PARTNERSHIP FOR LAND USE SCIENCE (FOREST-PLUS) PROGRAM

SAR Technical Protocol for Forest Monitoring

V. DAKSHINAMURTHY

January 2017

This publication was produced for review by the United States Agency for International Development. It was prepared by Tetra Tech.

This publication was produced for review by the United States Agency for International Development by Tetra Tech, through Contract No. AID-386-C-12-00002.

This report was prepared by:
Tetra Tech
159 Bank Street, Suite 300
Burlington, Vermont 05401 USA
Telephone: (802) 658-3890
Fax: (802) 495-0282
E-Mail: international.development@tetratech.com

Tetra Tech Contacts:
Ben Caldwell, Chief of Party
159 Bank Street, Suite 300
P.O. Box 1397
Burlington, VT 05402
Tel: (802) 495-0282
Email: ben.caldwell@tetratech.com

PARTNERSHIP FOR LAND USE SCIENCE (Forest-PLUS) PROGRAM

SAR Technical Protocol for Forest Monitoring

January 2017

TABLE OF CONTENTS

ACRONYMS AND ABBREVIATIONS

AGB	Above Ground Biomass
COP	Conference of the Parties
DBH	Diameter at Breast Height
ESA	European Space Agency
FD	Forest Department
Forest-PLUS	Partnership for Land Use Science
FPP	Forest-PLUS Program
FRI	Forest Research Institute, Dehra Dun
GIS	Geographical Information System
GOI	Government of India
GPS	Global Positioning System
IPCC	Inter-governmental Panel on Climate Change
ISRO	Indian Space Research Organization
IIRS	Indian Institute of Remote Sensing
MoEFCC	Ministry of Environment, Forests and Climate Change
NRSC	National Remote Sensing Centre
NASA	National Aeronautics and Space Administration
SAC	Space Applications Centre
SAR	Synthetic Aperture Radar
SFD	State Forest Department
UMass	University of Massachusetts
USAID	United States Agency for International Development
UNFCCC	United Nations Framework Convention on Climate Change

EXECUTIVE SUMMARY

Large-scale, national level monitoring of forest resources using field inventory techniques is a time as well as cost-intensive task. The technology of remote sensing has the ability to significantly improve the efficiency of forest resources monitoring through observations made from the air-borne and space-borne platforms. In recent years, India has made significant improvement in forest resources monitoring using optical remote sensing tools and techniques; however, persistent cloud cover limits the uses of optical remote sensing in various parts of the country. In contrast, microwave data obtained using Synthetic Aperture Radar (SAR) technology has the capability of penetration through cloud cover, in addition to day and night coverage possibility. Moreover, longer SAR wavelengths are capable of penetrating the canopy and thus, providing high accuracy estimates of the aboveground woody biomass of the forests. Though the utility of the SAR systems for forest carbon inventory is well-established, regular use of SAR data for forest carbon inventory is still limited. This is attributable to the difficulty in SAR data processing and interpretation, and the high cost of commercial software for data analysis.

To overcome these problems a SAR Task Group (STG), with support from the Ministry of Environment Forest and Climate Change (MoEFCC), the Indian Space Research Organization (ISRO) and the United States Agency for International Development (USAID), was created with the objective to develop and disseminate protocols to use SAR data in assessment of carbon in the Indian forests and also to build the capacity to institutionalize the SAR-based methods for forest monitoring tasks. The STG in India consists of seven senior remote sensing and forest scientists from the National Remote Sensing Center (NRSC) Hyderabad, the Space Applications Center (SAC) Ahmedabad, Forest Survey of India (FSI), and the Indian Institute of Remote Sensing (IIRS) Dehradun, along with a SAR Expert from University of Massachusetts and SAR Coordinator from Forest-PLUS Program.

The protocol developed by the STG under the USAID/India Forest-PLUS program aims to prepare well-defined techniques for forest monitoring including mapping of forest extent and carbon stock assessment of Indian forests using open source software with a step-by-step capacity development manual to provide State forest officers the materials they would normally need to implement the protocol. The protocol firstly provides an explanation of the background and rationale of SAR usage including synergy with the optical data and software requirements, followed by the availability of the sensors/data and software tools. The third part deals with the methodology, which includes available methods and their suitability, data requirements planning, pre-processing steps to be followed and the final protocol-based techniques followed by uncertainty analysis, limitations, and the delivery mechanism of the outcomes. The final part of the protocol is about the capacity building of the user community.

The intent of this document is to make the protocol useful to the forestry community and to assist in taking a step forward towards institutionalization of SAR technology in operational forest monitoring. A well-coordinated effort between Forest Survey of India and State Forest Departments shall be required for the use of SAR data together with the well-established optical remote sensing tools. The synergetic use of both the tools will not only help in tackling the problem of data gaps but also overcome the limitations of optical remote sensing techniques. Development of the SAR protocol is well-timed looking towards the efforts being made by NASA and ISRO (called NISAR) to launch a joint SAR satellite mission by 2020. The training is intended to build the capacity and ensure the use of data from this path-breaking first-of-its-kind mission.

1 BACKGROUND

India has a diverse range of forests, extending from the tropical rainforest in the south to the alpine scrubs in the north, from the thorn forests in the west to the tropical evergreen forests in the north-east. Indian forests can be divided into sixteen broad types with a number of sub-types according to climate, soil type, topography, and elevation (Champion & Seth, 1968):

1. Tropical wet evergreen (rain) forest
2. Tropical semi-evergreen forest
3. Tropical moist deciduous forest
4. Littoral and swamp forest
5. Tropical dry deciduous forest
6. Tropical thorn forest
7. Tropical dry evergreen forest
8. Sub-tropical broad-leaved hill forest
9. Sub-tropical pine forest
10. Sub-tropical dry evergreen forest
11. Montane wet temperate forest
12. Himalayan moist temperate forest
13. Himalayan dry temperate forest
14. Sub-alpine forest
15. Moist alpine scrub
16. Dry alpine scrub

Spatially explicit information on forest composition, stand structure, landscape configuration, and the changes in these forest types over time are essential for understanding and forecasting ecosystem function in relation to climate change. Optical remote sensing has been used successfully in various applications related to earth resources studies and forest monitoring. However, since sunlight cannot penetrate through cloud, fog, and haze, optical data acquisition encompassing all atmospheric conditions is not possible, especially in tropical countries like India. In such cases, data derived from SAR are a viable alternative because of radar's ability to capture earth features irrespective of atmospheric conditions. Due to this unique feature, radar data is the clear choice in many forestry applications (*e.g.*, forest cover and type identification and mapping, discrimination of forest biophysical components, estimation of forest stand parameters, and monitoring of the forests). Microwave remote sensing is also being used for biomass estimates and carbon accounting. Biomass estimation from SAR data has been under investigation for two decades and by now it is well established that the retrieval accuracy increases with increasing radar wavelength (Lucas *et al*., 2006). Radar data can also provide information about terrain and the vegetation surfaces.

The all-weather capability, signal independence to the solar illumination angle, and 3D vegetation responses are the highlights of active radar systems for forest vegetation monitoring. SAR provides important features of vegetative cover and soil such as inundation underneath the closed canopies, fresh woody biomass, soil moisture and surface roughness in areas of low vegetation, and orientation and structure of objects on the ground. Multiple polarizations and the large swath widths associated with radar data have enhanced the capabilities of SAR for land use/land cover mapping.

2 RATIONALE

While the utility of SAR data for forest biomass mapping is well established, regular usage of this is historically limited due to:

- The difficulty of pre-processing and interpretation
- the cost of commercial software

To overcome these barriers, the SAR protocol has been developed by the SAR Task Group (STG) created by MoEFCC under the USAID/India supported Forest-PLUS program. The SAR Task Group in India consists of seven senior remote sensing and forest scientists along with a SAR coordinator. The group is assisted by Prof. Paul Siqueira from University of Massachusetts. The STG consists of following members:

- Dr. Chandra Shekhar Jha, Group Director, Forestry & Ecology Group, National Remote Sensing Centre, Hyderabad
- Mr. Chakrapani Patnaik, Scientist/Engineer-SF, MHTD Division, Space Applications Centre, Ahmedabad
- Dr. Anup Kumar Das, Scientist/Engineer-SF, MHTD Division, Space Applications Centre, Ahmedabad
- Mr. Shashi Kumar, Scientist/Engineer-SD, PRS Division, Indian Institute of Remote Sensing, Dehradun
- Mr. Kamaljeet Singh, Deputy Director, FCM & GPU, Forest Survey of India, Dehradun
- Dr. Sunil Chandra, Deputy Director, System Manager, Forest Survey of India, Dehradun
- Dr. Abhay Kumar Saxena, Assistant Director, NFDMC, Forest Survey of India, Dehradun
- Dr. Uttara Pandey, IORA Ecological Solutions, Forest-PLUS, SAR Coordinator, New Delhi
- Prof. Paul Siqueira, University of Massachusetts, Amherst and Ecosystems Lead (NISAR)

The protocol developed by the STG under the USAID/India Forest-PLUS program aims to prepare well-defined techniques for forest monitoring including mapping of forest extent and carbon stock assessment of Indian forests using open source software with a step-by-step capacity development manual to provide State forest officers the materials they would normally need to implement the protocol. The pre-processing steps are clearly written and efforts made to automate the process to the extent possible for the ease of the new user community. To overcome the barrier of costly commercial software, which also restricts the use of SAR data, these protocols are developed using open source free software only. The main objective of the protocol is to assist the user community in estimation of the forest extent and change and the above ground biomass from SAR data, and to provide a measure of the accuracy of these estimates for the area under study.

