Microwave remote sensing in forestry

BACKGROUND:

Microwave remote sensing at wavelengths ranging from 1 cm to 1 m has gained a lot of importance over the past decade for a wide range of scientific applications with the availability of active radar imaging systems. Its potential in spatial applications has been scientifically established in various sectors like forestry, agriculture, land use and land cover, geology and hydrology. A variety of applications have been carried out world over using microwave data like discrimination of crop types, crop condition monitoring, soil moisture retrieval, delineation of forest openings, estimation of forest above ground biomass, forest mapping; forest structure and fire scar mapping, geological mapping, monitoring wetlands and snow cover, sea ice identification, coastal windfield measurement, wave slope measurement, ship detection, shoreline detection, substrate mapping, slick detection and general vegetation mapping (Kasischke et al., 1997).

There is an emerging interest on microwave remote sensing, as microwave sensors can image a surface with very fine resolution of a few meters to coarse resolution of a few kilometers. They provide imagery to a given resolution independently of altitude, limited only by the transmitter power available. Fundamental parameters like polarization and look angle can be varied to optimize the system for a specific application. SAR imaging is independent of solar illumination as the system provides its own source of illumination. It can operate independently of weather conditions if sufficiently long wavelengths are chosen. It operates in a band of electromagnetic spectrum different from the bands used by visible and infrared (IR) imageries.

Microwave applications in Forestry

Applications of microwave remote sensing in forestry have also been reported during the recent past. Recent reviews on the application of radar in forestry show that SAR systems have a good capability in discriminating various types of (tropical) forest cover using multi-temporal and multi-frequency SAR data (Vander Sanden, 1997; Varekamp, 2001; Quinones, 2002; Sgrenzaroli, 2004). These studies showed that the biomass dependence of radar backscatter varies as a function of radar wavelength, polarization and incidence angle. Also

recent studies have demonstrated that synthetic aperture radar (SAR) can be used to estimate above-ground standing biomass. To date, these studies have relied on extensive ground-truth measurements to construct relationships between biomass and SAR backscatter (Steininger, 1996; Rignot et al., 1997).

Many studies demonstrated the use of Synthetic Aperture Radar (SAR) remote sensing to retrieve biophysical characteristics from forest targets (Richards, 1990). Although radar backscatter from forest is influenced by their structural properties (Imhoff, 1995), earlier studies derived useful relationships between backscattering coefficients and the above-ground biomass (Baker et., 1994; Le Toan et al., 1992; Dobson et el., 1992; Imhoff; 1995). These relationships may provide a method of monitoring forest ecosystems which play such a vital role in carbon storage and NPP.

Microwave remote sensing has the advantage of all weather capability coverage overcoming the persistent problem of cloud cover in satellite

images like in optical data. Optical remote sensing is being used very successfully in various applications related to earth resources studies and monitoring of the environment. However, optical remote sensing is not suitable for all atmospheric conditions. It cannot penetrate through clouds and haze. In many areas of the world, the frequent cloud conditions often restrain the acquisition of high-quality remotely sensed data by optical sensors. Thus, radar data has become the only feasible way of acquiring remotely sensed data within a given time framework because the radar systems can collect Earth feature data irrespective of weather or light conditions. Due to this unique feature of radar data compared with optical sensor data, the radar data have been used extensively in many fields, including forest-cover identification and mapping, discrimination of forest compartments and forest types, estimation of forest stand parameters and monitoring of forests. In areas where vegetation cover is dense, it visually covers the underlying formation and it is very difficult to detect structural limiting the use of optical sensors. Radar however, is sensitive enough to topographic variation that it is able to discern the structural expression reflected in the tree top canopy, and therefore the structure may be clearly defined on the radar imagery.

Based on this background, the current thesis work has been carried out to explore the potential of microwave data in addressing core areas of tropical forestry viz., vegetation classification, above ground biomass estimation etc., and to provide the users/researchers a meaningful data base of SAR applications in tropical forestry, specifically over the India region.

