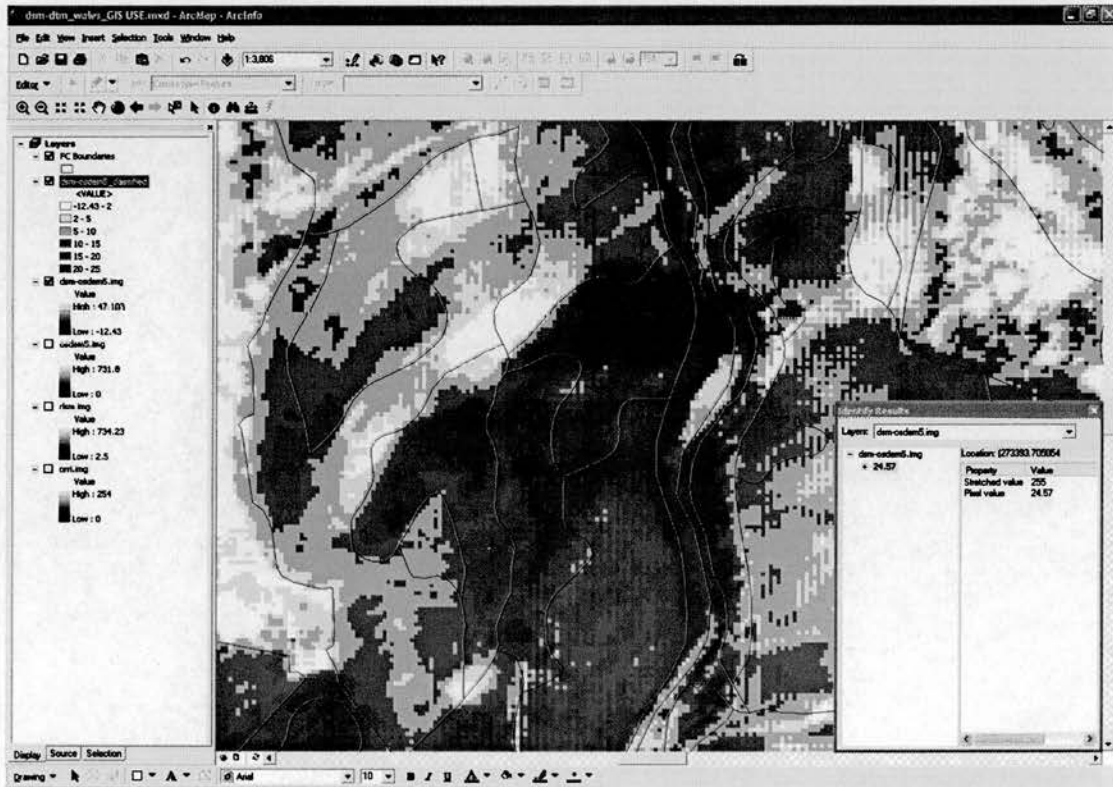


Figure 8.2 Tree height assessment at the sub-stand level.

