K&C Science Report – Phase 2

SAR Backscatter, InSAR and Lidar Studies for Measuring Vegetation Structure Over the Harvard Forest Region

Paul Siqueira
Microwave Remote Sensing Laboratory
University of Massachusetts, Amherst
siqueira@ecs.umass.edu

Razi Ahmed[1], Caitlin Dickinson[1], Richard Lucas[2], Bruce Chapman[3]
[1]University of Massachusetts, Amherst; [2]University of Aberwystwyth, Wales, U.K.
[3]Jet Propulsion Laboratory, Pasadena, CA

***Abstract*—The purpose of this work was to explore the dependence of remote sensing observations available from ALOS/PALSAR and full waveform lidar, on vegetation structure. For this study, an intensive ground validation effort was conducted at the Harvard Forest in Western Massachusetts. The ground validation data was used in conjunction with the remote sensing measures to determine the degree of accuracy that the remote sensing methods could be used to provide meaningful structure metrics of the vegetation. It was generally found that the interferometric measures alone were not sufficient to characterize the vegetation, largely due to temporal decorrelation. Better success was achieved with lidar measurements and backscatter data. For the radar backscatter, it was determined that speckle noise was a dominant source of error, and hence, large regions needed to be averaged (greater than one hectare) to produce satisfactory results.**

***Index Terms*—ALOS PALSAR, K&C Initiative, Vegetation structure, SAR Interferometry.**

I. Introduction

Among the areas necessary for continued scientific development identified by United Nations Framework Convention on Climate Change via the Kyoto Protocol and REDD (Reducing Emissions and Deforestation and Degradation) is the need for quantifying carbon stores held in the world's vegetation and characterization of species habitats through the measure of vegetation structure, both horizontal (on a hectare-to-hectare scale) and vertical (to a meter-level accuracy). Through JAXA's Kyoto & Carbon Initiative, the L-band SAR, ALOS/PALSAR, provides unprecedented access to detailed, expansive and continued coverage of the world's forests in the form of data that can be used to characterize the current state of the vegetation and its change (both seasonal and long-term) over time. In this study conducted by the University of Massachusetts, NASA's Jet Propulsion Laboratory, and the University of Aberystwyth, we are using data from ALOS/PALSAR and an Airborne lidar (LVIS; from NASA's Goddard Space Flight Canter) to image the vegetation structure over the Harvard Forest located in Western Massachusetts. The Harvard Forest (harvardforest.fas.harvard.edu) is a mixed hardwood, transitional forest that has been the subject of many studies, both large and small, for the purposes of characterizing the environment and the many species that benefit from the presence of the forest.

The series of repeat ALOS observations made available from the Japanese Space Agency since the launch of the platform in 2006 has provided a rich and consistent data set which provides an opportunity to explore relationships between the SAR, InSAR and lidar data, to better understand methods of combining these fundamental data sources for studying the ecosystems, carbon balance and vegetation three-dimensional structure in the Harvard region and to extrapolate the results as they would apply to similar observations worldwide.

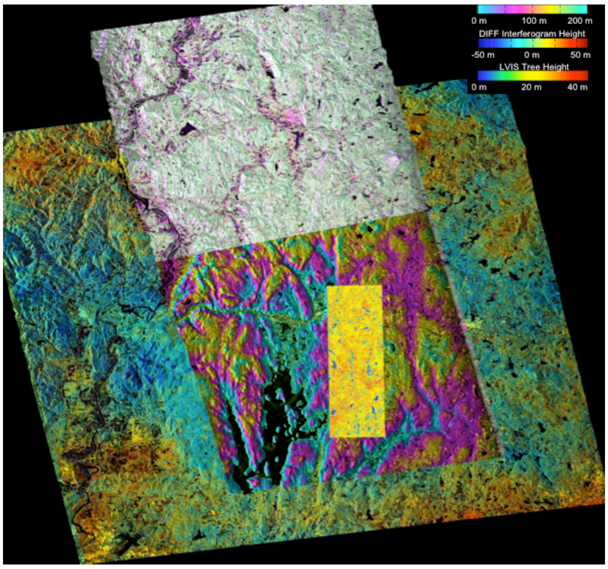

Figure 1. Image of a subset of the SAR (white), InSAR (pink colorwrap) and lidar (yellow patch) data over the Harvard Forest.

