Forest Management – Mapping, monitoring, and inference of biophysical parameters using ALOS PALSAR and Cosmo-SkyMed data

Francesco Holecz[1], Massimo Barbieri[1], Charles Eyre[2], and Nico Mönnig[3]

[1] sarmap – Cascine di Barico, 6989 Purasca, Switzerland, fholecz@sarmap.ch
[2] Eyre Consulting – Andover, Hampshire SP11 7QL, United Kingdom
[3] York Timbers (Pty) Ltd – Sabie, South Africa

***Abstract* — Current convention in establishing compartment level timber volume utilises a system of sample plot measurements of tree height, diameter at breast height, basal area, and other contextual information. Applying standard allometric equations these sample plot values are extrapolated to produce estimates of timber volume per compartment. The cost of conventional compartment enumeration limits the frequency and intensity of plantation wide estimates of timber volume and therefore the potential to improve accuracy at plantation level. A customized Earth Observation service aiming at the provision of transparent, comprehensive, and cost effective information has been designed and implemented by integrating, in forestry models, specific Earth Observation products derived (in primis) and inferred (exclusively) from high to very high resolution (15m to 3m) spaceborne Synthetic Aperture Radar (SAR) data. In essence, it consists of two main components:**

- **Generation of thematic products (maps and change maps;**
- **Inference of key biophysical forest parameters.**

In a series of trials in the Mpumalanga province of South Africa, SAR data were acquired and the service has been tested over a range of operational conditions to confirm its robustness for application in typical plantations. Overall, the proposed methodology clearly demonstrated that ALOS PALSAR combined with Cosmo-SkyMed data are a viable solution in reducing costs without compromising on data quality, while increasing data transparency with potential improvements in efficiency in forest management.

***Index Terms* — K&C Initiative, ALOS PALSAR, Cosmo-SkyMed, forest management, thematic products, biophysical forest parameters.**

I. INTRODUCTION

Optimized forest management requires a superior understanding and knowledge of forest science and extensive optimization and decision support systems. However, knowledge and systems, without relevant and accurate input data will not provide optimized solutions and may even lead to inferior decisions being made.

Data collection is expensive and the perceived benefits of good data have to be weighed against the cost. In order to mitigate this dilemma, whilst improving data quality and quantity, conventional data collection methods have to be executed more cost effectively, or one has to find alternative, more efficient ways of obtaining data. Earth Observation (EO) – conventional aerial photography in primis – is being increasingly used in forest management with many positive benefits, but to date little success has been shown particularly in obtaining biophysical forest parameters from EO sources suitable for supplementing more conventional field-based measurements.

The proposed service, which is primarily based on the integration of ALOS PALSAR and Cosmo-SkyMed data, consists of two main components:

- Generation of thematic maps (maps and change maps), in particular forest area, burnt areas and re-growth, status of fire breaks, clear cut and re-growth, forest homogeneity, and land cover in non forest areas;
- Inference of biophysical forest parameters such as tree height (TH), diameter-at-breast height (DBH), basal area (BA), and timber volume (TV).

Current practices for forest inventory in South Africa and many other parts of the world is based on a systematic sampling process using circular plots. These plots have a radius of 12.5 meter, giving a plot area of 500 sqm. Normal practice is for one sample plot per hectare, leading to the prerequisite 5% sampling intensity. A minimum of 5 plots per compartment is required. Occasionally the sampling strategy and/or intensity may be changed to meet particular requirements. It is worth mentioning that, generally, due to the time intensiveness and high cost of field enumerations, the sampling percentage is kept low, but this leads to the possibility of under-sampling some forest stands. Plot radii are measured electronically with a hypsometer. Within the

Paper presented to the JAXA Kyoto and Carbon Initiative, January 2010, Tokyo

plots all tree diameters (DBH) are measured with manual callipers, and a sub-set of DBH/TH pairs (two per plot with a minimum of 30 pairs) is collected. Tree heights are measured using the same hypsometer. These data are processed and provide key information on the forest stand, used to determine current standing volume and for projecting yields. The forest stand volume calculation algorithms require as inputs the DBH distribution in 2 cm intervals, and the number of trees per hectare (TPH) in each diameter class. A predicted TH is obtained for each diameter class through the DBH/height relationship. The outputs of this process are volume (m^3) for the stand in pre-defined log classes.

II. Method

The service, illustrated in Figure 1, consists of basic processing (blue), the provision of thematic products (green), and the inference of selected biophysical parameters (magenta). From an Earth Observation point of view, forest EO products are generated based on spaceborne SAR and – whenever required – optical data: depending upon the product type, geographical area, data availability, data cost, and user requirements, the most appropriate data set is selected.

Purpose and functionality of each module are shortly presented.

1. Basic Processing

The purpose of this component is to obtain geometrically and radiometrically calibrated EO data. With respect to the processing of SAR data following steps are performed:

Intensity

- Focusing, if raw data are provided, omitted if starting from SLC data, and multi-looking;
- Co-registration including Digital Elevation Model (DEM), if multi-temporal data are available;
- Single-image (Gamma Distribution Entropy MAP) or multi-temporal (De Grandi) speckle filtering;
- Terrain geocoding and radiometric calibration;
- Radiometric normalisation;
- Anisotropic Non-Linear Diffusion filtering.

Coherence

- Focusing, if raw data are provided, omitted if starting from SLC data;
- Co-registration including DEM.
- Generation of coherence including DEM;
- Terrain geocoding;
- Anisotropic Non-Linear Diffusion filtering.

For details refer to [1] and [2].