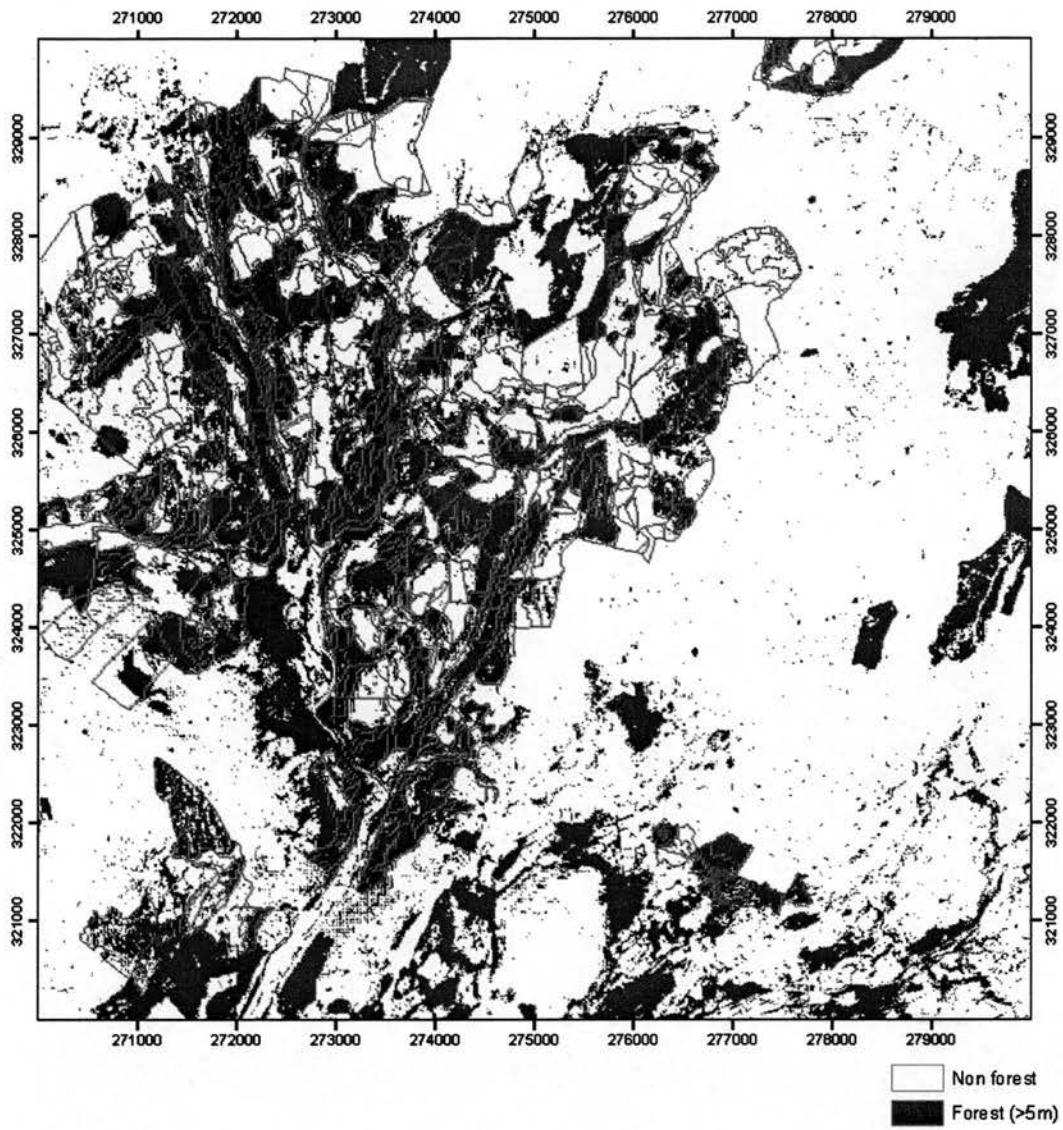


Figure 8.3 Forest / Non-forest classification based on height, Coed y Brenin.

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10 Appendix A – Tree height definitions

10.1 Introduction to tree height definitions

The term ‘tree height’ is often referred to in many publications, and as such has become the standard way of referring to the height of a tree. However, the actual height of a tree can be defined in many ways. In the following sections the various height measurements used to define the height of a single tree or stand are defined. It should be noted that these terms are of primary use in the UK, although similar terms are more widely used. Some of the terms used correspond to the same measurement, and these have been pointed out where appropriate.

Many of the terms, in particular for stands are used primarily for temperate even-aged plantation stands, and may not bare any resemblance if used in mixed-age/mixed-species stands. Definitions of tree height will also depend on whether it is referencing the land-use, stand or sub-stand/tree scales.

There is a need for consistent use of terminology when discussing ‘tree height’; this is not only pertinent to forestry discussions, but also when comparing heights retrieved from remote sensing. A miss representation of a sensor’s ability to accurately estimate tree height can occur if compared to ground data where a different tree height is being referenced.

10.2 Single tree height definitions

When measuring a single tree, there are a number of definitions for height (Table 10.1, Figure 10.1):

Table 10.1 Single tree height descriptions

Description	Definition
Breast height	As in Diameter at Breast Height (1.30m).
Total height	Height from base to uppermost tip.
Timber height	Height from base to 7cm diameter (over bark). In broadleaf trees, upper height is where first fork occurs.
Bole height	Height from base to crown point. Crown point is the first living branch that forms part of crown. i.e. the clear part of the stem (Clear bole height)
Merchantable height	Height from base to last useable portion of the stem. (i.e. to a top diameter, branching, irregularity, defect).
Clear bole height	See Bole height.
Stump height or Felling height	Height between ground and point on stem where tree is cut.
Crown height / length	Height from the tip to the crown point.

Nb. Crown point is the point on the stem where the first crown-forming branch occurs.

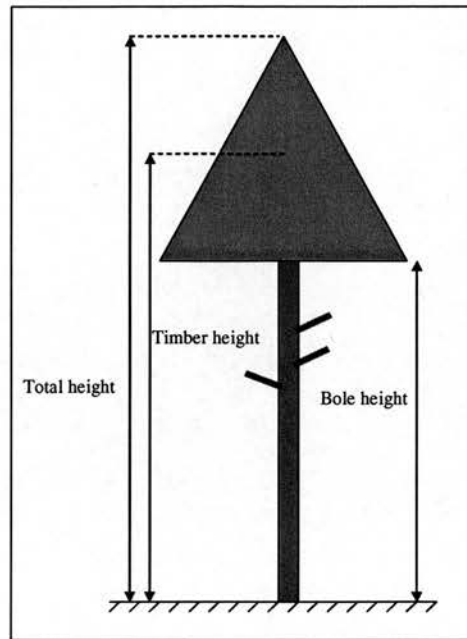


Figure 10.1 Single tree height descriptions

Note: vertical height is usually measured. A correction for a leaning bole can be applied, but this is not usually the case. So an underestimate of height is usually obtained. Care should also be taken when measuring trees on slopes, as over or under estimates can occur. Individual interpretation of measurement points is also subjective.