The potential stakeholders who can directly or indirectly benefit from this protocol and may contribute in the use of this protocol can be the Forest Survey of India (FSI). The FSI, an organization of MoEFCC, is officially mandated to map and monitor India's forests. Other beneficiaries include the State Forest Departments, academic institutions, researchers, and the professionals working in the field of SAR technology applications.

3 DATA AND SOFTWARE

3.1 SENSORS: PRESENT & FUTURE

Starting with Seasat, the first scientific SAR satellite launched in 1978, a number of microwave remote sensing satellites (viz., Radarsat-1&-2, ERS-1 &-2, JERS-1, SIR-A, -B, & -C, and SRTM) have been launched over time. With the progress of technology and removal of restrictions on the availability of data, SAR is becoming a more widely used technology. Globally, SAR data has effectively monitored forests and quantified their biomass. In addition to bringing better spatial resolutions and polarizations that are complementary to optical data, the SAR satellites also operate at different wavelengths and thus have the potential for improving the accuracy of the forest information. Some of these new systems are designed for operational use rather than for specific research tool objectives. For example, COSMO-Skymed, a commercially run X-band system, consists of a constellation of four identical satellites that orbit and provide more frequent SAR data than single-satellite systems. As time progresses and more national space agencies became involved, it is likely that the number of SAR satellites will continue to increase and that there will be a stronger commitment to ensuring data continuity, leading to a larger data availability. Because of the time-variable and time-critical nature of forest monitoring, all of this has the potential of great benefit in forestry sector. Annex 2: Sensors: Past, Present & Future lists the summary of key past, current, and planned spaceborne SAR sensors and their characteristics.

3.2 SAR DATA

SAR data are typically acquired using internationally agreed frequency bands in the radio spectrum reserved for scientific use. The frequency bands are specified by a letter designation that indicates which band is in use (see Table 1 below). At the low frequency end (long wavelength) are P- and L-band (~435 and 1.27 GHz, respectively), which are useful for their sensitivity to the tree trunk, and the soil moisture properties of a forest. The higher frequencies of S- and C-band (3.2 and 5.3 GHz, respectively) penetrate less into the canopy and are primarily sensitive to the branch and brunch-trunk structures of the tree. At X-band frequency (10 GHz) and higher, the scattering is dominated by the leaves and upper parts of the canopy. Theoretically, P-band is most sensitive to the larger structures of the forest, *i.e.*, trunk, primary, and secondary branches. This frequency regime is heavily used for several other non-imaging and defense applications of the radio spectrum and hence, its utility is limited compared to the other microwave bands.

The next important parameter of SAR data is the polarization of the signals. The polarization is the direction of the electric field of an electromagnetic wave and is the main factor that governs the interaction between signals and the object that reflects them. Most of the microwave sensors transmit signals in a horizontal (H) or vertical (V) mode. These orientations are specified relative to the plane of the ground. For polarization, SAR data are specified as a combination of the transmitted and received polarizations. Hence, a horizontally transmitted and horizontally received signal is written as HH, while horizontally transmitted and vertically received signals would be written as HV. It follows that a maximum of four linear polarization combinations (HH, HV, VV and VH) are possible. Cross-polarized (HV and VH) backscattering mainly originates from multiple scattering within the tree canopy and is less influenced by the ground surface than the co-polarized signal.

Given the above characteristic, normally P- and L-band observations are used for the estimation of Above Ground Biomass (AGB), and in some cases the C-band may be employed. Past studies have shown that the longer wavelengths (L- and P-bands) and the HV polarization have the highest sensitivity to AGB (Le Toan et *al*., 1992; Dobson *et al*., 1992; Imhoff, 1995; Luckman *et al*., 1997; Kurvonen *et al.,* 1999; Sun *et al.,* 2002; Lucas *et al*., 2006). Co-polarized data (HH and VV) at longer wavelengths, especially P-band, are sensitive to changing surface conditions.

AGB estimation using C-band data has been achieved in vegetation cover with lower biomass (Le Toan *et al.,* 1992; Beaudoin *et al*., 1994; Luckman *et al*., 1997); that is, the reflected energy from low-biomass sites such as grassland, bogs, clear cuttings, areas of forest regeneration, and young plantations at longer wavelengths is less than that from C-band. Ground surfaces covered with grass, brush, or young trees have very low backscattering in the P-band since the scattering elements of grass and small trees are small compared to the C-band. The same surfaces, however, will be very rough in C-band so strong backscattering may occur (Sun & Ranson, 1998; Ranson *et al*., 1997).

The main scattering component for C-band is considered to be leaves and small branches (Ranson & Sun, 1994; Leckie & Ranson, 1998), which are saturated at biomass levels above 50 t/ha (Leckie & Ranson, 1998). The backscattering of the L-band is more related to the trunk and main branches and is less sensitive to the environmental conditions and hence, valuable in the biomass estimation (Sader 1987; Luckman *et al.,* 1997; Kurvonen *et al.,* 1999; Sun *et al*., 2002). In tropical forests with a complex structure and mixed vegetation, the L- and P-bands saturate at approx. 100-150 t/ha (**Lucas** *et al*., 2007; **Solberg** *et al*., 2010). In areas with simple structure and one or two dominant species, the saturation level is about 250 t/ha (Ghasemi *et al*., 2011). The best wavelength bands for biomass estimation in coniferous forests are C- and L-bands with HV polarization (Ghasemi *et al*., 2011). For deciduous forests, a combination of L- and C-band with HH and HV polarizations are the most suitable (Ranson *et al*., 1997; Sun & Ranson, 1998). Using a combination of C- and L-band gives better results than using only one band (Hoekman *et al*., 1997). Table 1 explains the different frequency and wavelength bands of radar sensors and the main scatterers.

Table 1: Band designations, their frequencies, wavelength, and principal scattering components within a tree canopy.

Band	Frequency (GHz)	Wavelength (cm)	Main Scatterers
P	0.3-1	30-100	Branches & Trunks
L	1-2	15-30	Branches
S	2-4	7.5-15	Mixed Branches and Leaves
C	4-8	3.8-7.5	Leaves, Small Branches
X	8-12.5	2.4-3.8	Leaves, Twigs
K	12.5-40	0.7-1.7	Canopy Top

3.3 FIELD DATA

An important component in the estimation of AGB from SAR data is the collection of field data, which is used to establish a localized relationship between inventoried field biomass with the SAR data. In this section the selection of plot size, data collection, calculation of biomass from field measurements and preparation of training and validation of field sets is discussed. For more details on other field inventory, please refer the Field Inventory Manual of FSI (http://fsi.nic.in/documents/manualforest_inventory_2.pdf**).**

3.3.1 SELECTION OF PLOT SIZE

Selection of appropriate field plot size is important for establishing a relationship between forest parameters and SAR data. The National Forest Inventory carried by Forest Survey of India (FSI), which is intended to be the basis of field inventory data collection, is standardized at 0.1 ha square plot size and 0.08 ha for circular plot by FSI for field inventory. Other agencies which are also active in carrying out field inventory for biomass assessment using radar data, viz., National Remote Sensing Centre, Hyderabad have suggested using a bigger plot size of 0.5 to 1 ha for establishing better correlation of forest parameters with radar data. The selection of sample size will depend on the plot to plot variance of the forest under study and the spatial resolution and minimum mapping unit of the microwave data used. An alternative sample plot layout suggested by the University of Massachusetts (UMass), is to use either 1 ha, 100 m x 100 m, or alternatively 50 m x 200 m plots. These will be typically divided into 25 m x 25 m sub-plots that are used for relating SAR data to biomass measures and for better characterizing within-plot variation of biomass. A large plot is better able to record the geographic diversity of tree sizes and species compared to a small plot. The scale of the plot also fits better with the larger dimensions of single-look SAR pixels, which are normally in the order of 10m x 10m. Because of the unique noise source for SAR data known as speckle, these data are often multi-looked or averaged to reduce this noise source and thus, resolutions of 30m x 30m or larger can be more common.

3.3.2 DATA COLLECTION AND BIOMASS ESTIMATION

The following steps need to be followed:

Enumeration of Trees: In each sample plot, the diameter of all trees with 10 cm and higher diameter will be measured. For more details on the enumeration please refer to FSI Manual of Field Inventory.