2. *Generation of thematic maps*

Thematic products should be distinguished between:

- Maps, e.g. a particular theme connected with a specific geographic area, for instance forest area; and
- Change maps, e.g. a particular theme connected with a specific geographic area within a given timeframe, for instance forest area change.

While in the first case the product is derived from a single image, in the second one the thematic product is generated by considering two (bi-temporal) images.

Knowledge based classifier

The algorithm – an automatic pixel-by-pixel modular hierarchical knowledge-based one – has been developed based on the characteristics of PALSAR Fine Beam Dual (HH/HV) data and subsequently extended to the use of interferometric PALSAR FBD and FBS (HH) data. In a second round, the use of 1 day interferometric Cosmo-SkyMed StripMap data have been introduced. In synthesis, in this system, rules are designed to detected and extract well-known land cover signatures for L-band HH/HV data, L-band HH/HV data and HH-coherence, L-band HH data and HH-coherence, and finally X-band HH data and HH-coherence. It has to be pointed out that the rules have been initially derived from the literature, and later extended through the analysis of a significant amount of SAR scenes acquired over different ecological zones, geographic areas and time periods.

Bi-temporal classifier

Instead of visually comparing classes derived from SAR data, it is more convenient to consider a product (i.e. classification) including classes representing thematic information and related land cover changes, if any. The fundamental idea of the implemented algorithm is based on the fact that thematic information and changes can be defined in a semantic way rather than in statistical terms. In fact, knowing the symbolic (spectral, interferometric or pseudo-thematic) name of two classes, the new class can be set using a common denominator between them. For instance, if in the first date, the detected class is dense vegetation (e.g. forest), and, in the second one, the pixel id classified as bare soil, the resulting class will be clear fell.

3. Inference of biophysical forest parameters

A well established method for estimating forest biophysical parameters is to relate the observed backscattering coefficient to forest samples where they were previously measured during field visits. Using a semi-empirical model based on exponential function, bio-physical parameters are retrieved from SAR intensity (in this specific case using ALOS PALSAR) for the area of interest. Improvements in the estimation can be achieved by combining different polarisations and/or by ratioing several frequencies whenever available.

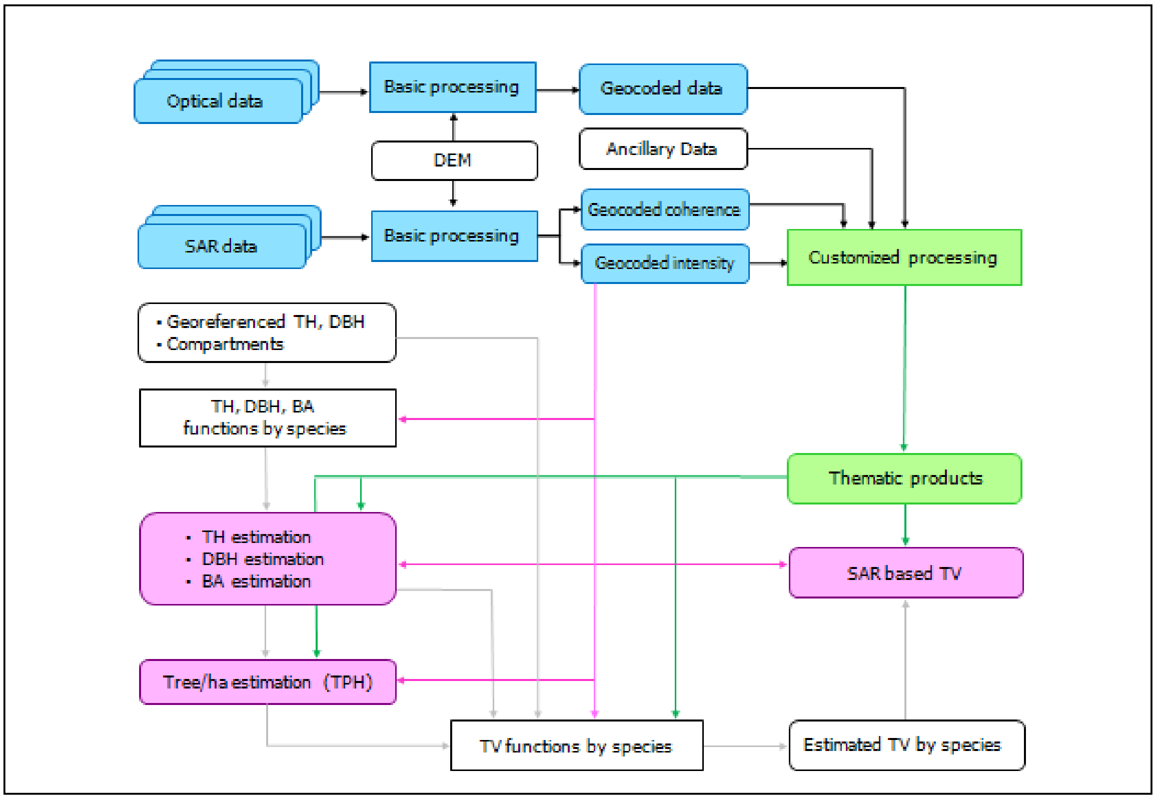

Figure 1 – Data Flow Diagram.

A major problem of this technique is the saturation level, i.e. the situation where an increase of the radar backscatter does not correspond to an increase of the above-ground biomass. A way to overcome/reduce the saturation problem is to push the saturation point towards higher values by using low frequency systems such as P- (400 MHz) or VHF-band (20-90 MHz). The consequence is that the attenuation is significantly reduced, and the large scale structures (of the order of the wavelength) dominate the backscatter.