In this science report, we provide insight into the use of SAR, InSAR and lidar for the use of vegetation structure characterization in the Harvard Forest with the intent that the results from this results can be used as part of a larger system for global products that would be based on a similar set of remote sensing observations. In particular, it is expected that the L-band observations available from ALOS/PALSAR, which is expected to be sensitive to vegetation structure through backscatter and interferometric (repeat-pass) observations, and full waveform lidar, which is directly sensitive to vegetation vertical structure, can be used in conjunction with one another for providing an observation set that can reach the desired goals

The report begins by providing a brief description of the Harvard Forest test site and of the ground validation work that our group has performed in the region for characterizing the vegetation structure. We then parse through the three different data types and then demonstrates how each has been used in the analysis of vegetation structure for the Harvard Forest, and then finish with a set of conclusions and recommendations for future work, much of which is ongoing by our group right now.

II. Input Data

A. The Harvard Forest

After heavy logging in the Northeast, the Harvard Forest was a 2000 acre site established in 1907 in Western Massachusetts (Figure 2), to study sustainable Forestry. The sight consists of mixed hardwoods and softwoods; dominated by Hemlock, Red and White Pine, Red and White Oak, and Sugar Maples. The average tree height within the forest is approximately 25m. As part of our group's study, a total of 15 one hectare plots were established, with the orientation of the plot meant to nominally follow the flight track of ALOS/PALSAR. Within each plot, a set of 16 25x25m subplots were created (Figure 2).

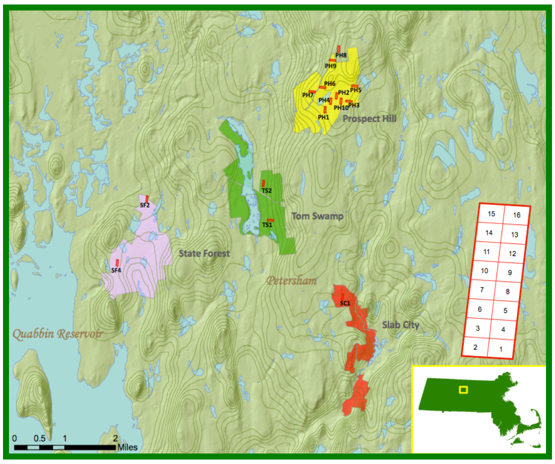

Figure 2. Relief map of the Harvard Forest geographic region and locations of the Harvard and State Forests (colored overlays). A total of 15 one hectare plots were established with 16 25x25m subplots were established within each of the plots, as shown.

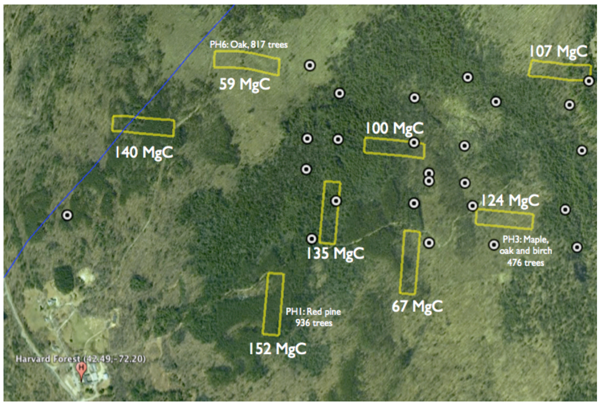

Figure 3. The "Prospect Hill" region within the Harvard Forest, shown on Google Maps. Also indicated are a subset of the one hectare plots set up in the area along with their biomass estimated using the measured diameter at breast height.