Estimation of Woody Biomass: The woody volume of trees for each sample plot can be estimated using volume equations developed by FSI for various species (FSI, 1996). The volume equations developed by FSI give the above ground woody volume of the tree trunk and primary and secondary branches. Woody volume, thus calculated, needs to be multiplied with the specific gravity (of the wood) for the particular tree to convert it in to woody biomass. Data of specific gravity need to be obtained from different published literature. The major source is the book Indian Woods (Vol. I to VI) published by Forest Research Institute, Dehradun.

***Estimation of AGB*:** Woody biomass thus calculated needs to be converted to Above Ground Biomass using a Biomass Expansion Factor (BEF). Alternatively, above ground biomass can be directly calculated using new biomass equations recently developed by Forest Survey of India and published in the book Carbon Stocks in India's Forests (http://fsi.nic.in/details.php?pgID=sb_15).

***Plot wise Summation*:** The biomass of each tree in a plot then should be summed up to get the plot-wise biomass, which can be multiplied by the appropriate scaling factor to convert it to per hectare biomass.

3.3.3 PREPARATION OF TRAINING & VALIDATION SET-

An important step after inventory data collection is to prepare the training and validation field inventory set. The training set will be used to train the model parameters and the validation field set will be used to test the accuracy of the generated biomass map. Selection of training and validation sets should be random to reduce the estimation bias.

3.3.4 TIME FOR FIELD DATA COLLECTION-

Appropriate time for field data collection is potentially an important criterion to achieve a better relationship between collected field parameters and any remotely sensed data. The impact is significant in the case of microwave data, as microwave interaction with forest can be very dependent on the physical properties of the target's physical structure and moisture regime which can change rapidly with time. While it is desired that the field work be carried out within the same period of remote sensing observation from the satellite or airborne platform, what is more important for the field characterization is to have some knowledge of the forest stability of the region. Hence, those forests that are not undergoing significant change or growth can be sampled less often than those locations where disturbance is most likely, or where a forest is in the first two decades of regrowth.

3.3.5 SOFTWARE TOOLS

Different software are available in public or commercial domain to process and analyze the SAR data products:

3.3.5.1 OPEN SOURCE:

SNAP (Sentinel Application Platform): The European Space Agency (ESA) is developing free open source toolboxes for the Scientific Exploitation of Earth Observation Missions (SEOM). A common architecture for all Sentinel Toolboxes is being jointly developed by Brockmann Consult, Array Systems Computing and C-S called the SNAP. The SNAP architecture is ideal for Earth Observation processing and analysis due the following technological innovations: Extensibility, Portability, Modular Rich Client Platform, Generic EO Data Abstraction, Tiled Memory Management, and a Graph Processing Framework.

The highlighted features of SNAP are a) Common architecture for all Toolboxes, b) Very fast image display and navigation even of giga-pixel images, c) Graph Processing Framework (GPF): for creating user-defined processing chains, d) Advanced layer management allows adding and manipulation of new overlays such as images of other bands, images from WMS servers or ESRI shapefiles, e) Rich region-of-interest definitions for statistics and various plots, f) Easy bitmask definition and overlay, g) Flexible band arithmetic using arbitrary mathematical expressions, h) Accurate reprojection and ortho-rectification to common map projections, i) Geo-coding and rectification using ground control points, j) Automatic SRTM DEM download and tile selection, k) Product library for scanning and cataloging large archives efficiently, l) Multithreading and Multi-core processor support and m) Integrated World Wind visualization.

DORIS (Delft Object-Oriented Radar Interferometric Software): Doris is a standalone program that can perform most common steps of the interferometric radar processing in a modular set up. Doris handles SLC (Single Look Complex) data to generate interferometric products, and can be used to geo-reference unwrapped products.

PolSARpro: The Polarimetric SAR Data Processing and Educational Tool aims to facilitate the accessibility and exploitation of multi-polarized SAR datasets including those from ESA (Envisat ASAR Alternating Polarization mode products and Sentinel-1) and Third Party Missions (ALOS-1 PALSAR, ALOS-2 PALSAR, COSMO-SkyMed, RADARSAT-2, RISAT, TerraSAR-X and Tandem-X).

A wide range of tutorials and comprehensive documentation provide a grounding in polarimetry and polarimetric interferometry necessary to stimulate research and development of scientific applications that utilize such techniques; the toolbox of processing functions offers users the capability to implement them.

TARANG (Toolbox for Advanced Radar data Analysis and Interpretation for Geosciences): Software has been developed by Space Application Centre, Ahmedabad and Indian Institute of Technology, Bombay for processing of SAR data, particularly to process the indigenous satellite RISAT-

ISCE (InSAR Scientific Computer Environment): ISCE is currently under development by NASA for the large-scale production and analysis of SAR imagery. The suite of programs is written in the Python programming language and is available under a mostly unrestrictive license from the California Institute of Technology.

ROI_PAC (Repeat Orbit Interferometry Package): ROI_PAC is a suite of legacy software written in FORTAN and PERL programming languages and can be used for the processing of Level-1 satellite data (reformatted signal data) into Single Look Complex (SLC) imagery and multi-looked ground-projected imagery. This software is available for license through the Open Channel Foundation.

3.3.5.2 PROPRIETARY DOMAIN- THE FOLLOWING SOFTWARE ARE AVAILABLE FOR SAR DATA PROCESSING IN PROPRIETARY DOMAIN:-

SARScape: SARscape is a widely used SAR data processing software in the commercial domain. The software is a modular set of functions supporting the processing of spaceborne and airborne SAR data. Its basic module includes a set of processing steps for intensity and coherence, e.g. multi-looking, co-registration, single- and multi-date speckle filtering, temporal feature extraction, geocoding, radiometric calibration and normalization, and mosaicking. This is complemented by a multi-purpose tool, which includes a wide range of functions - from image visualization, to Digital Elevation Model import and interpolation, to cartographic and geodetic transforms.

Interferometric modules support the processing of Interferometric SAR (2-pass interferometry, InSAR) and Differential Interferometric SAR (n-pass interferometry, DInSAR) data for the generation of Digital Elevation Model, Coherence, and Land Displacement maps. It also has a SAR stereo module which supports the processing of stereo SAR data for DEM generation.

Among the spaceborne sensors ERS-1 & 2, JERS-1, Radarsat 1&2, Envisat ASAR, ALOS PALSAR 1&2, SAR lupe, TerraSAR-X & TanDEM-X, COSMO-SkyMed, RISAT-1, KOMPSAT-5, Sentinel-1 and PAZ are supported, as well as a few airborne sensors. SARscape can be bought as an extension of Envi and Arc View GIS software.

Gamma: The software offered by Gamma Remote Sensing offers a similar capability as SARscape but is command line driven and is intended to be used in a Linux environment. Gamma software is capable of converting level 1 raw data from satellite sensors into ortho-rectified products that can be used within GIS and other remote sensing manipulation packages, including IDL, Envi, and PolSARPro. Because the Gamma software is command-line driven, it is amenable to large-scale processing.

Detailed information about these software products can be found on the respective websites which are given in Annex 3: Software information.

4 METHODOLOGY

Available Methods and Suitability:

Biomass estimation methods using SAR data can be categorized in two ways-

- Methods based on input parameters and
- Those based on modelling type

4.1 BASED ON INPUT PARAMETERS-

The estimation methods can be further divided into two subtypes; the methods which use backscatter values and the methods which use the interferometric products.

4.1.1 BACKSCATTER VALUES:

The most convenient and simplest method for biomass estimation is relating the backscatter values to field biomass measurements using regression analysis. This approach has been tested on different areas. The major problem in using this method is the saturation level of different wavelengths and polarizations. The saturation levels 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. Some applications have used the backscatter ratio at different wavelengths and polarizations to improve estimates under saturation conditions.

4.1.2 INTERFEROMETRIC INPUTS:

In recent years, the use of interferometric techniques for forest biomass estimation is gaining momentum. These techniques use coherence or a temporal decorrelation of data collected over a short time period by two identical instruments. This technique produces more reliable estimates than the simple backscatter approach. However the accuracy of the technique depends on site conditions, such as wind speed, moisture and temperature. Because of the time-varying nature of these error sources, algorithms such as these are considered to be still in development.

4.2 BASED ON MODELING TYPE-

Based on modelling type biomass estimation methods can be divided in different types:

4.2.1 MULTIPLE LINEAR REGRESSION MODEL

(Hussein *et. al*., 1991; LeToan *et al*., 1992; Dobson *et al*., 1992; Beaudoin *et al.,* 1994; Jha *et al*., 2006; Vyjayanthi *et al*., 2008 & 2010; Pandey *et al*., 2010; Sinha *et al.,* 2016**):**

Traditionally, biomass inversion models are developed based on the regression function of SAR backscatter at different polarizations with field-measured above ground biomass (AGB) at different locations within the vegetation cover. The sensitivity of SAR backscatter to vegetation above-ground biomass determines the accuracy and efficiency of an inversion model. SAR data at higher wavelength bands such as L- and P-band are more suitable for estimation of forest above ground biomass of higher density (up to ≈100 t/ha).