A conventional way to derive the coefficients of the exponential function is to use individual geo-located field measurements for biometric parameters and link them to corresponding terrain geocoded backscattering coefficient sample. Typically, the following geo-referenced enumeration data are required for each sample site:

– Diameter at Breast Height (DBH) of all trees in a circular plot with a radius of 12.5 meter centered around a selected centre point with known position (GPS measurement) is measured;
– Tree Height (TH) of two typical trees within the sample group is measured;
– Slope of the surrounding area is measured using a clinometer;
– Only homogeneous areas are considered.

Once that the relationships between in situ measurements (for TH and DBH), calculated parameters (for BA), modeled parameters (for TV) and radar backscatter are established, following bio-physical parameters over the whole compartments are estimated:

– Tree Height (TH);
– Basal Area (BA);
– Diameter Breast of Height (DBH);
– Timber Volume (TV).

Straightforward, whenever BA and DBH (in meter corresponding to *d*) are available, the number of Tree Per Hectare (TPH corresponding to *N*) can be estimated using the relationship:

$$BasalArea = \frac{\pi}{4} \cdot \sum_{i=1}^{N} d^2$$

However, it is worth mentioning that due to interference from the trees and canopy, GPS systems cannot accurately pick up signals from satellites close to the horizon, leading poor spatial location with typical offsets of 20 meter or more. Compounding this, is the time it takes for the GPS to register the few available signals, typically five minutes or more per point, which adds to field costs. Due to these issues, several forestry companies have abandoned the use of GPS receivers under canopy and geo-locating the enumeration field trial plots. Foresters therefore establish growth and yield models at the compartment level by extrapolating in situ sample data across the compartment. Based on this situation, i.e. whenever geo-located bio-physical parameters are not available, the coefficients of the exponential function are derived exclusively from homogeneous (low variance) compartments, by taking in situ data and establishing average compartment level estimates of the selected biophysical forest parameter.

III. Pilot Area and Data Sets

York Timbers owns and leases about 86,900 hectares of land, of which 57,400 hectares are used for FSC-certified plantations and 29,500 hectares are reserved for conservation, streams, heritage sites, roads and access routes. Of the 57,400 hectares, 53,100 hectares are softwoods (approximately 63% *Pinus patula*, 27% *Pinus elliottii*, 9% *Pinus taeda*, and 1% other) and the balance is primarily *Eucalyptus nitens* and *Eucalyptus fastigata*. The plantations have been managed in 22-28 year rotations for over 50 years, and the silvicultural and pruning regimes have resulted in a high percentage of clear wood and Mean Annual Increments (MAI) of approximately 16 cubic meters per hectare per year.

Two different pine plantations areas have been identified: Jessivale – largely flat (maximum variations up to 400 meters) area with an average height of 1700 masl – and Mauchsberg – a relatively mountainous (maximum variations up to 1300 meters) area with an average height of 1650 masl.

Following SAR data have been collected:

Jessivale

- ALOS PALSAR data acquired on:
  11 August 2007 (winter), FBD
  11 February 2008 (summer), FBS
  13 August 2008 (winter), FBD
  28 September 2008 (spring), FBD
  13 November 2008 (late spring), FBS
- Cosmo-SkyMed data acquired on:
  8 December 2009 (late spring), StripMap HH
  9 December 2009 (late spring), StripMap HH
- ENVISAT ASAR data acquired on:
  10 December 2009 (late spring), AP

Mauchsberg

- ALOS PALSAR data acquired on:
  22 January 2007 (summer), FBS
  25 July 2007 (winter), FBD
  25 January 2008 (summer), FBS
  27 July 2008 (winter), FBD
  11 September 2008 (spring), FBS

All products have been processed using the Shuttle Radar Topographic Mapping DEM and referenced to the UTM zone 36, Southern hemisphere, WGS-84 system.

IV. Results and Discussion

The relevant results for Jessivale are illustrated in Figures 2 to 7. Note that the results for Mauchsberg, not shown in this paper but reported in [3], are similar to the Jessivale ones.

The performance of the products has been validated and evaluated by York Timbers for 199 compartments and during a joint three days field visit in November 2009. Following conclusions can be drawn:

Thematic products

- Clear evidence of usefulness of PALSAR FBD thematic products (Figure 2 and 3). In overall, the level of detail (in terms of information) is slightly increased in non-forest areas, if HH coherence is additionally considered within the knowledge based classifier. In general ALOS PALSAR FBD data provide a more detailed information (with respect to forest) than SPOT-4 or -5 (today used at York Timbers). The reason is that, being L-band data correlated with forest biomass (this is not true for optical), a better discrimination of different forest operations across compartments – in particular with respect to the variability in growth – levels can be achieved. All compartments have been correctly classified.

- Due to the higher spatial resolution of Cosmo SkyMed (3 meter) and complementary X-band frequency, the information content is significantly increased, particularly – but not exclusively – in non forest area (Figure 4), when 1-day interferometric Cosmo-SkyMed products are fused with the ALOS PALSAR ones.

- By analyzing multi-temporal (interferometric, whenever applicable) ALOS PALSAR FBD data, it is possible to identify, over the whole forest concession, cover changes (mainly logged compartments), the status of fire breaks to a given period of the year, and the effective forest area at compartment level. On this subject, it is worth mentioning that compartments are assumed in terms of coverage and biophysical parameters homogeneous, but in fact they are not. In this sense, geo-spatial data provides precious information in terms of effective forest area and compartment heterogeneity.