Research questions:

- Which SAR wavelength/frequency band is appropriate for vegetation classification in tropical forests?

- To what extent above ground biomass can be measured in tropical forests?

- Which frequency band and polarization are suitable for above ground biomass estimation?

- Is there any enhancement in vegetation classification with polarimetric / interferometric data than stand alone amplitude data?

Research hypothesis:

Based on the previous studies and earlier mentioned research questions, we understand that the backscatter increases with the increase in above ground biomass and depends on wavelength bands, polarizations used and on the study area, topographic variations and species composition. So, the present study attempts to derive the application potential of airborne and space borne SAR data in the quantification of the forest resources in tropical regions like India, both as a complementary and supplementary role to optical datasets. Different techniques such as Regression analysis, multi-sensor fusion, texture measures and interferometric coherence characterize different biomass ranges of the test sites and classification of major land cover classes. This study would facilitate scope for future research in tropical regions to explore the potentials of SAR data in land cover classification and above ground biomass estimation using the polarimetric and interferometric techniques.

OBJECTIVES:

Based on this background, the present study aims at the following objectives:

- Vegetation type classification using polarimetric and interferometric SAR data.
- Forest above-ground biomass estimation using multi-frequency SAR data and ground inventoried data.

Vegetation classification is necessary to understand the diversity of species in a given area which gives above ground biomass with measured parameters. Hence, vegetation classification enhances the estimation of the above ground biomass.

Forest biomass is a key parameter in understanding the carbon cycle and determining rates of carbon storage, both of which are large uncertainties for forest ecosystems. Accurate knowledge of biophysical parameters of the ecosystems is essential to develop an understanding of the ecosystem and their interactions, to provide input models of ecosystem and global processes, to test these models and to monitor changes in ecosystem dynamics and processes over time. Thus, it is a useful measure for assessing changes in forest structure, comparing structural and functional attributes of forest ecosystems across a wide range of environmental conditions.

Knowing the spatial distribution of forest biomass is important as the knowledge of biomass is required for calculating the sources and sinks of carbon that result from converting a forest to cleared land and vice versa, to

know the spatial distribution of biomass which enables measurement of change through time.

Field sampling is the most followed conventional method for vegetation type classification. The identification of different species in field yields good results in the estimation of the above ground biomass. It is very time consuming, expensive and very complicated.

With the use of multiple sensors, varied data collection and interpretation techniques, remote sensing is a versatile tool that can provide data about the surface of the earth to suit any need (Reene et al, 2001). Remote sensing approach for vegetation classification is cost effective and also time effective. Though the identification of the tree species is possible only from the aerial imagery, major forest types can be identified from the airborne and the spaceborne remote sensing data. Visual image interpretation provides a feasible means of vegetation classification in forests. The image characteristics of shape, size, pattern, shadow, tone and texture are used by interpreters in tree species identification. Phenological correlations are useful in tree species identification. Changes in the appearance of trees in different seasons of the year some times enable discrimination of species that are indistinguishable on single dates. The use of multi-temporal remote sensing data enables the mapping of the different forest types.

SAR has shown its potential for classifying and monitoring geophysical parameters both locally and globally. Excellent works were carried out on the classification using several approaches such as polarimetric data decomposition (Lee et al., 1998), knowledge based approaches considering

the theoretical backscatter modeling and experimental observations (Ramson and Sun , 1994) ; Backscatter model-related inversion approaches (Kurvonen et al., 1999), neural networks and data fusion approaches (Chen et al., 1996). Dong et al. (2001) have shown that the classification accuracy of 95% for the vegetation classes could be achieved through the segmentation and classification of the SAR data using Gaussian Markov Random Field Model (GMRF).