10.3 Stand level tree height definitions

When measuring stands of trees, there are a number of descriptions for height (Table 10.2):

Table 10.2 Tree height descriptions for a stand (generally 100 trees per ha used)

Description	Definition	
Mean height	Arithmetic average of tree height in stand in a stand. Can use all trees or sample of trees.	$h = \sum^n h_i/n$
Top height / H_{100}	Mean height of the trees with the largest dbh. Or Mean height of the tallest trees. DBH method usually used.	
Weighted Average or Lorey's Mean height	Average height weighted by basal area.	$h_L = \frac{\sum^n g_i h_i}{\sum^n g_i}$
Mean timber height	Arithmetic average of timber height in stand. Can use all trees or sample of trees.	
Dominant height	Mean height of the dominant trees (tallest trees).	
Dominant and Codominant	Mean height of the tallest and second tallest trees.	
Form height	Product of the mean height and the form factor. Top height is used to estimate form height (from tables). Form height multiplied by basal area to give a volume.	

Where:

h = height

h_L = Lorey's height

g = basal area

n = number of trees used in sample

It is usual to measure crops by way of sample plots, as measuring an entire stand or forest is not necessarily feasible. Plot sizes typically range in size from 0.01-0.10 ha. And can be circular or square. 100 trees per hectare is the usual sample density.

Example of differences in tree height estimates depending on definition used (based on tree measurements made in Glen Affric):

Use 100 trees per ha⁻¹

1 hectare (ha⁻¹) = 10000m² = 100x100m

0.01 ha⁻¹ plot = 100m² = 10x10m

e.g., if require 100 trees per ha⁻¹, then this is 1 tree per 0.01 ha⁻¹ plot.

Example:

Plot = 71 trees

Mean H = 13.87m

Top H (top 25 trees) = 15.41m

Lorey's H = 14.54m

10.4 Remote sensing terms

When assessing height estimation retrieval by remote sensing, ground data is required for verification. At this stage it is essential that both data sets are assessing the same height, as different heights will immediately give poor comparisons. It is therefore imperative that the foresters and remote sensors are both using the same terminology, so as to alleviate miss-understanding and to minimise potential errors. Even if the heights being measured are not the same, knowing which heights are being used for evaluation will improve reliability.

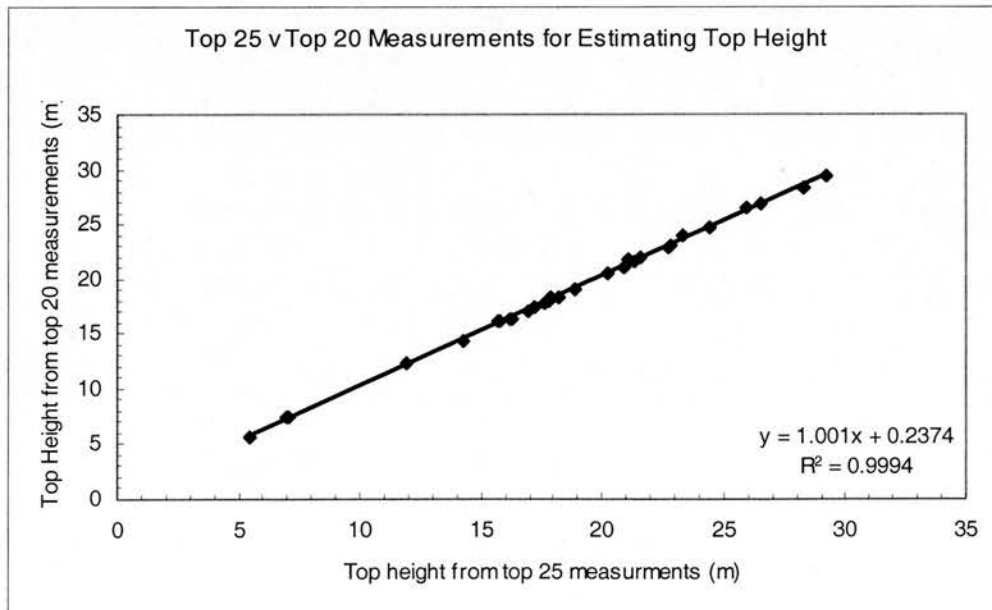
Once the terminology is synonymous, it is necessary to be aware of which height remote sensing is retrieving. In terms of SAR, this can vary depending on scale, resolution and technique. For example, using coherence of a plot to estimate stand

height will retrieve a different height to using PolInSAR to estimate the height of a single tree.