Inference of biophysical forest parameters

- Clear relationships were established between L-band HV data and field based, geo-referenced plot level standing volume, average tree height, average DBH and basal area (Figure 5). The number of trees per hectare (TPH) have not been estimated from ALOS PALSAR data, but mathematically derived from the basal area/DBH/TPH relationship.

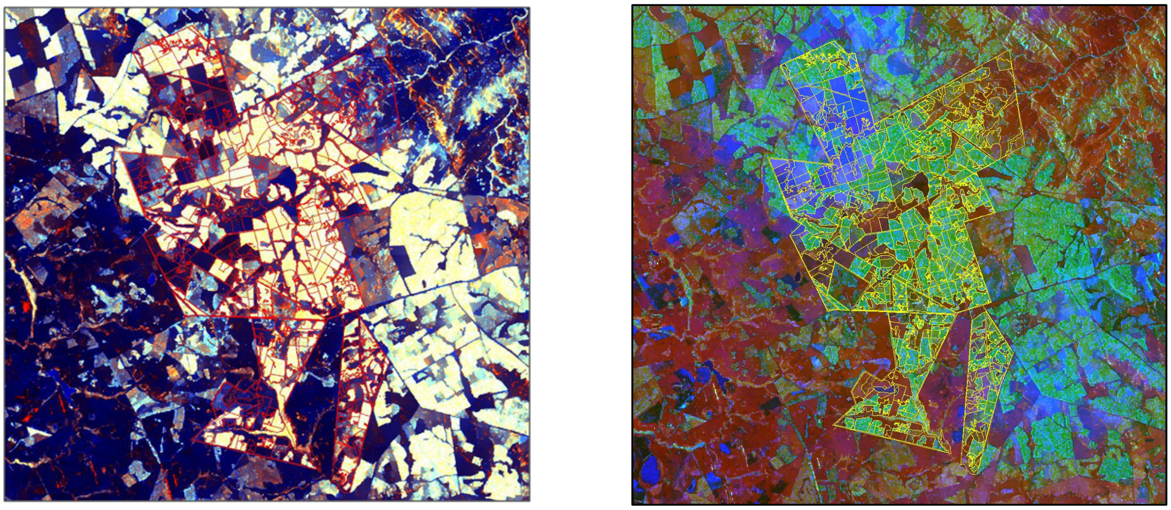

Figure 2 – Jessivale: ALOS PALSAR FBD acquired on 18th August 2008 (left) and interferometric ALOS PALSAR FBD acquired on 18th August and 28th September 2008 (right). Forest compartments are overlaid in red and yellow respectively.

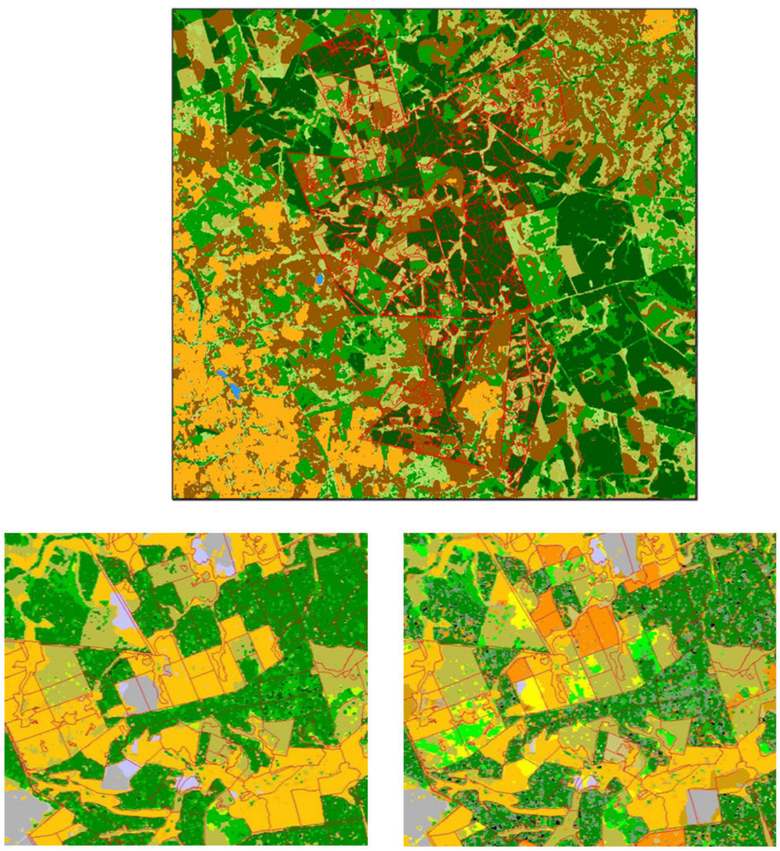

Figure 3 – Jessivale: Top – Land cover map based on ALOS PALSAR FBD data acquired on 18th August 2008. Green: forest (the different tones corresponds to the different timber volume levels; Brown: rough (dark) and smooth (light); Blue: water. Bottom (detail) – Land cover map (left) based on ALOS PALSAR FBD data acquired on 11th August 2007 and corresponding land cover change map (right) between 11th August 2007 and 18th August 2008. Clear cut harvested areas are marked in orange.

The coefficient of determination, R^2, is typically higher than 80% between plot parameters and the L-band HV backscatter, while at L-band HH backscatter R^2 is in general 20% lower for Jessivale and up to 35% for Mauchsberg due to the influence of the topography in particular at this polarization (note that the data have been radiometrically normalized). At L-band HV, over the range of data available (up to 400 m^3/ha timber volume) there is little evidence of saturation, although the relationship is non-linear and tending to an asymptote around 500 m^3/ha.