It has been observed that vegetation biomass shows the highest correlation with SAR backscatter in HV polarization, followed by HH and VV polarizations. The L-band SAR data in HH and HV polarizations from the ALOS PALSAR-1 has shown great potential in retrieving forest aboveground biomass. Recently, it was reported that ALOS PALSAR-1 backscatter ratio of HH and HV polarizations not only produces high correlation with vegetation biomass, but also helps in separating forest vegetation from non-forest regions (Shimada, *et. al*., 2014; Avtar *et. al*., 2013). Known as the multi-linear regression model (MLR), the backscatter power of HV and the HH/HV ratio is suitable for above ground forest biomass retrieval using global ALOS PALSAR-1 data. The MLR model using HV and HH/HV ratio can be expressed as:

$$\boldsymbol{Y}_{\boldsymbol{Biomass}\left(\frac{t}{ha}\right)} = \boldsymbol{A} + \boldsymbol{B} * (\boldsymbol{\sigma}^{0}\boldsymbol{HV}) + (\boldsymbol{C} * \boldsymbol{\sigma}^{0}_{\boldsymbol{HH-HV}}) \qquad \textbf{(1)}$$

where, ‘Y’ is the above-ground biomass in ton/ha, ‘A’, ‘B’ and ‘C’ are model calibration coefficients obtained from the regression of SAR backscatter with ground measured biomass.

Different forests, depending upon the relation of SAR backscatter with forest biomass at several points (plots) can produce different calibration coefficients. Figure 1 depicts MLR based methodology for forest above-ground biomass estimation.

4.2.2 VECTOR RADIATIVE TRANSFER (VRT) MODEL

(Ulaby *et al.,* 1990; Liang *et al*., 2005; Brolly and Woodhouse, 2014)**:**

The vector radiative transfer (VRT) model that describes individual components of vegetation scattering is important for understanding the influence of forest vegetation type, density and structure on the observed radar cross-section. This greatly helps in understanding the limits of biomass and retrieval of biomass beyond 100t/ha. The VRT model assumes three major scattering components contribute to the total backscatter from the forest via the trunk: trunk-ground, canopy and canopy trunk interactions. Using polarimetric SAR data these individual scattering contributions can be modeled and through this informed assumptions made in the model.

The vector form of the radiative transfer equation is most conveniently expressed using Stokes vectors. In order to fully describe scattering problem, defining the forms of the extinction and phase matrices that appear in the VRT equation are needed to solve the coupled integro-differential equations. The extinction and phase matrices are formed for an ensemble of scattering elements by a summation of extinction and Mueller matrices for different scattering element types. A number of algorithms can be used to solve the inverse problem are - the minimization algorithms, among these are lookup tables (LUT), and neural networks (NN). The use of prior information is identified as a very efficient way to solve this problem. In this context, the effect of measurement and model uncertainties on the accuracy of the solution can also be evaluated. The major variables to be retrieved are the different tree parameters. This will help not only in structurally characterizing forest vegetation, but also lead to estimation of forest biomass.

4.2.3 SEMI-EMPIRICAL MODELLING APPROACH:

Informed by model-derived functional trends of radar backscatter on biomass, remote sensing-based methods of biomass estimation sometimes are improved by empirically derived models. These models have no theoretical basis but are based on empirical data, which is produced by experiments and observations. A few semi-empirical models which are mostly used for biomass estimation are i) Water Cloud Model (WCM) [Attema & Ulaby, 1978; Leeuwen, 1991; Askne *et al.,* 1995; Arslan *et al.*, 2000; Santoro *et al*., 2002; Kumar *et al.,* 2012] ii) Extended Water Cloud Model (EWCM) [Sai *et al*., 2015] and iii) Interferometric Water Cloud Model (IWCM) [Ulaby *et al.,* 1990; Askne *et al*., 1995; Askne *et al.,* 1997; Dammert & Askne, 1998; Kumar *et al*., 2012] which can be used for retrieval of forest bio-physical parameters.

Proposed Model: For the current protocol, multiple linear regression is used, which uses and relates the backscatter and forest parameters. In addition to this, the users can also use the other models as per their expertise.

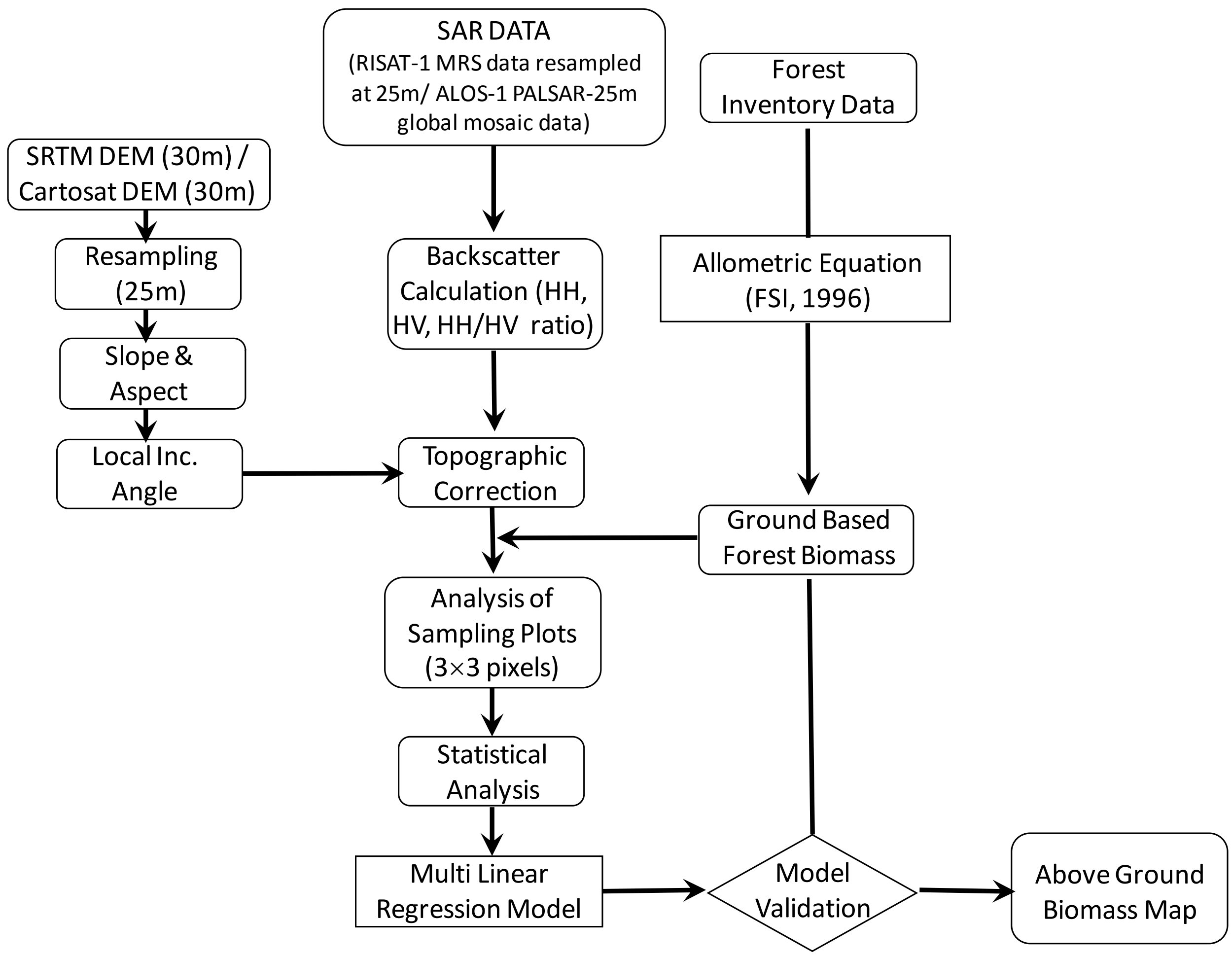

Figure 1 MLR-based methodology for forest AGB estimation.

5 DATA REQUIREMENT PLANNING

Remote sensing systems provide different information features, such as spectral observations over one or more areas, radiometric, spatial, and temporal resolutions, and in polarization and incidence angle. Recognizing and understanding the strengths and weaknesses of different types of sensor data are essential for selecting suitable sensor data for AGB estimation in a specific study. In rugged or mountainous regions, topographic factors such as slope and aspect can considerably affect vegetation reflectance, resulting in spurious relationships between AGB and backscattering values. The necessary steps to preprocess the data need to be in place. In addition, planning is required to develop a suitable ancillary database and data paths where ground validation observations and other data can be incorporated into the processing stream.