Within each subplot, each tree with a diameter of greater than 4 cm were catalogued in terms of its diameter at breast height (DBH), species, and whether it was alive or dead. In total, over 10,000 trees were catalogued. As part of the post processing of collected data, individual tree biomass was estimated using a set of equations developed for Northeastern US Hardwoods and Softwoods [Jenkins et al., 2004] and the results aggregated to make stand biomass determinations (Figures 3 & 4).

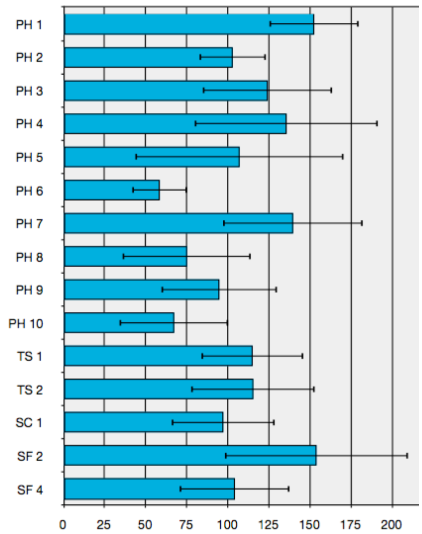

Figure 4. Estimates of above ground biomass (in MgC/ha) for each of the established Harvard Forest plots. Shown as error bars are the range of per hectare biomass' estimated from the subplots established within each of the one hectare plots.

B. SAR

Two sources of SAR data were used in this study. One from JAXA's ALOS/PALSAR, and the other from UAVSAR, an airborne, fully polarimetric L-band SAR operated by NASA. A comparison of the copolarized (HH) backscatter is shown in Figure 5, where it can be seen that excellent agreement between UAVSAR and PALSAR exists when the two sensors are sampling the scene at the same incidence angle (38 degrees). Further, as a test for consistency, UAVSAR was flown in a repeat track, with a time separation as short as 40 minutes. Backscatter observations from the scene with these repeat tracks is also shown in Figure 5, where the backscatter stability of both the scene and the instrument can be seen to be better than 0.1 dB, as would be expected under these observing conditions. In essence, this plot verifies both the radiometric accuracy of the two instruments as well as the radiometric stability of the target over short time periods.

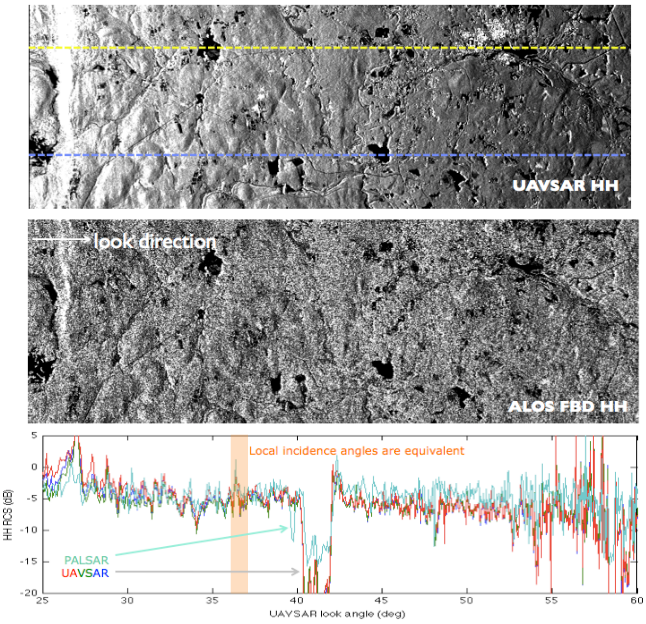

Figure 5. Backscatter comparison between UAVSAR and ALOS FBD data. Shown are sections from the two data sources from the same geographic area. A cross-section in the range direction (shown as a yellow dashed line) is used to create a backscatter plot as a function of look angle in the lower plot.