– For completeness, ENVISAT ASAR AP data have been acquired and biophysical parameters inferred. As expected, at both polarizations the coefficient of determination is very low (Figure 6).

– The L-band HV inferred biophysical functions were extrapolated to all pixels within and averaged by compartment in order to be compliant with the existing forest database. Thus a comprehensive set of biophysical products were provided at compartment level over the whole concession (Figure 7), and subsequently imported into existing forest management system for further validation and evaluation according to:

Extrapolation – The purpose of this test is to validate the relationships established in this study with field-measured data of compartments within the region of interest. The relationship established with the training compartments is tested against other field-enumerated compartments. Items 1, 2, 3 and 5 as indicated in Table 1 were calculated by extrapolation.

Volume equation input variables – L-band HV inferred parameters, DBH and TH are used to calculate an average TV for each compartment, using York Timbers' volume equations. To convert the average TV to a compartment level volume, the L-band HV BA and DBH are used to establish a calculated TPH value. This TPH multiplied with the average TV to provide a compartment volume. Item 4 in Table 1 is determined in this way.

Hybrid approach – In this test, field measured DBH are combined with L-band HV estimates of BA and TH. The rationale behind this approach is that it is easy and efficient to measure diameters in-field, but more cumbersome to obtain the other required measures. Making use of easily obtainable DBH field data and combining it with L-band HV inferred BA and TH, provides outputs indicated as items 6, 7 and 8 in Table 1.

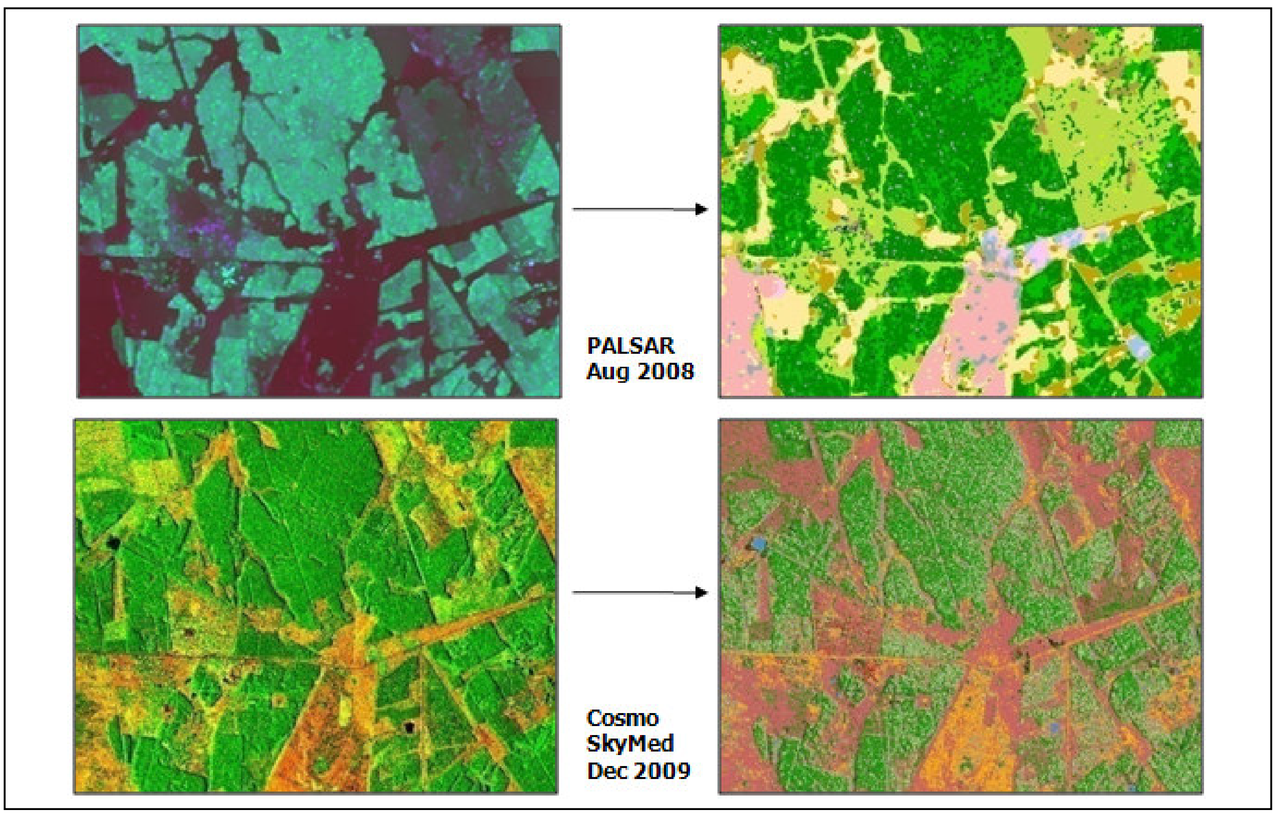

Figure 4 – Jessivale (detail): ALOS PALSAR FBD data acquired on 18th August 2007 and corresponding land cover map (top) and interferometric Cosmo-SkyMed data acquired on 8th and 9th December 2009 and corresponding land cover map (bottom).