Many methods have been employed for classification of polarimetric SAR data, based on the maximum likelihood (ML) (Lee et al. 1994), artificial neural network (NN) (Chen et al. 1996, Ito and Omatu, 1998), support vector machines (SVMs) (Fukuda et al. 2002), fuzzy method (Chen et al. 2003, Du and Lee 1996), or other approaches (Kong et al. 1988, Lee and Hoppel 1992, van Zyl and Burnette 1992, Cloude and Pottier 1997, Lee et al. 1999, Alberqa 2004) Among these methods, the ML classifier (Lee et al. 1994) can be employed for obtaining accurate classification results, but it is based on the assumption of the complex Wishart distribution of the covariance matrix.

Assessing the total aboveground biomass of forests (biomass density when expressed as dry weight per unit area at a particular time) is a useful way of quantifying the amount of resource available for all traditional uses. It either gives the quantity of total biomass directly or the quantity by each component (e. g., leaves, branches, and bole) because their biomass tends to vary systematically with the total biomass. However, biomass of each component varies with total biomass by forest type, such as natural or planted forests and closed or open forests. For example, leaves contribute

about 3-5% and merchantable bole is about 60% of the total aboveground biomass of closed forests.

Many researchers have developed various methods based on field inventory and remote sensing approaches for the estimation of above ground biomass (Kira and Ogawa, 1971). Traditionally, field-measured approach is considered as the most accurate source for above-ground biomass estimation. It has been converted to volume, or biomass, using allometric equations that are based on standard field measurements (tree height and diameter at breast height).

Different approaches, based on field measurement (Brown et al. 1989, Brown and Iverson 1992, Schroeder et al.. 1997, Houghton et al., 2001, Brown, 2002); remote sensing (Tiwari 1994, Roy and Ravan 1996, Tomppo et al., 2002, Foody et al., 2003, Santos et al., 2003, Zheng et al., 2004, Lu, 2005); and GIS (Brown and Gaston 1995) have been applied for AGB estimation. Traditional techniques based on field measurement are the most accurate ways for collecting biomass data. A sufficient number of field measurements is a prerequisite for developing AGB estimation models and for evaluating the AGB estimation results. However, these approaches are often time consuming, labour intensive, and difficult to implement, especially in remote areas and are generally limited to 10-year intervals. Also, they cannot provide the spatial distribution of biomass in large areas.

For the above reasons, the perspectives of using remote sensing techniques to estimate forest biomass have gained interest. Remote sensing data available at different scales, from local to global, and from various sources,

optical to microwave are expected to provide information that could be related indirectly, and in different manners, to biomass information. The possibility that aboveground forest biomass might be determined from space is a promising alternative to ground-based methods (Hese et al., 2005).

The advantages of remotely sensed data, such as in repetivity of data collection, synoptic view, digital format that allows fast processing of large quantities of data, and the high correlations between spectral bands and vegetation parameters, make it the primary source for large area AGB estimation, especially in areas of difficult access. Therefore, remote sensing-based AGB estimation has increasingly attracted scientific interest.

In general, AGB can be estimated using remotely sensed data with different approaches, such as multiple regression analysis, K nearest-neighbour, and neural network (Roy and Ravan 1996, Nelson et al. 2000a, Steininger 2000, Foody et al. 2003, Zheng et al. 2004), and indirectly estimated from canopy parameters, such as crown diameter, which are first derived from remotely sensed data using multiple regression analysis or different canopy reflectance models (Wu and Strahler 1994, Woodcock et al. 1997, Phua and Saito 2003, Popescu et al. 2003).

Spectral signatures or vegetation indices are often used for AGB estimation in optical remote sensing. Many vegetation indices have been developed and applied to biophysical parameter studies (Anderson and Hanson 1992, Anderson et al. 1993, Eastwood et al. 1997, Lu et al. 2004, Mutanga and Skidmore 2004). Vegetation indices have been recommended to remove variability caused by canopy geometry, soil background, sun view angles,

and atmospheric conditions when measuring biophysical properties (Elvidge and Chen 1995, Blackburn and Steele 1999).