10.5 Tree height definition used in this study

Tree height estimates retrieved from SAR were to be compared to ground data, so it was necessary to ensure these two height estimates were compatible measurements. To stay in line with forestry stand top height measurement procedure, the top 25 SAR retrieved height estimates were used to estimate the estimated top height of the trial stands. This is equivalent to top height (H_{100}) definitions used in forestry.

For completeness, comparison of the top 25 and the top 20 retrieved heights were used to calculate top height to see if this any significant effect on the retrieved height. The figure below shows that there is no difference in using either, and so the top 25 was used so as to mirror forestry methods.



11 Appendix B – Forest Classification and height indicators using L-band SAR

The following is a reproduction of:

Wallington, E.D.; Woodhouse, I.H. and Suárez, J.C. (2004): Forest classification and height indicators using L-band SAR. *In* Remote Sensing in Transition. Goossens, R. (Ed). Proceedings of the 23rd EARSeL Symposium, Ghent, Belgium, 2-5 July 2003. Millpress, Netherlands. pp. 167-172.

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Forest classification and height indicators using L-band SAR

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ABSTRACT: This paper presents an analysis of optimised coherence produced from airborne L-band SAR at 10m and 20m baselines. It is shown that a supervised classification based on coherence appears to produce an improved differentiation between tree heights and densities when compared to a backscatter classification. The relationship between coherence and tree height is also examined; it is found that coherence increases with tree height, an explanation of why this may be is given.

1 INTRODUCTION

The use of remote sensing techniques in operational forestry and vegetation studies has, until recently, been limited to visual interpretation of aerial photographs. This process is time consuming, both for data acquisition and the analysis (requires many man-hours per data set). Advancements in technologies have seen the introduction of digital systems on airborne and satellite platforms. This has allowed extensive research over large areas. Other optical sensors, both airborne and satellite based, have been at the front of recent research initiatives, and have proven promising for estimating several forest parameters. Optical sensors still however suffer from weather restrictions and in particular cloud cover, with many data scenes cloud covered for many days a year, and data sets are characterised by generally having some cloud cover present, or they are limited to a small time-window each year. This issue is particularly pertinent in tropical climates and temperate Europe.

Synthetic Aperture Radar (SAR) is increasingly approaching a cost effective alternative for data capture in operational forestry. SAR, being an active microwave instrument, is independent of light conditions and is minimally attenuated by cloud cover. Additionally, interferometry and polarimetry techniques mean that previously

unobtainable information can be gathered, such as tree height and below canopy terrain. These techniques will be briefly discussed in the following sections.

The current study is assessing the capabilities of L-Band ESAR data to aid forest management, with validation in Glen Affric, an area of mountainous terrain in Northern Scotland that includes both plantation and natural forest. This paper will present results of quantifying the success of different classification methods using a range of SAR data channels to identify the optimal configuration for mapping different forest characteristics. Results will be assessed by comparison with ground truth and forest management data.

The mapping products assessed will be of interest to parties concerned with the management of forests. As such, estimates of forest structure parameters are possible and fall into two classes; qualitative maps provide indication of forested area, forest cover type and species, and quantitative maps potentially giving estimates of tree height, dbh and tree densities. These parameters can then be used as inputs to current models to produce improved estimates of age, timber volume, biomass and change detection (e.g. fires, deforestation and planting, which will assist forest certification).

2 BACKGROUND

2.1 SAR

SAR operates in the microwave part of the electromagnetic spectrum, and as such has wavelengths ranging from cm to metres (Table 1). SAR, being an active microwave instrument, is independent of light conditions and is minimally attenuated by cloud cover, and thus can be operated when other sensors cannot. One further advantage of SAR over other sensors is the ability to penetrate through the canopy. This enables more information about the target area to be gathered compared to optical systems. The size of the wavelength is important when deciding what needs to be measured, as the signal will interact with a target scatterer which is the same size as the wavelength. The amount of signal penetration through a vegetation canopy is therefore dependent on wavelength. As such, C-band receives a return from the upper part of the canopy (commonly referred to as the top of the canopy, although some penetration occurs) as the wavelength is on the same scale as the leaves and smaller branches; whereas P-band receives returns from the ground and larger branches and trunks. This study utilises L-band system data as longer wavelengths allow good penetration through the canopy to the ground.