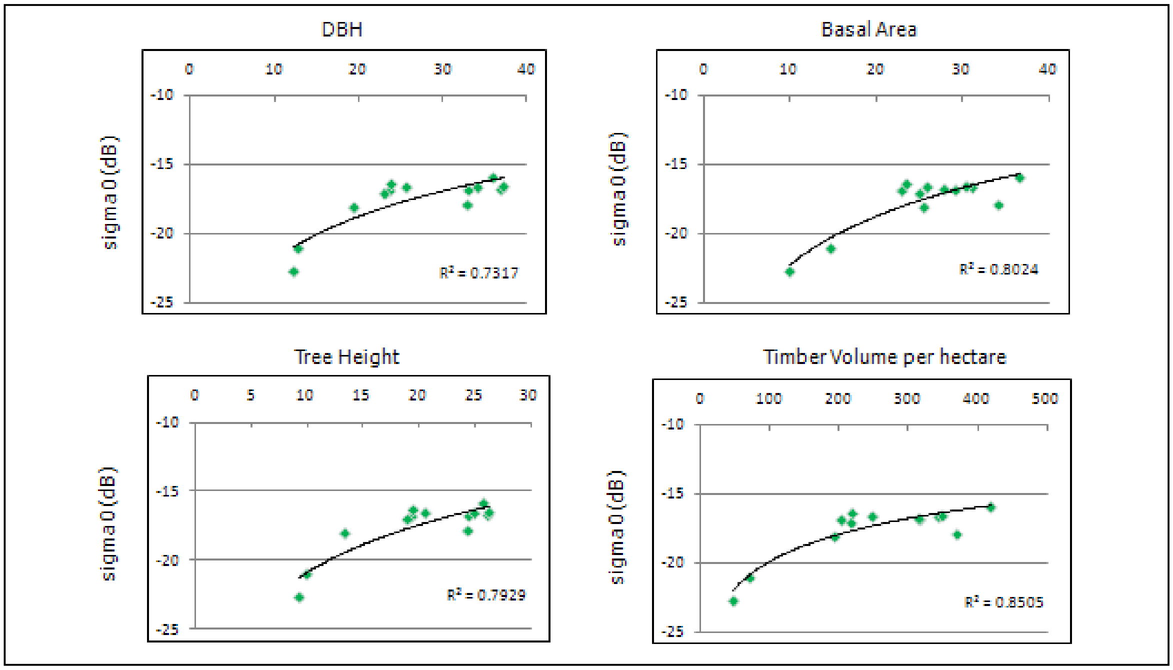

Figure 5 – Jessivale: Relationship between selected biophysical parameters and ALOS PALSAR HV data acquired on 18th August 2008.

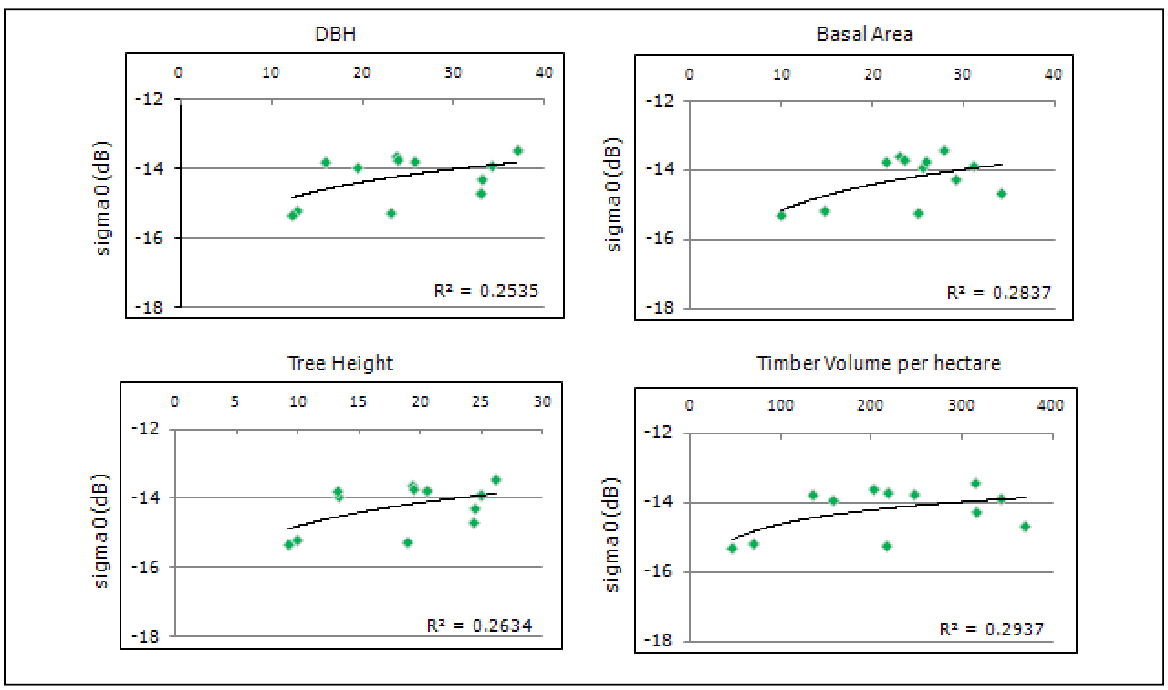

Figure 6 – Jessivale: Relationship between selected biophysical parameters and ENVISAT ASAR HV data acquired on 10th December 2009.