Radar remote sensing has potential to provide information on above ground biomass. The information content of SAR data in terms of the retrieval of biomass parameters will be assessed based on an understanding of the underlying scattering mechanisms, which in turn are derived from observations and modeling results. For this purpose, an analysis of data acquired by multiple frequency, incidence and polarisation systems and by interferometric systems is carried out. It has been proved that the sensitivity to biomass parameters differ strongly at different frequencies, polarisations and incidence angles.

In general, long wavelength SAR backscatter (P and L band) is more sensitive to forest biomass than shorter wavelength C-band backscatter and the relationships saturate at certain biomass levels (Imhoff 1995b). The strength of the relationships and the saturation levels are dependent on the type of forest being analysed (Ferrazoli et al. 1997). The saturation levels for the estimation of above ground biomass depend on the wavelengths (i. e. different bands, such as C, L, P), polarization (such as HV and VV), and the characteristics of vegetation stand structure and ground conditions. C-band can measure forestry biomass up to app. 50 tons/ha, L-band can measure up to 100 tons/ha and P-band can measure up to 200 tons/ha (Floyd et al., 1998). The combination of multiple channels and polarizations provides greater advantage for estimating total biomass (Harry Stern, 1998).

RELEVANCE OF THE STUDY:

The present study is the part of Radar Imaging satellite – Joint Experiment Programme (RISAT-JEP) for forestry applications undertaken by Forestry and Ecology Division of National Remote Sensing Centre (NRSC), as a pilot campaign with specific objectives of above ground biomass estimation and vegetation type classification using airborne DLR (German Aerospace Center) carrying ESAR (Experimental Synthetic Aperture Radar) data for Rajpipla (Gujarat) study site and space borne ENVISAT (Environmental Satellite) carrying Advanced Synthetic Aperture Radar (ASAR) data for three test sites viz., Rajpipla (Gujarat), Dandeli (Karnataka) and Bilaspur (Chattisgarh), India.

SCOPE OF THE STUDY:

The specific objectives of the present study are above ground biomass estimation and vegetation type classification using airborne DLR (German Aerospace Center) carrying ESAR (Experimental Synthetic Aperture Radar) data for Rajpipla (Gujarat) study site and space borne ENVISAT (Environmental Satellite) carrying Advanced Synthetic Aperture Radar (ASAR) data; ALOS (Advanced Land Observing Satellite) carrying Phased Array L-band Synthetic Aperture Radar (PALSAR) for three test sites viz., Rajpipla (Gujarat), Dandeli (Karnataka) and Bilaspur (Chattisgarh), India.

Different techniques such as Regression analysis, multi-sensor fusion, texture measures and interferometric coherence were used to characterize different biomass ranges of the test sites and to classify the major land cover classes using spaceborne C-band ENVISAT-ASAR data and L-band ALOS-PALSAR data. Polarimetric signatures, polarimetric decompositions, multi-

sensor fusion techniques etc. were used for the classification of different vegetation types in the Rajpipla study area using the airborne DLR-ESAR data.

The study has its uniqueness and gains importance in the application potential of SAR interferometry over tropical regions like India, both in terms of an alternate/substitute to optical data sets due to persisting cloud cover and to the lack of availability of any earlier scientific work over the study region. This study is useful for the applications of to be launched Radar Imaging Satellite (RISAT) in 2010.

The study has amply demonstrated the application potential of airborne and space borne SAR data in the quantification of the forest resources in tropical regions like India, both as a complementary and supplementary role to optical datasets. The study would facilitate future research in tropical regions to explore the potentials of SAR data in land cover classification and above ground biomass estimation using the polarimetric and interferometric techniques.

LITERATURE SURVEY:

During the last decade, many potential applications of SAR in different frequency bands have been studied for forestry applications using data acquired by both airborne and space-borne systems. Various techniques like Polarimetry, Interferometry and Polarimetric-Interferometry enhanced the use of SAR data in forestry applications. The backscatter from vegetation is used to infer information about amplitude data for forest cover mapping and estimation of above ground biomass in regenerating forests. Use of SAR

polarimetric data delineated vegetation classes within the forest and also enhanced the capability in estimating the above ground biomass. The use of repeat pass interferometric data enables to calculate the forest stand height and also used for the land cover classification. The emerging Pol-InSAR technique is used to derive the three dimensional forest structures.