5.1 SAR DATA PRE-PROCESSING

Data acquired by airborne and spaceborne SAR sensors contain uncertainties due to variations in altitude, velocity of the sensor platform, relief displacement and non-linearities. The datasets need to be properly calibrated and pre-processed so that they can be used for desired applications. Pre-processing of SAR data includes radiometric calibration, speckle suppression and SAR image geocoding. In order to derive the Stokes vectors, this complex data needs to be used. This calls for processing the complex data, analyzing it and later on, conversion of the data from slant range to ground range. Next, the steps required to analyze the ground range data mentioned previously need to be taken. Pre-processing and backscatter image generation from datasets is carried out following the steps mentioned below. The preprocessing of SAR data for Level 1 and Level 2 products is shown separately in Table No. 2:

Table 2 Pre-processing and backscatter generation from SAR data.

Steps	Level-1 Product (Complex data)	Level-2 Product (Amplitude data)
1	Obtain the Single Look Complex (SLC) data	Obtain the amplitude data
2	Convert to amplitude data in slant range	Apply filter to remove speckle
3	Multi-looking	Convert data into backscatter image
4	Application of special filters for speckle	Geocode and co-register data
5	Derivation of Stokes vectors and decomposition	Local incidence angle correction

The following two steps of *slant to ground range conversion* and *generation of amplitude images* is exclusively for complex data.

5.1.1 SLANT TO GROUND RANGE CONVERSION AND MULTI-LOOKING

The effect of slant range distortion is removed by the conversion of slant range image to ground range, where ground range is the horizontal distance along the ground for each corresponding point measured in slant-range. This conversion includes the re-projection of Single Look Complex (SLC) data from slant-range to a flat ellipsoid surface or a digital elevation map (DEM) of the region itself. Multi-look processing refers to the combining of single-look amplitude pixels into a lower resolution average pixel that has reduced speckle noise characteristics. Multi-look intensity image is created with number of looks in azimuth and range. The number of looks changes from sensor to sensor and depends on different pixel sampling in different incidence angles.

5.1.2 GENERATION OF AMPLITUDE IMAGES

Normally, the Level 2 product obtained as a data product contains amplitude data. This can be subjected to speckle filtering directly followed by conversion to a backscatter image. However, in the case of complex data the data processing will be initially different. The complex data of SAR images in SLC domain contain two pairs of channels; one real and one imaginary channel. Generally, the first channel of each pair is taken as "I" (representing In-phase or the cosine of real component), and the second as the "Q" (representing quadrature, sine of imaginary component). To obtain the amplitude image, the two channels are processed as following to get the amplitude image:

$$\boldsymbol{A} = \sqrt{\boldsymbol{I}^2 + \boldsymbol{Q}^2} \quad \textbf{(2)}$$

5.1.3 SPECKLE REDUCTION

Speckle noise is a phenomenon of complex-valued data where information is obtained from the magnitude of the complex numbers. Speckle is caused by the high coherence of the illumination source that causes phase interference from random scattering points. Generally speaking, for SAR backscatter images, it is the unwanted and dominating noise that degrades the desired SAR image products. This is the case for much of SAR data analysis and is what gives rise to the grainy appearance of these images if they have not been multi-looked or gone through speckle filtering. The reduction of speckle in SAR imagery is an important part of SAR data analysis. This speckle reduction can be performed at various stages of the processing depending on the application. Ideally, speckle reduction should be performed before geo-coding, which gives improved object identification for Ground Control Point (GCP) measurements. However, if it is done later in the processing chain, it is acceptable as well.

5.1.4 LINEAR BACKSCATTER IMAGE GENERATION FROM POWER IMAGE

The conversion of power image represented by digital numbers into a linear backscatter image is done using sensor specific equations. Most software has an automatic in-built module for different sensors which they support. Alternative methods of calibration can be applied by quantitatively comparing backscatter imagery with known targets, either spatially distributed or confined to a single resolution element (known as a point target).

5.1.5 LINEAR TO DECIBEL CONVERSION-

The backscatter cross-section (σ^0), which is represented by the ratio of power levels per unit area, is usually expressed on a logarithmic scale i.e. decibel (dB) scale. The conversion of backscatter cross-section from linear to decibel scale is done using Eq. 3;

$$\sigma_{i,j}^{0}(dB) = 10 * log_{10}\, \sigma_{i,j}^{0}(linear) \quad (3)$$

5.1.6 GEOCODING OF SAR DATA

The speckle suppressed and backscatter image generated from SAR datasets should be geocoded by affine transformation with a reference geo-rectified image. This would render the current SAR image into appropriate projection system with coordinates.

5.1.7 LOCAL INCIDENCE ANGLE EFFECT CORRECTION AND ILLUMINATED AREA EFFECT-

Forest classification and biomass estimation using SAR data are complicated in the presence of a strong topographic gradient. Undulating terrain changes and the local radar incidence angle causes several effects, such as foreshortening, overlay, and shadows on radar image data. Terrain-effect correction techniques are designed to reduce effects of incidence angle and illuminated target area. Figure 2 explains the method of terrain correction. If an external DEM is used for geocoding, the same DEM can be used for local incidence angle correction.

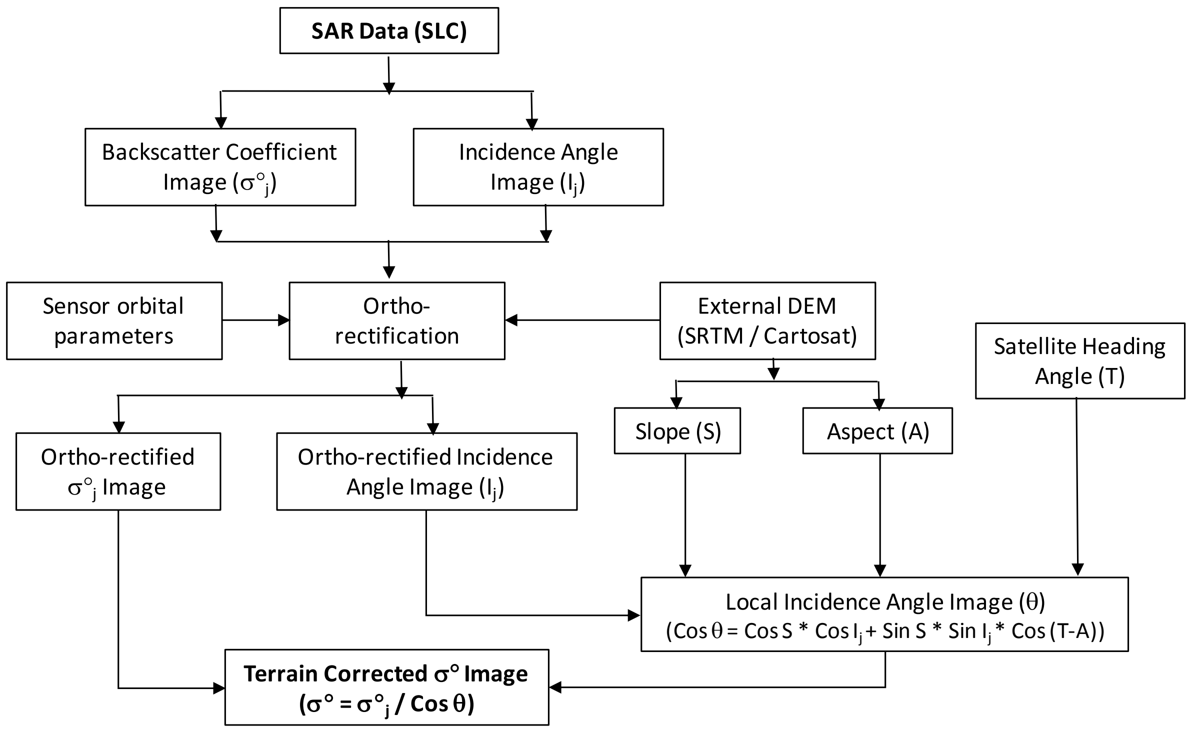

Figure 2 Methodology for topographic correction of SAR data.

6 PROTOCOL-BASED DETAILED TECHNIQUES

6.1 PROTOCOL 1: MAPPING OF FOREST EXTENT AND CHANGE USING SAR DATA

6.1.1 OBJECTIVE:

The objective of this protocol is to learn the step-by-step process to map the forest extent and change using C-& L-band SAR data.

Inputs:

- C- and L-band SAR data
- Ground truth information
- Annual Forest &Non-Forest (FNF) products
- Any reference/ancillary data for validation

Outputs:

- Maps of forest extent
- Annual maps of forest change with time series of imagery

6.1.2 TECHNIQUE:

Approach:

- Preprocessing and conversion of SAR data into backscatter imagery.
- The geocoded image/multi temporal images (as per need), is then used for the extraction of forest area, by subjecting the image(s) to suitable classification.
- Extraction and comparison of forest area with a previously validated data set to detect the change.
- Creation of Forest – Non-Forest (FNF) two class image.
- Carrying out change detection as simple difference image or as an output of appropriately threshold co-variance image.

6.1.3 METHODOLOGY:

- Data download to preferred location such as a local drive or storage area.
- Un-compress (unzip/untar) SAR data using preferred tool such as winzip or 7-zip.