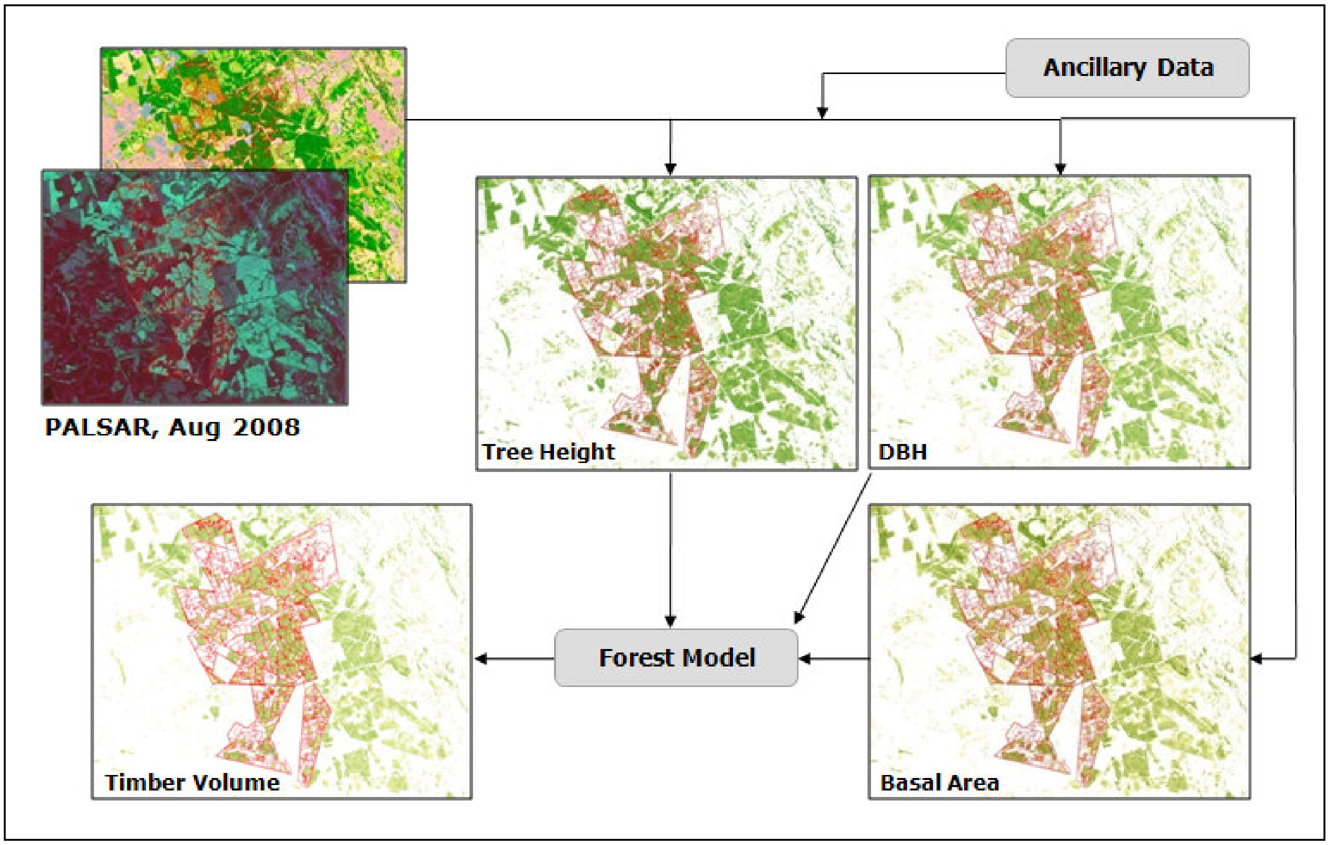

Figure 7 – Jessivale: ALOS PALSAR FBD acquired on 18th August 2008 with corresponding land cover map and inferred biophysical parameters. The illustration shows also the selected strategy.

Ref	Variable	Route	Δ %
1	BA based on PALSAR	Extrapolation	-7.9
5	TH based on PALSAR	Extrapolation	-3.3
2	DBH based on PALSAR	Extrapolation	-1.3
6	TPH using PALSAR BA, PALSAR DBH		+2.7
7	TPH using PALSAR BA and measured DBH	Hybrid	-10.0
3	TV based on PALSAR	Extrapolation	-24.0
4	Modeled TV using PALSAR BA, PALSAR TH, PALSAR DBH	Volume equation	-11.1
8	Modeled TV using PALSAR TH, PALSAR BA, with calculated TPH using measured DBH	Hybrid	-11.7

Table 1 – Summary of the validation results. Difference is L-band HV inferred, expressed as a percentage of the field-measured equivalent.

In general, and except for some outliers which most probably are due to inconsistencies between the two approaches (geospatial data versus average parameters at compartments level), the estimated parameters are more than satisfactory. Specifically:

– The EO obtained results (Table 1, Ref 1 and 2) for DBH and Height are encouragingly good, so much so that supplanting the EO DBH measurement with the field-measured DBH degraded the accuracy of the results. The EO volume measurement (Table 1, Ref 4) was not as reliable and the high standard deviation around this variable may indicate more research is required to fully understand the EO interaction.

– Using EO derived variables as inputs into standard volume equations showed the best results for standing volume estimation. This implies that only DBH, TH and BA need to be estimated from EO data in order to obtain acceptably accurate volume estimates.

– The hybrid approach (combining EO with field-measured data) did not result in improved results for either volume or number of trees per hectare.

It is further concluded the methods explored in this work will not totally displace field-based forest inventories as there are occasions where very high accuracy levels are required or where the comfort afforded by direct measurements would be preferred. However, at this stage, the cost implications of employing EO data vs. field measured data have not investigated, and due to the large spatial footprint of EO, it is clear that there is a point in spatial coverage where EO will become financially beneficial.