C. *InSAR*

Cross-track Interferometric SAR (InSAR) is known to be fundamentally sensitive to topographic height and topographic change [Rosen et al., 2000]. It has also been shown to be useful for characterizing vegetation structure [Treuhaft and Siqueira, 2000]. Because of the large number of observations that ALOS/PALSAR has made over Western Massachusetts (Figure 6), there are many opportunities to explore the interferometric response as well.

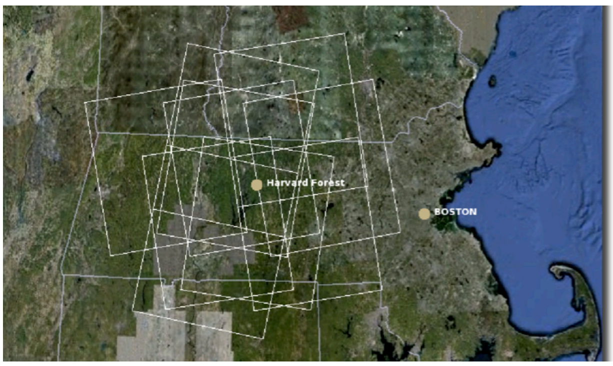

Figure 6. A Google Earth image of Massachusetts with various outlines for scenes that have been observed by ALOS/PALSAR.

The large number of collected scenes allows for the opportunity to perform repeat pass interferometry (minimum repeat period of 46 days) with the instrument. An important parameter in forming interferograms for the purpose of characterizing the vegetation structure, is the perpendicular baseline of the interferometric pair; or more concisely, the distance between the two satellite passes measured perpendicular to the look direction. Because of variation in the orbit of the ALOS platform, this distance varied quite a bit throughout the observing period; a summary of some of these perpendicular baseline measures is shown in Figure 7.

Interferometric data were processed using the processing software produced by Gamma Remote Sensing. This software takes into account the existing DEM and makes orbital corrections based on the observed fringe rate to optimize the alignement of the two collected SAR scenes. Once aligned, the interferometric phase and coherence can be determined and explored for information related to the vegetation structure.

	20060702	20060827	20061012	20061127	20070112	20070414	20070530	20071015	20071130	
	PLR	4270	3800	4510	2440	5150	4580	6170	6220	20060702
		PLR	470	240	1830	890	310	1900	1950	20060827
			PLR	710	1360	1350	780	2370	2420	20061012
				PLR	2070	650	70	1660	1710	20061127
20070105	FBS				PLR	2720	2140	3730	3780	20070112
20070708	2690	FBD				PLR	570	1020	1070	20070414
20070823	2670	80	FBD				PLR	1590	1640	20070530
20071008	3030	345	270	FBS				PLR	50	20071015
20080108	3600	910	830	570	FBS				PLR	20071130
	20070105	20070708	20070823	20071008	20080108					

Figure 7. A "map" of perpendicular interferometric baselines and time separations for a subset of the ALOS PLR and FBS/FBD scenes collected from 2006-2008. Color coding for different entries in the table provide a qualitative look at those baselines that would be most effective at probing the relationship between the interferometric observations and the vegetation vertical structure. Dates of scenes are shown in white, with year, month and then day.

D. *Lidar*

For this project, the LVIS (Laser Vegetation Imaging Sensor) built by NASA Goddard Space Flight center was flown over the Harvard Forest in early August of 2009. This collected data set complements a similar data collection over the Harvard Forest that was performed in 2003 (see the yellow highlighted region in Figure 1). The LVIS instrument has a footprint of 25m and records the full scattered waveform with a 30 cm resolution, of the laser pulse reflected from the near-nadir looking system. This system also scans from side-to-side as the aircraft platform moves forward, thus creating a three-dimensional image of the terrain below. An example of the lidar waveform behaviour over a nadir-looking transect is shown in Figure 8. Where slight errors in the registration of the waveform to the ground surface show up as negative heights, and are due to errors in the detection of the ground surface from the LVIS waveform.