Table 1 SAR wavelengths used in vegetation studies

Radar Band	Frequency (GHz)	Wavelength Range (cm)	Typical Wavelength (cm)
X	8.0 - 12.5	2.4 - 3.8	3
C	4.8 - 8.0	3.8 - 7.5	5.6
L	1.0 - 2.0	15.0 - 30.0	23.5
P	0.3 - 1.0	30.0 - 100.0	75

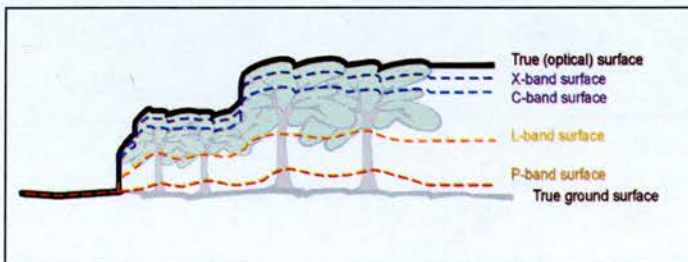


Figure 1 SAR penetration through canopy

2.2 Techniques

There are currently four techniques being used to assess the potential of SAR for forestry applications, these are Backscatter, Interferometry, Polarimetry and Polarimetric SAR Interferometry. These will be briefly outlined below.

2.2.1 Interferometry

Interferometry utilises phase measurements and the differences in phase between two sensor positions (temporal or spatial separation) to make accurate estimates of distance. Knowing the distance to an object from two positions, this coupled with the geometry of the SAR system can be used to estimate the location of a target. The technique is also used to estimate the height of targets (see Madsen and Zebker, 1998).

2.2.2 Polarimetry

Polarimetry uses information on the orientation of the transmitted and received electromagnetic wave, and thus information on the shape of the target can be gathered. Knowing the orientation of the signal, it is possible to differentiate between orientation effects of the target, and therefore differentiate between types of scatterer. For example, between ground and canopy or ground and vegetation (see Cloude and Pottier, 1996).

2.2.3 Polarimetric SAR Interferometry

PolSARIn combines the advantages of Interferometry in estimating location with the differentiating properties associated with polarimetry to differentiate signals returned from the ground and the canopy to give improved height estimations (see Cloude and Papathanassiou, 1998; Stebler *et al.*, 2002).

3 DATA SETS

SAR data for the study was collected by DLR using airborne L-band fully polarimetric dual-baseline interferometry which formed part of the E-SAR SHAC campaign during June 2000. Ground data has been gathered from the corresponding area comprising plantation and semi-natural remnants of Caledonian Scots pine (*Pinus sylvestris*) forest in Glen Affric, Northern Scotland (Figure 2). Glen Affric offers a unique opportunity to assess the capabilities of SAR, as the area is characterised by rapidly undulating terrain, as well as varied vegetation composition (Cloude *et al.*, 2001).

Polarimetric SAR Interferometry (PolSARIn) techniques (Cloude and Papathanassiou, 1998) were used to produce optimised coherence images from the initial data. These comprised three optimised images for both a 10 and 20 metre baseline.

4 APPROACH

The use of backscatter to classify SAR images has been used to map forests with varying degrees of success. This technique does not necessarily use the data to its optimum, and produces little more detail than that of optical sensors. Research has more recently been assessing the capabilities of coherence (correlation between images) to produce more detailed information (Luckman *et al.*, 2000; Gaveau *et al.*, 2003; Fransson *et al.*, 2001; Castel *et al.*, 2000). The parameters which govern coherence (e.g. vegetation height, density, structure) may tell us more about the land cover than other techniques. This study took a three stage approach to assess the optimised coherence from our test site.

A visual interpretation of the optimised coherence images was undertaken. This involved comparing the 10m and 20m images as RGB colour composites of the three optimised images per baseline (Figures 3a and 3b). Coherence ranges from low (black) to high (white).

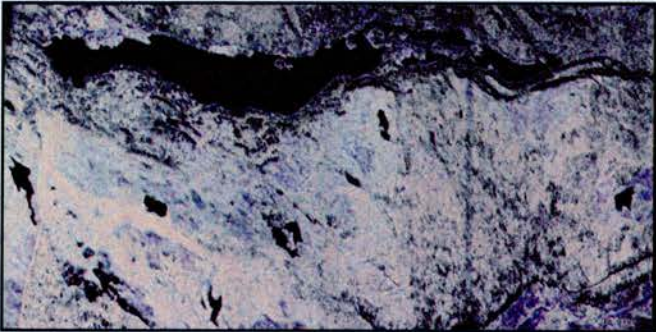


Figure 3a. RGB colour composite of the three optimised coherences for 10m baseline.

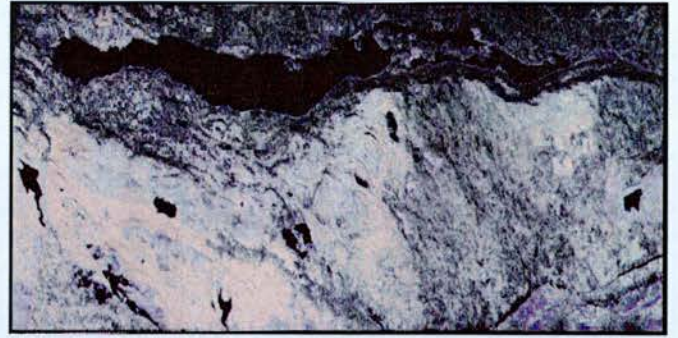


Figure 3b. RGB colour composite of the three optimised coherences for 20m baseline.