- Preprocessing of SAR data.
- Application of a supervised classification technique e.g., knowledge based decision rules on the geo-rectified SAR backscatter data to extract the forested areas from non-forested areas.
- For complex data, the decomposition of data can be carried out using Freeman-Durden or Pauli technique. This image is then used for extraction of forest and non-forest classes.
- Two main categories exists, FNF: data has 2 values: one for non-forest and another for forest.
- On the forest area obtained, a suitable validation is to be carried out by comparing a few training sites data with the classified output.
- A forest mask of the current year should be accepted only after proper validation.
- The change detection is to be carried out with the help of a reference image containing forest mask of a previous year, using appropriate GIS or Image Processing software
- The change matrix is then generated and afforested areas can be rendered
- Cross validate the change matrix against the reference data.

6.2 PROTOCOL 2: ACCURACY ASSESSMENT OF A FOREST EXTENT/CHANGE MAP

Thematic maps derived from remote sensing data can contain various errors. Care should be taken to identify the sources of the errors, minimize them, and perform an accuracy assessment. After this process, the remaining uncertainties should be quantified and metadata should be created to describe the processing and origin of the data.

6.2.1 OBJECTIVE

The objective of this protocol is to assess the accuracy of the thematic map derived from remotely sensed imagery.

Inputs:

- Classified thematic output
- Reference Data

Outputs:

- Accuracy percent of the classified output

6.2.2 APPROACH:

The approach is to assess the accuracy of the generated thematic output against the reference data using statistical tools.

6.2.3 METHODOLOGY:

- **Selecting the correct reference source:** The reference source as per the Protocol should be a well authenticated and published source of information. If not, the reference should be generated for a previous year's data set, well calibrated and verified. Accurate GPS location from ground data is an important component for putting ground validation data in the proper context.
- **Determining the size of reference plots**: It is useful to match the spatial scale of reference plots and remotely sensed data. That is, GPS locations of ground plots that are 5 m x 5 m may not be useful if microwave data cells are of a coarser resolution. It is generally desired to have at least some ground validation data at the same resolution of the imaging instrument and/or to characterize the variation of the ground validation measures over larger spatial scales.
- **Take into account spatial frequencies of image:** This means to take note of the natural dimensions of the region being imaged. For instance, tree canopies tend to extend from 5-8 m, and homogeneous regions of tree species or structural compositions can extend from 10 m regions to one of many hectares.

In order to determine the position and number of samples for ground validation measures:

- The landscape should be adequately sampled.
    - An appropriate sampling scheme should be chosen (Random, stratified random, systematic, etc.).
    - The number of reference plots should be decided as per the application and the sampling fraction should be statistically determined for the area. The more reference plots, the better accuracy; normally 20% area can be used for drawing samples. However, the number should be statistically derived for each forested area for better representation
    - Landscapes often change rapidly, especially during the monsoons. Therefore it is best to collect the ground reference as close to the date of remote sensing data acquisition as possible.
- **Accuracy Assessment:** After choosing reference source, plot size, and locations
    - Determine class types from reference source.
    - Determine class type claimed by classified map.
    - Finally compare them through generation of error matrixes.
- Statistical tests based on Kappa statistics should be used to test the precision and significance of the results.
    - Kappa>0.80 represent strong agreement and good accuracy. 0.40-0.80 is middle, <0.40 is poor.

6.3 PROTOCOL 3 MAPPING OF ABOVE GROUND BIOMASS WITH SAR

6.3.1 OBJECTIVE: THE OBJECTIVE OF THIS PROTOCOL IS TO MAP THE ABOVEGROUND BIOMASS USING SAR DATA

Inputs:

- SAR Satellite data
- Field sample data on above ground biomass (AGB)
- Forest Mask
- Allometric equations

Outputs:

- Biomass map of the area under study at the SAR sensor resolution

6.3.2 APPROACH:

The approach is to use the multiple linear regression method to develop coefficients for extrapolating plots or predicting forest characteristics across un-sampled locations using the comprehensive remote sensing data.

6.3.3 METHODOLOGY:

1. Obtain a geo referenced field data set as a dependent variable.
2. Generate a set of statistical measures of the SAR data such as average and standard deviation, for band ratios in different polarizations as an independent variable.
3. Extract the values of the generated statistical measures at the field sample locations using standard GIS packages.
4. Perform a linear regression between individual independent variables with field sample biomass. In case of field data unavailability, allometric equations should be used.
5. Compare Pearson's Correlation, SE and Probability of each independent variable to choose the best independent variables for multiple regression.
6. Develop a multiple regression between the chosen independent variables with the field sample locations and obtain the coefficients for extrapolation.
7. Use the remote sensing data and the generated coefficients to get the above-ground biomass map of the area.

6.4 PROTOCOL 4-ACCURACY ASSESSMENT OF ABOVE GROUND BIOMASS MAP

6.4.1 OBJECTIVES:

To assess the accuracy of thematic maps

Inputs:

- Above Ground biomass Map
- Reference Data

Outputs:

- Accuracy percent of the classified output

6.4.2 APPROACH:

The approach is to assess the accuracy of the aboveground biomass map output against the reference data using observed vs. predicted analysis.

6.4.3 METHODOLOGY

As in protocol 3 until determining position and number of samples

Accuracy Assessment

- Accuracy is assessed with generation of scatter plots of observed vs predicted values of Above Ground Biomass (AGB). Estimation of errors are best done by measuring the Root Mean Square Error (RMSE) between the model fit and ground-measured values of AGB. Values can be 30-45 t/ha and vary dependent on the type and structure of the forest.

Uncertainty Analysis

- Radar remote sensing-based AGB estimation is a complex procedure in which many factors, such as atmospheric conditions, mixed pixels, data saturation, complex biophysical environments, insufficient sample data, extracted remote sensing variables, and the selected algorithms, may interactively affect AGB estimation performance. To identify the major uncertainties during the process of developing the AGB estimation models is critical for improving the AGB estimation. Some potential solutions include (1) accurate radiometric calibration to reduce the impacts of uncertainty; (2) selection of suitable vegetation indices and image textures to reduce the impacts of environmental conditions and canopy shadows (3) the integration of optical and radar data to reduce the data saturation; and (4) the integration of multi-source data. One should try to minimize the potential factors causing uncertainty to the greatest extent possible.

6.4.4 LIMITATIONS

AGB estimation using SAR data may have certain limitations:

Data Limitations- Data limitations can be of two types, a) Spatial and radiometric resolution, and b) data availability. The limitations due to spatial and radiometric resolutions are inherent and they affect the AGB estimation significantly. Sensors having coarser spatial resolution mainly capture canopy information instead of individual tree information. Likewise the suitable data availability itself is a data limitation. Synergistic use of multi frequency radar and optical data may improve the mixed pixels and data saturation problem. While considering this one should also take into account the economic parameter such as increased time and labor cost involved.

Software Limitations- The software which will be used for data processing and interpretation may also have certain limitations which contribute to the error.

Model Limitations- Transferability of a developed model at a specific model to any other study site is a big limitation particularly in SAR data as SAR backscatter can change significantly with even small changes in terrain characteristics. In addition the disparity between remote sensing acquisition date and field data collection and the size of sample plot with the spatial resolution of remotely sensed data can severely affect the success of model transferability.

Scope Limitation- It is not feasible to use all kinds of data products available, along with the available models. The choice of model should be optimum as per the time and labor cost incurred to generate an output at desired accuracy.

7 CAPACITY BUILDING

The processing and analysis of SAR data will be a tedious job at first, so proper capacity building will be required to fully institutionalize the SAR techniques. Adoption of the multi-pronged strategy of technology use through sensitization workshops, hands-on training, awareness workshops and national level seminars will be required.

8 REFERENCES:

Arslan, A.N., Koskined, J., Pulliainen, J. & Hallikainen, M. (2000). "A semi empirical backscattering model of forest canopy covered by snow using SAR data", *IEEE Transactions on Geoscience and Remote Sensing*, 1904-1906.

Askne, J., Dammert, P.B.G., Fransson, P., Israelsson, H. & Ulander, L.M.H. (1995). "Retrieval of forest parameters using intensity and repeat-pass interferometric SAR information", *Proceedings of Retrieval of Bio- and Geophysical parameters from SAR data for Land Applications*, Toulouse, 10-13 October, 119-129.

Askne, J., Dammert, P.B.G., Ulander, L.M.H. & Smith, G. (1997). "C-Band repeat-pass interferometric SAR observations of the forest", *IEEE Transactions on Geoscience and Remote Sensing*, 35(1), 25-35.

Attema, E.P.W. & Ulaby, F.T. (1978). "Vegetation modelled as a water cloud", *Radio Science*, 13(2), 357–364.

Avtar, R., Suzuki R., Takeuchi W. & Sawada H. (2013). "PALSAR 50 m Mosaic Data Based National Level Biomass Estimation in Cambodia for Implementation of REDD+ Mechanism", *PLoS ONE* 8(10): e74807. doi:10.1371/journal.pone.0074807.