Forest cover maps were prepared for the boreal, temperate and tropical forests using SAR data. Forest was separated from non-forest regions using multi-temporal C-band ERS SAR data on the test sites of United Kingdom, Poland and Finland (Quegan et al., 2000). The study applied a threshold value to separate forest from other classes. Tropical rainforest of Borneo was mapped from SIR-B data of different incidence angles (Ford and Casey, 1988). Different vegetation covers along with wetlands and clear-cut areas were distinguished. Forest cover mapping was done with JERS-1 SAR data on the coastal regions of Gabon (Simard et al., 2000). The study used decision tree method utilizing both radar amplitude and texture information. Forest cover map was prepared for Southern Chittagong using JERS-1 SAR data (Rahman and Sumantyo, 2007) and the study separated forest, degraded forest, shrubs, coastal plantations, agriculture, shrimp-farms, urban and water.

Although radar backscatter from forest is influenced by their structural properties (Imhoff, 1995a), many studies have demonstrated useful relationships between backscattering coefficients and the areal density of above-ground biomass within particular types of forest (Baker et., 1994; Le Toan et al., 1992; Dobson et al., 1992; Imhof et al; 1995b).

Many airborne and spaceborne SAR systems have been used to carry out a large amount of experiments for investigating the forest ecosystems. The airborne systems, such as the NASA/JPL AIRSAR, DLR-ESAR, etc., operating at P, L and C band, has been flown over many forest sites (Zebker et al., 1991; Le Toan et al, 1992; Beaudoin et al., 1994; Rignot et al.; 1994; Skriver et al., 1994; Ranson et al., 1996). The experiments of the Canadian CV-580, as well as the European airborne system, mainly operating at C and X band also have been carried out in North America and Europe (Drieman et al., 1989; Hoekman, 1990). Spaceborne SAR is being used from regional to global monitoring in a periodic basis. The spaceborne systems, such as the Seasat SAR, SIR-B, SIR-C/X-SAR and ERS-1, ERS-2, ENVISAT-ASAR, RADARSAT etc., were used for investigations of boreal, temperature and sub-tropical forestry test sites (Ford et al., 1988; Dobson et al., 1992; Ranson et al., 1995; Stofan et al., 1995; Rignotet al., 1995). These experiments and studies have shown that radar is sensitive to forest structural parameters such as diameter at breast height (dbh) and tree mean height including above-ground biomass (Dobson et al., 1992; Pulliainen et al., 1994; Skriver et al., 1994; Ferrazzoli et al., 1995; Ranson et al., 1996).

Earlier studies has shown the potential of radar data in estimating AGB (Hussin et al. 1991, Ranson and Sun 1994, Dobson et al. 1995, Rignot et al. 1995, Saatchi and Moghaddam 1995, Foody et al. 1997, Harrell et al. 1997, Ranson et al. 1997, Luckman et al. 1997, 1998, Pairman et al. 1999, Imhoff et al. 2000, Kuplich et al. 2000, Castel et al. 2002, Sun et al. 2002, Santos et al. 2003, Treuhaft et al. 2004). Kasischke et al. (1997) reviewed radar data for ecological applications, including AGB estimation. Lucas et al. (2004) and

Kasischke et al. (2004) reviewed SAR data for AGB estimation in tropical forests and temperate and boreal forests, respectively. Different wavelength radar data have their own characteristics in relating to forest stand parameters. Backscatter in P and L bands is highly correlated with major forest parameters, such as tree age, tree height, DBH, basal area, and AGB (Leckie 1998). In particular, SAR L-band data have proven to be valuable for AGB estimation (Sader 1987, Luckman et al. 1997, Kurvonen et al. 1999, Sun et al. 2002). However, low or negligible correlations were found between SAR C-Band backscatter and AGB (Le Toan et al. 1992). Beaudoin et al. (1994) found that the HH return was related to both trunk and crown biomass, and the VV and HV returns were linked to crown biomass.