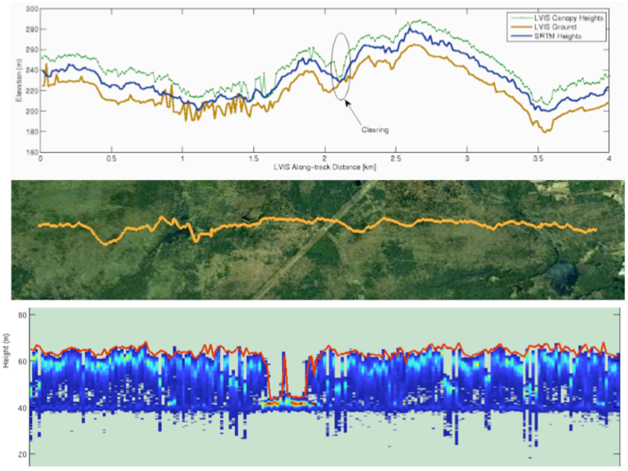

Figure 8. Transect of the LVIS lidar waveform shown in terms of the ground elevation (top), as a transect projected onto an image from Google Earth (middle), and in terms of reflected intensity as a function of height and along the transect (bottom). Clearly seen in the bottom plot is the presence of a tower that supports power lines in the forest clearing (center of bottom image).

III. Characterization of Vegetation Structure

A. *SAR Backscatter*

Because of difficulties associated with the effect of temporal decorrelation on interferometric data [Ahmed et al., 2010], much of the radar analysis for relating vegetation structure to observables that are available from ALOS/PALSAR, much of the effort in this task was associated with analyzing the backscatter data at both co-polarized (HH) and cross-polarized from ALOS, and compared with similar observations made by NASA's airborne UAVSAR. Shown in Figure 9 is the observed relationship between the cross-polarized radar backscatter power and field measured biomass (from DBH) as described in Section IIA, plotted as a function of resolution and the number of looks. Observations were also collected over multiple days (a ten day period for UAVSAR) and same-seasons, but multiple months and years using PALSAR.

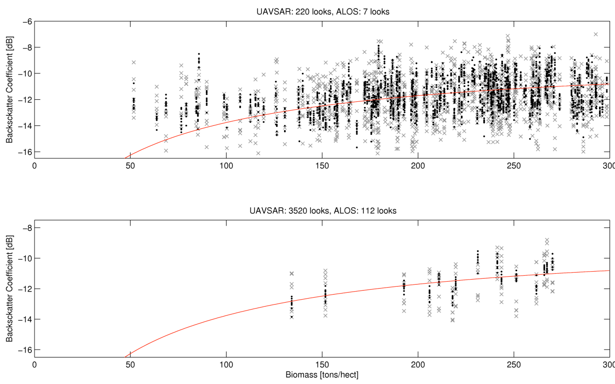

Figure 9. A comparison of UAVSAR (black dots) and PALSAR backscatter (x's) as a function of geographic area and the number of looks. The upper plot illustrates the observed backscatter at a resolution of 25x25m and the lower plot, using one hectare size plots, obtained from the ground validation effort described in Section IIA. Multiple observations were obtained over same-seasons (ALOS) and within a ten day period (UAVSAR).

What can be determined from Figure 9 is the fact that at narrow resolutions, the backscatter power is dominated by speckle (top plot). This can be noted because the UAVSAR instrument has a much higher single-look resolution than ALOS (1.5m versus 12m), and therefore more looks can be made for one ground validation subplot (upper plot) or ground validation hectare (lower plot). Here it can be seen that while the mean backscatter from both UAVSAR and PALSAR are similar, the variation in PALSAR is much greater.