Beaudoin, A., LeToan, T., Goze, S., Nezry, E., Lopes, A., Mougin, E., Hsu, C.C., Han, H.C., Kong, J.A. & Shin, R.T. (1994). "Retrieval of forest biomass from SAR data', *International Journal of Remote Sensing*, 15(14), 2777-2796.

Brolly, M. & Woodhouse, I.H. (2014). "*Long Wavelength SAR Backscatter Modelling Trends as a Consequence of the Emergent Properties of Tree Populations"* *Remote Sensing*, 6, 7081-1709. ISSN 2072-4292.

Champion, H.G. & Seth, S.K. (1968). *A Revised Survey of Forest Types of India*, Government of India Publications, New Delhi.

Dammert, P.B.G.; & Askne, J. (1998). "Interferometric tree height observations in boreal forests with SAR interferometry", *IEEE Transactions on Geoscience and Remote Sensing*, 1363-1336.

Dobson, M., Ulaby, F. T., Toan, T. L., Beaudoin, A., Kasischke, E., & Christensen, N.L. (1992). "Dependence of radar backscatter on coniferous forest biomass", *IEEE Transactions Geoscience and Remote Sensing* 30, 412–415.

F.S.I. (1996). *Volume Equations for Forests of India, Nepal and Bhutan*. Forest Survey of India, Ministry of Environment and Forests, Govt. of India, Dehradun.

Ghasemi, N., Mahmod R.S., Mohammadzadeh A., (2011), "A review on biomass estimation methods using synthetic aperture radar data", *International Journal of Geomatics and Geosciences*, 1(4), 2011, 776-788.

Hoekman D.H & Quinones M.J (1997). "Land cover type and forest biomass assessment in the Colombian Amazon", *In: Geoscience and Remote Sensing, 1997. IGARSS '97*, Remote sensing—a scientific vision for sustainable development. 1997 IEEE International. IEEE IGARSS 4:1728–1730.

Hussin, Y. A., Reich, R. M., & Hoffer, R. M. (1991), Estimating Slash Pine Biomass Using Radar Backscatter, *IEEE Transactions on Geoscience and Remote Sensing*, 29, 427-431.

Imhoff, M. L. (1995). “Radar backscatter and biomass saturation: ramifications for global biomass inventory”, *IEEE Transactions on Geoscience and Remote Sensing*, 511-518.

Jha, C.S., Rangaswamy, M. & Murthy, M.S.R. (2006). “Estimation of forest biomass using Envisat-ASAR data”, *Proceedings of SPIE*, 6410, 641002.

Kurvonen, L., Pulliainen, J. & Hallikainen, M. (1999). "Retrieval of biomass in boreal forests from multitemporal ERS-1 and JERS-1 SAR images", *IEEE Transactions on Geoscience and Remote Sensing,* 37(1), 198-205.

Le Toan, T., Beaudoin, A., Riom, J., & Guyon. D. (1992). “Relating forest biomass to SAR data”, *IEEE Transactions Geoscience and Remote Sensing*, 30, 403-411.

Leckie, D. G., & Ranson, K.J. (1998). “Forestry applications using imaging radar. *Principles and Applications of Imaging Radar*”, Vol. 2, 3d ed., *Manual of Remote Sensing*, F. M. Henderson and A. J. Lewis, Eds., John Wiley & Sons, 435–509.

Leeuwen, H.J.C.V. (1991). “Multi frequency and multitemporal analysis of scatterometer radar data with respect to agriculture crops using the Cloud Model”, *IEEE*, 1893-1897.

Liang. P., Pierce, L.E. & Moghaddam, M. (2005). “Radiative Transfer Model for Microwave Bistatic Scattering from ForestCanopies*”, IEEE Transactions on Geoscience and Remote Sensing 43(11), 2470 - 2483 · December 2005.*

Lucas R.M., Cronin N., Lee, A., Moghaddam, M., Witte, C. & Phil T. (2006)."Empirical relationships between AIRSAR backscatter and LiDAR-derived forest biomass, Queensland, Australia," *Remote Sensing of Environment*, 100(3), 407-425.

Lucas, R. M., Mitchell, A. L., Rosenqvist, A., Proisy, C., Melius, A., & Ticehurst, C. (2007). “The potential of L-band SAR for quantifying mangrove characteristics and change: case studies from the tropics”. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 17,245264.doi:10.1002/AQC.833.

Luckman, A., Baker, J., Kuplich, T.M., Yanasse, F. & Alejandro C. F. (1997). "A study of the relationship between radar backscatter and regenerating tropical forest biomass for spaceborne SAR instruments”, *“Remote Sensing of Environment,* 60(1), 1-13.

Ranson, K.J. & Sun, G. (1994). Mapping biomass of a northern forest using multi-frequency SAR data”, IEEE *Transactions on Geosciences and Remote Sensing*, 32(2), 388-395.

Ranson, K.J., Sun, G., Weishampel, J.F. & Knox, R.G. (1997), “Forest biomass from combined ecosystem and radar backscatter modeling”, *Remote Sensing of Environment*, 59, 118–133.

Kumar, S., Pandey, U., Kushwaha, S.P.S., Chatterjee, R.S. & Bijker, W. (2012). “Aboveground biomass estimation of tropical forest from Envisat advanced synthetic aperture radar data using modeling approach", *Journal of Applied Remote Sensing*, 6(1), 063588, Oct. 2012, doi: 10.1117/1.JRS.6.063588.

Sader, S. A. (1987). “Forest biomass, canopy structure, and species composition relationships with multi-polarization L-band synthetic aperture radar data”, *Photogrammetric Engineering and Remote Sensing*, 53(2), 193− 202.

Sai P. B., Kumar, S., Kushwaha, S.P.S. & Bijker, W. (2015). “Polarametric scattering model for estimation of above ground biomass of multilayer vegetation using ALOS-PALSAR qual-pol data”, *Physics and Chemistry of Earth*, 83-84, 187-195.

Santoro, M., Askne, J., Smith, G. & Fransson, J.E.S. (2002). Stem volume retrieval in boreal forests from ERS-1/2 interferometry, *Remote Sensing of Environment*, 81(1), 19– 35.

Shimada M., Itoh, T., Motooka, T., Watanabe, M., Shiraishi, T., Thapa R. & Lucas, R. (2014). "New global forest/non-forest maps from ALOS PALSAR data (2007–2010)", *Remote Sensing of Environment*, 155, 13-31. December 2014.

Sinha S., Jeganathan, C., Sharma, L.K., Nathawat, M.S., Das, A.K. & Mohan, S. (2016). "Developing synergy regression models with space-borne ALOS PALSAR and Landsat TM sensors for retrieving tropical forest biomass" *Journal Earth Systematic Science*., DOI 10.1007/s12040-016-0692-z, 125, No. 4, June 2016, 725–735.

Solberg, S., Astrup, R., Gobakken, T., Næsset, E. & Weydahl, D.J. (2010). "Estimating spruce and pine biomass with interferometric X-band SAR," *Remote Sensing of Environment* 114(10), 2353-2360.

Sun, G & Ranson, K. J. (1998). "Radar modelling of forest spatial patterns", *International Journal of Remote Sensing*, 19, 1769-1791.

Sun, G., Ranson, K.J. & Kharuk, V.I (2002). "Radiometric slope correction for forest biomass estimation from SAR data in the Western Sayani Mountains, Siberia", *Remote Sensing of Environment*, 79(2), pp.279-287.

Ulaby, F. T., Sarabandi, K., McDonald, K., Whitt, M. & Dobson, M. (1990). "Michigan microwave canopy scattering model", *International Journal of Remote Sensing* 11, pp. 1223– 1253.

Pandey, U., Kushwaha, S.P.S., Kachhwaha, T.S., Kunwar, P. & Dadhwal. V.K. (2010). "Potential of Envisat ASAR data for woody biomass assessment," International Society for Tropical Ecology*, Tropical Ecology*, 51(1), 117-124.

Vyjayanthi, N., Jha, C. S. & Madugundu, R. (2010). "Estimation of above ground biomass in Indian tropical forested area using multi-frequency DLR-ESAR data", *International Journal of Geomatics and Geosciences*" Volume 1, No 2, 2010,pp167-178.

Vyjayanthi, N., Jha, C. S., Murthy, M.S.R., Yadav D.K. & Singh. L. (2008). "*Forest biomass and structure analysis from multi-frequency and multi-polarization SAR data*", Technical Document RISAT-JEP-Microwave Program, FED, LRG, RS&GIS AA, NRSC, Hyderabad, 1-154.