When visually analysing the coherence, it can be seen that when increasing the spatial baseline, the sensitivity to vegetation increases. It is possible to attain a qualitative impression of vegetation structure in Glen Affric by comparing the two baselines. The 10m baseline allows discrimination of the most dense or largest vegetation (Figure 3a), with the 20m baseline being additionally sensitive to smaller or less dense vegetation (Figure 3b).

Classification

The next stage was to classify the optimised coherence images, a supervised maximum likelihood classification utilising all six images was undertaken to create a structure map comprising four classes (Figure 4). The resulting classification was then compared to a supervised maximum likelihood classification of the backscatter (Figure 5, Wallington *et al.*, 2002). It should be noted that this image was created from a georectified RGB colour composite of the HH, HV and VV channels.

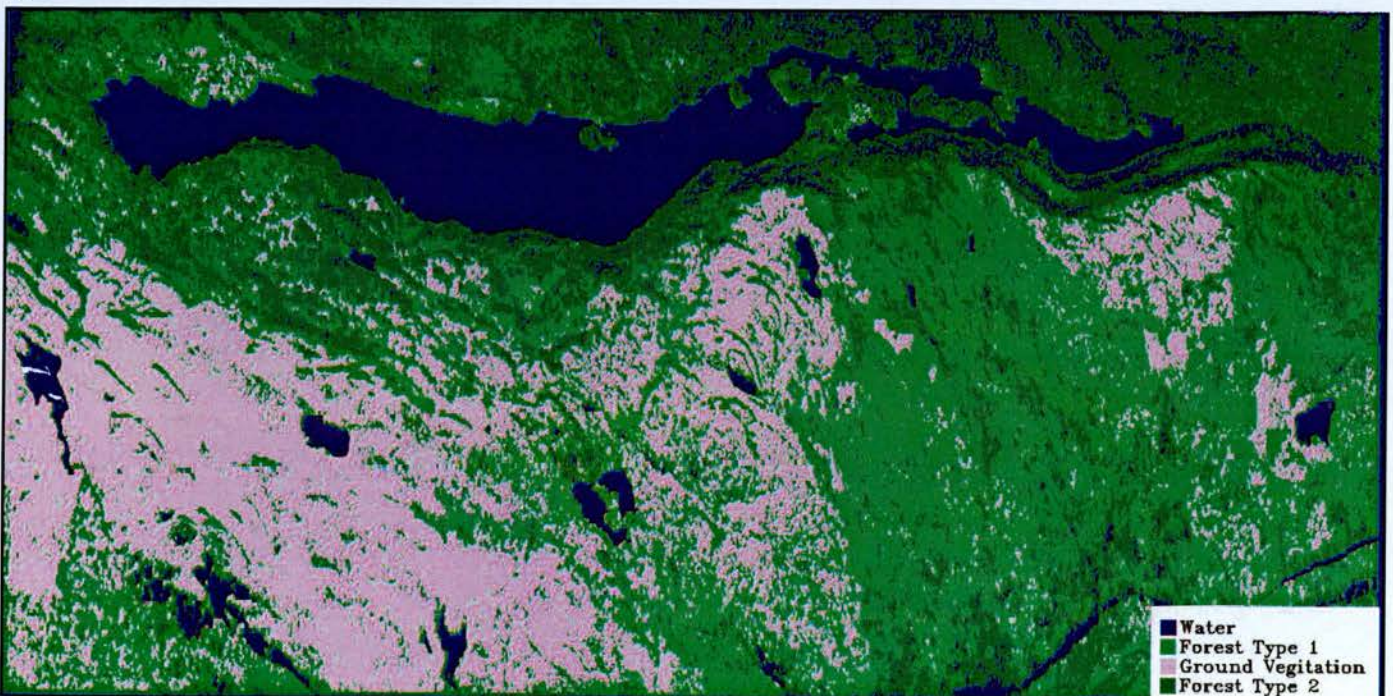


Figure 4 Supervised classification of 6 optimised coherence images

Classification of the six image data set (Figure 4) has proven to give a more detailed view of the vegetation structure than that of the backscatter image (Figure 5). The most noticeable improvement is the differentiation between vegetation density, whereby plantation and semi-natural areas are more apparent. This is also true for differentiation of high and low trees around the test sites.