Harrell et al. (1997) evaluated four techniques for AGB estimation in pine stands using SIR C- and L-Band multi-polarization radar data and found that the L-Band HH polarization data were the critical elements in AGB estimation. Kuplich et al. (2000) used L-band JERS-1/SAR data for AGB estimation of regenerating forests and concluded that these data had the potential to estimate AGB for young, regenerating forests. Sun et al. (2002) found that multi-polarization L-Band SAR data were useful for AGB estimation of forest stands in mountainous areas. Castel et al. (2002) identified the significant relationships between the backscatter coefficient of JERS- 1/SAR data and the stand biomass of a pine plantation. The study observed the improvement in AGB estimation results for young stands, compared to estimation for old stands. Santos et al. (2002) used JERS-1 SAR data to analyse the relationships between backscatter signals and biomass of forest and savanna formations. This study concluded that forest structural-

physiognomic characteristics and the radar's volume scattering, double bounce scattering are two important factors affecting these relationships. The saturation levels of backscattering co-efficient with respect to AGB depend on the wavelengths (i. e. different Bands, such as C, L, P), polarization (such as HV and VV), and the characteristics of vegetation stand structure and ground conditions. Luckman et al. (1997) found that the longer-wavelength (L-Band) SAR image was more suitable to discriminate different levels of forest biomass up to a certain threshold, indicating that it is suitable for estimating biomass of regenerating forests in tropical regions. Austin et al. (2003) indicated that forest biomass estimation using radar data may be feasible when landscape characteristics are taken into account.

The radar backscattering coefficient is correlated with forest biomass and stem volume (Le Toan et al. 1992, Israelsson et al. 1994, Kasischke et al. 1994, Dobson et al. 1995). The sensitivity of Synthetic Aperture Radar (SAR) data to forest stem volume increases significantly as the radar wavelength increases (Israelsson et al. 1997). The imaging process makes SAR suitable for mapping parameters related to forest biomass, like stem volume (Baker et al, 1999; Fransson et al, 1999; Hyyppa et al, 1997; Israelsson et al., 1997; Kurvonen et al, 1999; Pulliainen et al, 1996), total growing stock (Balzter et al, 2000; Schmullius et al, 1997), LAI (Imhoff et al, 1997), or above ground net primary productivity (Bergen et al, 1998).

Le Toan et al., (1992) used multi-polarisation L- and P-band airborne radar data, and found that the dynamic range of the radar backscatter corresponded highly with forest growth stages and is maximum at P-band HV polarization. The analysis of P-band data indicated a good correlation

between the radar backscatter intensity and the main forest parameters including trunk biomass, height, age, diameter at breast height (dbh), and basal area. Dobson et al., (1992) showed an increasing range of backscatter with changing biomass from C to P-band, as well as higher biomass levels at which backscatter relationships to biomass saturate. Hoekman, (1990) found poor relationships between X- and C-band backscatter and volume and other stand parameters.

The spaceborne systems, such as the Seasat SAR, SIR-B, SIR-C/X-SAR and ERS-1, ERS-2, JERS, ENVISAT-ASAR and recently ALOS-PALSAR etc. were used for investigations of boreal, temperature and sub-tropical forestry test sites (Ford et al., 1988; Dobson et al., 1992; Ranson et al., 1995; Stofan et al., 1995; Rignot et al., 1995). These experiments and studies have shown that radar is sensitive to forest structural parameters including above-ground biomass (Dobson et al., 1992; Pulliainen et al., 1994; Skriver et al., 1994; Ferrazzoli et al., 1995; Ranson et al., 1996).