Webliography:

http://fsi.nic.in/documents/manualforest_inventory_2.pdf

https://earth.esa.int/handbooks/asar/CNTR5-2.html

http://fsi.nic.in/details.php?pgID=sb_15

9 ANNEX 1: GLOSSARY

Table 3 Glossary of Terms

Amplitude	Measure of the strength of a signal, and in particular the strength or "height" of an electromagnetic wave (units of voltage).The amplitude may imply a complex signal, including both magnitude and the phase.
Attenuation	Decrease in the strength of a signal. Common causes of attenuation of an electromagnetic wave include losses through absorption and by volume scattering in a medium as a wave passes through.
Azimuth	The relative along-track position of an object within the field of view of an antenna following the moving radar's line of flight. The term is commonly used to indicate linear distance or image scale in the along-track direction.
Backscatter	The (microwave) signal reflected by elements of an illuminated scene back in the direction of the radar. It is so named to make clear the difference between energy scattered in arbitrary directions, and that which returns to the radar and thus may be received and recorded by the sensor.
Backscattering Coefficient (σ 0)	It is the ratio of the energy received by the sensor to what it would have received if the surface scattered the incident energy on it in an isotropic fashion. The σ_0 often exhibits a large dynamic range, so to compress its range it is usually expressed in decibels (dB). σ 0 (dB) = 10 log σ 0 (m^2 /m^2)
Carbon Stock	The quantity of carbon contained in a "pool", meaning a reservoir or a system which has the capacity to accumulate or release carbon. (FAO Forestry).
Complex (Number)	For radar systems, this implies that the representation of a signal or data file needs both magnitude and phase measures. In the digital SAR context, a complex number is often represented by an equivalent pair of numbers, the in-phase (I) component and the quadrature (Q) component.
Deforestation	The long-term or permanent removal of forest cover and conversion to a non-forested land use. (IPCC, LULUCF, 2.2.3.3. Deforestation)
Decibel (dB)	Measurement of signal strength, properly applied to a ratio of powers: a signal power P compared, by ratioing, to a reference power Pref. The formal definition of the power ratio in the decibel scale is PdB = 10 log10 (P / Pref). For example, the power ratio of 1/2 corresponds to "-3 dB", derived from log10 (0.5) = -0.3010.
Degree of Polarization	Ratio of the power in the polarized part of an electromagnetic wave to the total power; P.

Dielectric	Material which has neither "perfect" conductivity nor is perfectly "transparent" to electromagnetic radiation. The electrical properties of all intermediate materials, such as ice, natural foliage, or rocks, may be described by two quantities: relative dielectric constant and loss tangent. Reflectivity and penetration of microwave into a material are determined by these two quantities.
Dielectric Constant	Fundamental (complex) parameter, also known as the complex permittivity that describes the electrical properties of a lossy medium, e.g., a target which has attenuation. By convention, the relative dielectric constant of a given material is used, defined as the (absolute) dielectric constant divided by the dielectric constant of "free space".
Filtering	In order to remove the speckles and make the image look friendlier for analysis, a mathematical algorithm is used to filter out the unwanted information. The filter used depends on the user and the nature of the study involved.
Forest	As a land cover type a forest is an ecosystem characterized by more or less dense and extensive tree cover; with a minimum area of 0.05 ha, a minimum tree crown cover of 15% (or equivalent stocking) and a minimum tree height of 2 meters (India's UNFCCC CDM A/R definition).
Geographic Coordinates	Coordinate system that are most often associated with maps. Imagery presented in geographic coordinates are in terms of latitude/longitude, angular coordinates, or in spatial coordinates such as meters, made by a planar approximation to the surface of a sphere, as in Universal Transverse Mercator (UTM) coordinates.
GIS	Geographic Information System (GIS) is a system designed to capture, store, manipulate, analyze, manage, and present all types of spatial or geographical data.
GPS	The Global Positioning System (GPS) is a space- based navigation system that provides location and time information anywhere on or near the Earth.
Ground Range	Range direction of a side-looking radar image as projected onto the nominally horizontal reference plane, similar to the spatial display of conventional maps Ground range projection requires a geometric transformation from slant range to ground range, leading to relief or elevation displacement, foreshortening, and layover unless terrain elevation information is used.
Incident Angle	Angle between the line of sight from the radar to an element of an imaged scene, and a vertical direction characteristic of the scene. Smaller incident angle refers to viewing line of sight being closer to the (local) vertical, hence "steeper".
Loss Tangent	Ratio of the imaginary part of the dielectric constant to the real part, written as tan ($\tan\delta = \varepsilon''/\varepsilon'$). Low loss materials satisfy $\tan 2\delta \ll 1$.
Map	A diagrammatic representation of an area of land or sea showing physical features, forest, cities, roads, etc.

Polarization	Orientation of the electric (E) vector in an electromagnetic wave, frequently "horizontal" (H) or "vertical" (V) in conventional imaging radar systems. Polarization is established by the antenna, which may be adjusted to be different on transmit and on receive. Reflectivity of microwaves from an object depends on the relationship between the polarization state and the geometric structure of the object.
Range	Line of sight distance between the radar and each illuminated scatterer. In SAR, the term is also applied to the dimension of an image away from the line of flight of the radar.
SAR	Synthetic Aperture Radar is a coherent mostly airborne or space borne side looking radar system which utilizes the flight path of the platform to simulate an extremely large antenna or aperture electronically, and that generates high-resolution remote sensing imagery.
Scattering Matrix	Array of four complex numbers that describes the transformation of the polarization of a wave incident upon a reflective medium to the polarization of the backscattered wave. It is the polarization vector counterpart to the coefficient of reflectivity.
Slant Range	Image direction as measured along the sequence of line-of-sight rays from the radar to each and every reflecting point in the illuminated scene. Since a SAR looks down and to the side, the slant range to ground range transformation has an inherent geometric scale which changes across the image swath.
SLC	Single Look Complex Image. Associated with the highest resolution imagery available from SAR data, stored in complex number form. SLC's are typically stored in slant-range (not map or ground-projected) coordinates.
Volume Scattering	Multiple scattering events occurring inside a medium, generally neither dense nor having a large loss tangent, such as the canopy of a forest. The relative importance of volume scattering is governed by the dielectric properties of the material.

10 ANNEX 2: SENSORS: PAST, PRESENT & FUTURE

Table 4 Table of Earth Observation Sensors

Satellite/ Sensors	Country	Period of Operation	Band	Wave-length (cm)	Polarizations	Spatial Resolution (m)	Orbital Repeat (days)
ERS-1	Europe	1991-2000	C	5.6	Single (VV)	26	3-176
JERS-1	Japan	1992-1998	L	23.5	Single (HH)	18	44
ERS-2	Europe	1995-2011	C	5.6	Single (VV)	26	35
RADARSAT-1	Canada	1995-2013	C	5.6	Single, Dual	8-100	3-24
ENVISAT/ASAR	Europe	2002-2012	C	5.6	Single, Dual	30-1000	35
ALOS/PALSAR	Japan	2006-2011	L	23.6	Single, Dual, Quad	10-100	46
RADARSAT-2	Canada	2007-	C	5.6	Single, Dual, Quad	3-100	24
TerraSAR-X TanDEM-X	Germany	2007- 2010-	X	3.1	Single, Dual, Interferometric	1-16	11
COSMO SkyMed (4 Satellites)	Italy	2007, 2008, 2010-	X	3.1	Single, Dual	1-100	16
RISAT-1	India	2012-	C	5.6	Single, Dual, Quad	1-50	25
ALOS-2/PALSAR	Japan	2014-	L	23.8	Single, Dual, Quad	1-100	14
Sentinel-1A Sentinel-1B	Europe	2014- 2016-	C	5.6	Single, Dual, Quad	9-15	12
SAOCOM-1A SAOCOM-1B	Argentina Italy	Scheduled 2016, 2017	L	23.5	Single, Dual, Quad	10-100	16

Satellite/ Sensors	Country	Period of Operation	Band	Wave-length (cm)	Polarizations	Spatial Resolution (m)	Orbital Repeat (days)
NovaSAR	U.K.	Scheduled 2016	S	9.4	Single, Dual, Triple, Quad	6-30	14
RADARSAT Constellation 1/2/3	Canada	Scheduled 2018	C	5.6	Single, Dual, Quad	1-100	12
BIOMASS	Europe	Scheduled 2020	P	69	Quad	50	Varying
NISAR	US/India	Scheduled 2021	L, S		Single, Dual, Compact Pol, Quad		12

11 ANNEX 3: SOFTWARE INFORMATION

- http://step.esa.int/main/toolboxes/snap/
- http://doris.tudelft.nl/
- https://earth.esa.int/web/polsarpro/home
- http://www.sarmap.ch/page.php?page=sarscape
- http://www.gamma-rs.ch

12 ANNEX 4: OPTIMUM HARDWARE REQUIREMENT

- 8 GB of RAM. 16 GB or more is desired.
- A PC running Linux or Windows operating system. Multi-core processors, preferably Xeon based 10 core processor of E5 2600 family on Intel C612 chipset can be used to improve computational throughput.
- 1-2 TB or more SATA II Hard Disk Drive.

U.S. Agency for International Development
1300 Pennsylvania Avenue, NW
Washington, DC 20523
Tel: (202) 712-0000
Fax: (202) 216-3524
www.usaid.gov