Therefore, despite using only one non geo-referenced point per compartment reflecting average measurements of biophysical parameters across the compartment, York Timbers is highly encouraged by the results obtained so far and believes results could only improve by using either more points or a closer geo-referencing of point source field data and EO derived data.

Finally, it is well known that moisture has a significant effect on the radar backscatter. Radiometric changes in the order of 2 to 3 dB have been observed between data acquired during the dry (August) and the wet (February) season. Two considerations:

– This information can be provided to the forest manager in qualitative form (very wet, wet, normal, dry, very dry) which can be used to interpret conditions on the ground.

– With respect to the inference of biophysical forest parameters, these radiometric variations must be considered. In this way the reference function is applicable irrespective to the acquisition date.

CONCLUSIONS

The outputs of this work, based on two discrete and disparate pine sawn timber producing areas belonging to York Timbers in South Africa, indicate that the developed service can be successfully used to determine the input variables required to calculate standing timber volume at a compartment level.

Using the proposed strategy, there could be many applications in plantation forestry. The main ones identified are:

– To obtain forest inventory data for the first time, e.g. when investigating a possible purchase or when field-based information is unavailable or of questionable accuracy.

– To obtain data data for the first time on large tracts of young compartments where the cost/benefit of field measurements may be prohibitive. High accuracy inventory data is normally not crucial for younger compartments.

– To obtain data obtain data for unmeasured compartments in a mix of measured areas, i.e. filling gaps where some compartments may not yet have been enumerated These are often in accessible areas, hence the fact that they had not been enumerated.

– Could be used to reduce the frequency of ground data collection or the intensity of data collection.

– Could supplant some field measures that are relatively difficult and expensive to acquire (e.g. BA and tree height) and combine these with the easier to measure field based variables.

– Loss and damage assessments such as fire and other disasters – quick and easy means of obtaining loss value for damage valuations and insurance claims.

– Could be useful as an independent means and in due diligence exercises.

– Forest certification uses – perhaps not that important for as long as certifiers or FSC continue to rely on forestry companies' data. But it would be valuable where certification bodies wanted to source independent data to investigate resource management and increase efficiency. For potential new certifications, it could satisfy certifiers that operations are economically and environmentally sustainable.

ACKNOWLEDGEMENTS

This work has been undertaken within the framework of the JAXA Kyoto & Carbon Initiative. ALOS PALSAR data have been provided by JAXA EORC, Cosmo-SkyMed data by ASI/e-GEOS, and ENVISAT ASAR data by ESA. The European Space Agency is additionally acknowledged to financially support the work performed in the DUE Innovators II program. Dr. Denis Alder is acknowledged for the critical review of this work from a forest perspective.

REFERENCES

[1] Holecz F., M. Barbieri, A. Cantone, P. Pasquali, and S. Monaco, Synergetic use of ALOS PALSAR, ENVISAT ASAR and Landsat TM/ETM+ Data for land cover and change mapping, K&C Science Report Phase 1, JAXA, 2009.

[2] Holecz F., M. Barbieri, A. Cantone, P. Pasquali, and S. Monaco, Synergetic Use of multi-temporal ALOS PALSAR and ENVISAT ASAR data for topographic/land cover mapping and monitoring at national scale in Africa, Proceedings IGARSS Symposium, Cape Town, 2009.

[3] Holecz F., C. Eyre, and N. Mönnig, Timber Volume Estimation in Forestry Plantations – Forest Modeling from Earth Observation Data, DUE Innovators II program, Final report, ESA/ESRIN, 2009.

sarmap S.A. – a Swiss company, www.sarmap.ch – currently constituted by 9 employees, was founded in January, 1998 to provide product / service development in the field of remote sensing (SAR and optical), particularly airborne and spaceborne Synthetic Aperture Radar (SAR) data processing. Training courses are also offered to extend the understanding of the utilization of SAR data, products and services. Application areas of expertise include Digital Elevation Model, agriculture, forestry, ground deformation, and change detection. In the past 12 years, sarmap has been involved in around 80 projects: approximately 2/3 on algorithm/product/service developments at the European Space Agency. The remaining 1/3 focused on the developments of innovative remote sensing based products/services for the World Bank, EC Joint Research Centre, JAXA, and private sector (re-insurance sector in primis). sarmap developed SARscape®, a software tool for the processing of airborne and spaceborne SAR data integrated in ENVI® and world-wide commercialized by ITT Visual Information Solutions Inc., Sierra Atlantic Inc., and Beijing WenWu Space Technology Co, Ltd..

Eyre Consulting Ltd. is managed by Charles Crosthwaite Eyre, who has a broad business background with both UK and international management experience. Eyre Consulting provides consulting services in two strategic and operational areas: 1. The policy impacts of regulated and non regulated emissions trading. This covers both avoided emissions as well as carbon sequestration through avoided deforestation and reforestation; 2. The potential use of remote sensing services across sustainable forestry.

York Timbers Organisation Ltd. is a forest products enterprise based in Eastern South Africa. York Timbers (Pty) Ltd is fully owned by the York Timbers Organisation Limited, whose shareholding is currently made up of Public shareholders (24,6%), the UK-based Blackstar (19%) and the South African Industrial Development Corporation (28,6%). York Timbers owns and leases about 86,900 hectares of land, of which 57,400 hectares are used for FSC-certified plantations and 29,500 hectares are reserved for conservation, streams, heritage sites, roads and access routes. Nico Mönning is forest manager and planner at York Timbers.