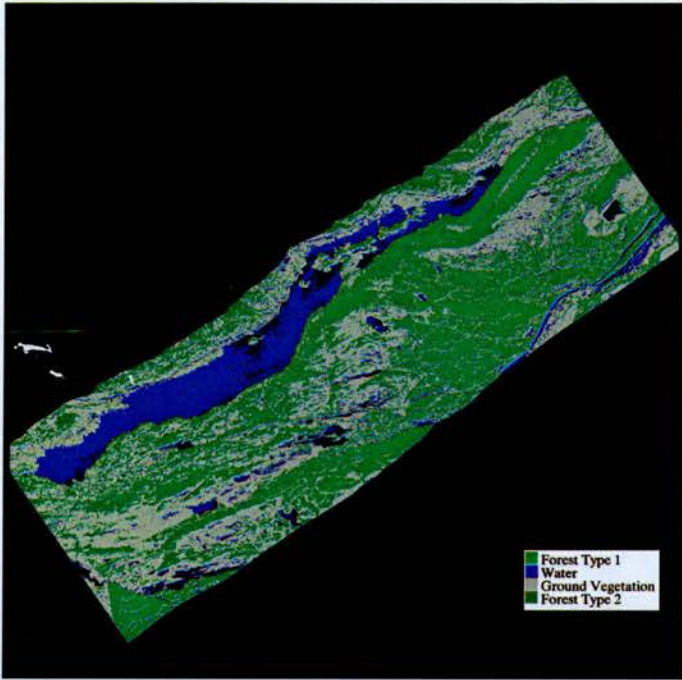


Figure 5 Supervised classification of backscatter (georectified)

Some interesting differences in the classifications are apparent. One of which is the opposite of what may be expected. For example, the triangular block of plantation in the south-west of the images (Figures 4 and 5), appears as a solid block of forest in the backscatter image (Figure 5), but in the coherence image (Figure 4), the block is more broken up. This is not as you would expect, as the coherence is anticipated to be low for dense vegetation, however areas classified as ground vegetation are found. One possible explanation for this is that the trees are so dense, there is little movement between them, and hence show a relatively high coherence, and have thus been classified as ground vegetation.

Height indicators

The final stage was an assessment of the relationship between coherence and average stand height. This was carried out using the optimal

coherence image for each of the 10 and 20m baselines, and compared to ground data. Table 2 shows the values obtained for each plot.

Table 2 Plot data

Plot Number	Average Tree Height (m)	Coherence			
		10m	20m	Difference	Ratio
1	10.76	0.81	0.54	0.26	0.67
2	13.87	0.84	0.72	0.12	0.86
3	13.84	0.87	0.76	0.11	0.87
4	15.50	0.81	0.72	0.08	0.90
5	13.10	0.81	0.71	0.10	0.88
6	13.79	0.80	0.75	0.05	0.94
7	14.25	0.90	0.85	0.05	0.94
8	12.35	0.86	0.74	0.12	0.86
9	16.25	0.66	0.54	0.12	0.81
10	0.50	0.93	0.91	0.02	0.98
11	0.50	0.93	0.92	0.01	0.99
12	0.50	0.94	0.90	0.05	0.95

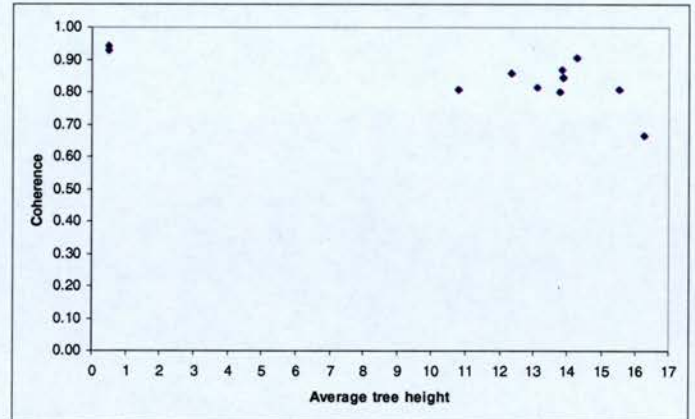


Figure 6 Coherence values for 10m baseline

As expected, for increasing tree height, the coherence drops (Figure 6). For a more detailed indication of the relationship between average tree height and coherence, analysis was carried out in areas of plantation stands only, so as to compare within areas of similar tree structure (plots 1-8).

The coherence values for the 10m and 20m baselines were compared to ground data (Figures 7 and 8). A trend line was applied to each dataset. It was found that with increasing tree height coherence increased, with the 20m baseline increasing at a steeper rate than the 10m. This is somewhat unexpected. This increase is believed to be due to there being an increased contribution to the returned signal from the ground, and less

contribution from the canopy as the trees grow in height, i.e. a returned signal from tall trees is comprised of primarily ground return with a little canopy decorrelation. This explains why at the 10m baseline, it is observed that an increase in tree height gives a slight increase in coherence, and at 20m the increase is larger, as the proportion of ground return increases and canopy return decreases.