Kasischke et al., (1997) reviewed radar data for ecological applications, including AGB estimation. It is being reported in literature that the radar backscatter in the P and L bands is highly correlated with major forest parameters, such as tree age, tree height, DBH, basal area, and AGB. In particular, SAR L-Band data have proven to be valuable for AGB estimation (Sader, 1987; Luckman et al., 1997; Kurvonen et al., 1999; Sun et al., 2002). Kuplich et al., (2000) used JERS-SAR data for AGB estimation of regenerating forests and concluded that these data had the potential to estimate AGB for young, regenerating forests. Luckman et al., (1997) found that the longer-wavelength (L-Band) SAR image was more suitable to discriminate different

levels L-Band backscatter shows no sensitivity to increased biomass density after a certain threshold, such as 100 tons ha-1, indicating that it is suitable for estimating biomass of regenerating forests in tropical regions.

The radar backscattering coefficient is correlated with forest biomass and stem volume (Le Toan et al. 1992; Israelsson et al., 1994; Kasischke et al., 1994, Dobson et al., 1995). The sensitivity of Synthetic Aperture Radar (SAR) data to forest stem volume increases significantly as the radar wavelength increases (Israelsson et al., 1997). The imaging process makes SAR suitable for mapping parameters related to forest biomass, like stem volume (Baker et al., 1999; Israelsson et al., 1997; Pulliainen et al., 1996), total growing stock (Balzter et al., 2000; Schmullius et al., 1997), LAI (Imhoff et al., 1997), or above ground net primary productivity (Bergen et al., 1998).

The dependency of backscatter on above ground biomass was observed and related to the penetration of the radiation into the canopy and interaction with the trunk, where most of the volume, therefore, biomass of the vegetation is concentrated (Sader 1987, Le Toan et al. 1992, Dobson et al. 1992). HV polarization in longer wavelengths (L or P band) is the most sensitive to above ground biomass (Sader 1987, Le Toan et al. 1992, Ranson et al. 1997a) because it originates mainly from canopy volume scattering (Wang et al. 1995), trunk scattering (Le Toan et al. 1992) and is less affected by the ground surface (Ranson and Sun 1994).

As forest backscatter in different wavelengths and polarizations originate from separate layers of a canopy, the use of multiple channels or multi-step approaches (e. g., Dobson et al. 1995) could be used to estimate total

above-ground biomass (Kasischke et al. 1997). Sun and Ranson (1994) estimated biomass in mixed conifer temperate forest upto 250 Mg/ha.

Band ratios (HH/HV and VV/VH) were also used for the above ground biomass estimation. However, Dobson et al. (1995) considered these band ratios too simplistic (as the corresponding backscatter will be much higher for the few tall trees than for the many short ones), although effective in estimating biomass at higher ranges. In spite of this, a combination of bands and polarizations in a multi-step approach made possible the mapping of biomass in a mixed temperate forest upto 250 Mg/ha (Dobson et al. 1995). Establishing a strong link between backscatter and forest variables is an important part of the successful estimation of forest biomass from backscatter. Models are often used to explain the relationship between forest variables, scattering mechanisms and SAR configuration parameters (Richards 1990, Kasischke and Christensen 1990). Another approach is the use of statistical analysis, where forest variables are related to SAR backscatter by regression models (Sader 1987, Le Toan et al. 1992, Rauste et al. 1994). The combination of the two approaches, in most cases to assess the results of the predicted biomass or backscatter via regression (Ranson and Sun 1994, Ferrazzoli et al. 1997, Franson and Israelson 1999). Statistical procedures such as stepwise regression analysis were also used to determine the best set of bands and polarizations to discriminate biomass levels (Ranson et al. 1997a).

The three-band (C, L, and P) polarimetric AIRSAR sensor has been used in many forest biomass studies (e. g., Green, 1998; Kasischke et al., 1991, 1995; Moghaddam et al., 1994; Ranson & Sun, 1997). The strongest

correlation between SAR backscatter and forest biomass has been reported in P-band and the weakest in C-band (e. g., Beaudoin et al., 1992; Dobson et al., 1992; Israelsson et al., 1992; Rauste et al., 1992;