Note too that as the resolution is reduced from 25x25m subplots to one-hectare plots, the variation in backscatter as a function of biomass is much reduced, and the functionality of this relationship follows the exponential model for backscatter (red line) that is often used for characterizing this relationship. What this demonstrates is that the natural variability that is expected within a region of "uniform" vegetation growth and homogenous or heterogeneous species population (which is how the one hectare plots were chosen), has considerable variability within the plot. In short, as these within-plot variations are removed through averaging, the expected functional relationship between SAR backscatter and biomass becomes more apparent.

Shown in Figure 10 below is a more concise comparison of the observed cross-polarized backscatter from UAVSAR (with 3520 looks; 80 MHz) versus PALSAR (112 looks; 28 MHz) over the fifteen, one hectare ground validation regions. The increased variation in PALSAR can be attributed to the dominance of speckle, even at these courser resolutions. This courser resolution is a function of the bandwidth of the instrument, and ultimately is a fundamental limiting factor in collecting spaceborne data. The effect of this limitation in characterizing the backscatter, and ultimately the estimation of biomass, can clearly be seen in this set of figures.

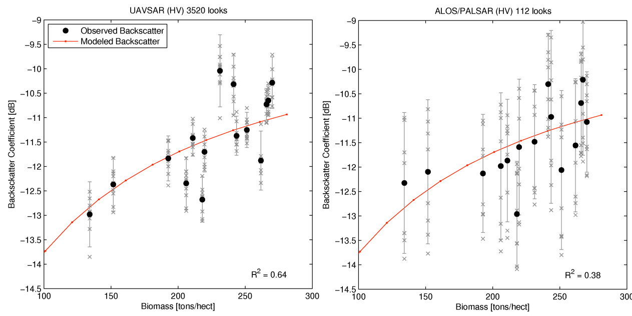

Figure 10. Comparison between UAVSAR and ALOS/PALSAR cross-polarized backscatter for the fifteen, one hectare plots. Similar to Figure 9, it can be seen that the variation in backscatter for ALOS is much larger than that for UAVSAR. This difference in behaviour for the two instruments can be attributed to the improved resolution (higher bandwidth) of UAVSAR compared to PALSAR.

As a final analysis that was performed with the PALSAR and UAVSAR data, was a comparison of the observed co-polarized (HH) and cross-polarized (HV) backscatter over the fifteen, one hectare plots. The results of this comparison are shown in Figure 11, where the backscatter is plotted as a function of biomass, and shown against a exponential function often used to provide an empirical relation between these two quantities. It can be seen in this set of plots that while the absolute value of the backscatter does change depending on the polarization (-12 dB for cross-pol versus -7 dB for co-pol), the dependence of this backscatter on biomass does not change appreciably between the two types of observations. What this essentially means, from the first-order point of view depicted in Figure 11, is that the amount of information that is sensitive to the volume of vegetation, between these two measurement types, is essentially the same, at least for the fifteen plots used for comparison by this study.

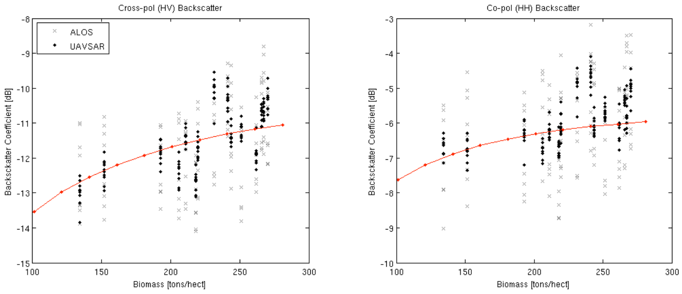

Figure 11. A comparison between cross-polarized (HV; left) and co-polarized backscatter and biomass. These two plots show that the two measurement quantities have a similar behavior in terms of their fundamental relationship to biomass.

B. SAR Interferometry

As described in Section IIC, the data collected by ALOS over Western Massachusetts, could not only be used for the backscatter versus biomass analysis described in the previous section, but also for forming interferograms which could possibly be used to explore the sensitivity of vegetation structure (or biomass) to the interferometric variables of phase (relative to a known DEM, such as that available from SRTM) and coherence, as in [Treuhaft and Siqueira, 2000]. For this project, both of these avenues were explored using the data made available through the K&C Initiative. The set of plots and images shown in Figure 12, below, provide a summary of this analysis in graphical form.