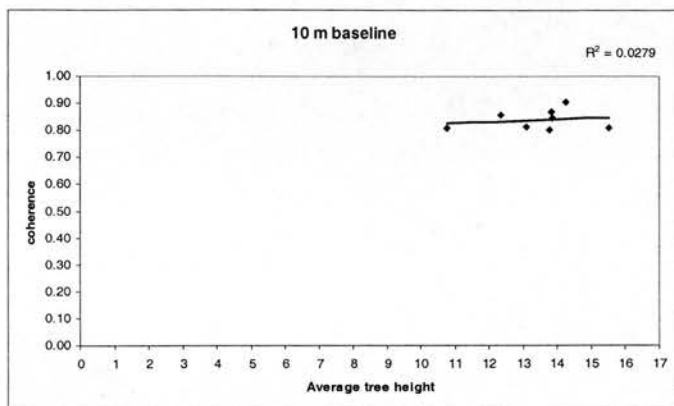


Figure 7 Coherence against height comparison at 10m baseline

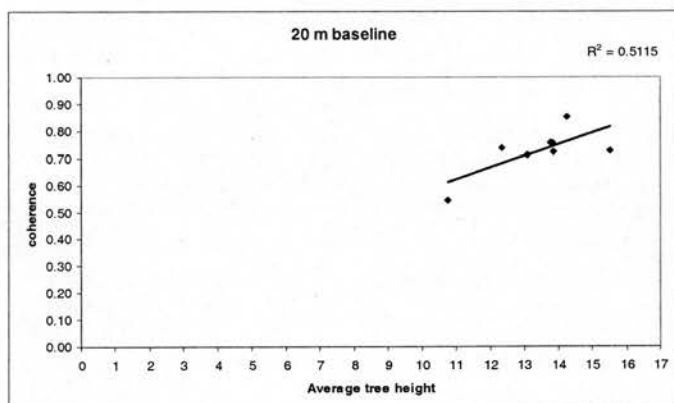


Figure 8 Coherence against height comparison at 20m baseline

When the difference between the coherence values of the 10m and 20m baselines were assessed, the difference was found to decrease with increasing tree height (Figure 9). As tree height increases, a larger contribution to the return signal comes from the ground, and so the coherence will be more similar for the two baselines. Consider the coherence of a canopy to that of bare ground, a canopy will produce different coherence values due to decorrelation, whereas the ground will produce higher coherence as its temporal change is low. The ratio between the two baselines was found to increase with increasing tree height (Figure 10). This corresponds to a decreasing difference.

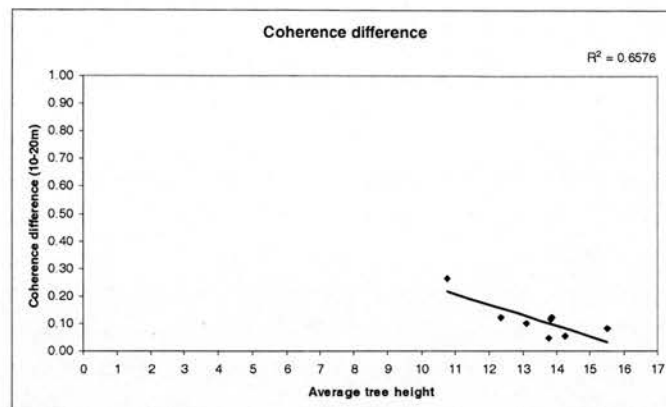


Figure 9 Coherence difference between 10m and 20m baselines

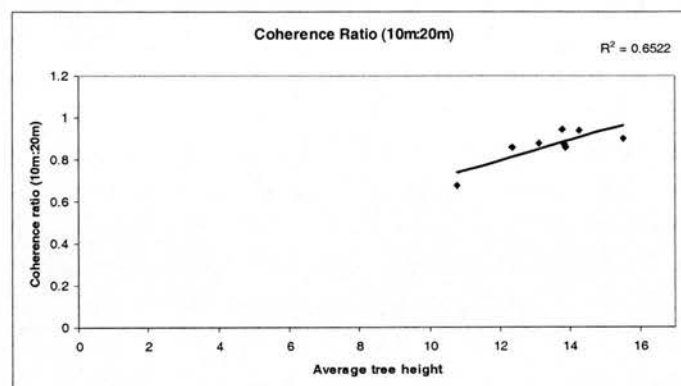


Figure 10 Coherence ratio between 10m and 20m baselines

5 CONCLUSION

This paper has demonstrated the use of L-band fully polarimetric dual-baseline interferometry for use in forest studies. The use of optimised coherence has improved differentiation between vegetation densities and heights when compared to backscatter intensity. The trend of coherence when compared to average tree height is shown to be acting in a way that is not expected, and reasons for this have been addressed. It has been concluded that coherence is of potential use for forest mapping and height discrimination, and future studies will be focused on assessing single and multiple data sets.

ACKNOWLEDGEMENTS

The authors would like to thank Professor Shane Cloude for supplying the optimised coherence data. Thanks are also due to Dr. Izzawati for assisting in coordinate transforms.

This work is funded by the NERC and the Forestry Commission, and their assistance is gratefully acknowledged.

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