The first of these plots (topmost) shows the LVIS ground topography (bottommost line), the LVIS canopy top topography (topmost line), the SRTM topography (blue line), and the topography observed by ALOS, after using the Gamma interferometric processing software and the SRTM DEM as a reference for phase unwrapping and baseline calculation (red line with 'dot' symbols). While the overall behavior of interferometric phase obtained by ALOS/PALSAR repeat-pass interferometric processing can be considered to be quite good in this example, it is difficult to see a direct relationship between the interferometric penetration into the canopy and the canopy height itself. In other words, the interferometric processing for phase does do a reasonable job of determining the topography, but its relationship to the vegetation structure is not apparent. This observation, obtained from this plot, has also been verified by making a direct comparison of this penetration depth versus the vegetation height, through an analysis not shown in this short paper. Suffice it to say however, that no direct relationship was observed by making a plot of these two quantities against one another.

The lower plot of Figure 12 shows the 'best fit' relationship between the interferometric correlation magnitude and the observed vegetation height, projected onto the same set of axes as the upper plot of this same figure. In this case, the vegetation height is calculated not by the differential penetration between the ALOS/PALSAR repeat-pass interferometric data and the SRTM data, but by relating the correlation magnitude to the vegetation height using an empirical relationship between the interferometric observations and the vegetation height measures available from the LVIS sensor. It can be seen in this plot that while on average the correlation magnitude dependent estimate does correctly estimate the vegetation height (which would be expected given that an empirical fit was used), it does not in general perform well at correlating to the vegetation height variations seen in the lidar data. In short, the observed correlation magnitude from ALOS/PALSAR repeat-pass observations does not perform well in estimating the lidar derived vegetation height.

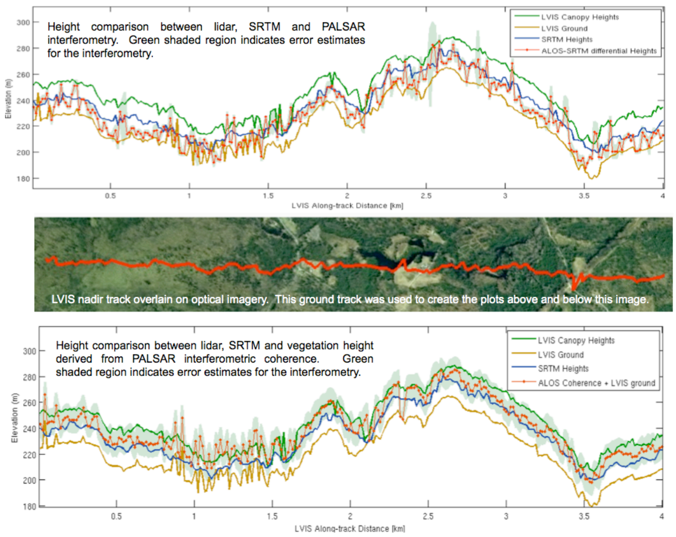

Figure 12. Plots and images used to explore the interferometric response to vegetation height and perhaps biomass. See comments within the plots and text within Section IIIC for details.

The reason for this general lack of sensitivity between the interferometric observations of correlation magnitude and phase can be generally attributed to the effect of temporal decorrelation in the data (which affects both the magnitude and the phase; see [Ahmed et al., 2010]) and the effect of differential propagation paths of the L-band signal through the troposphere (which affects primarily the phase). A clear picture of this effect can be seen in Figure 13, where a histogram of the observed correlation is shown alongside an image of the correlation magnitude for a repeat-pass interferogram from PALSAR in the Harvard Forest region. It can be seen here that the observed correlation magnitudes are much less than what would be expected for a short baseline (100m) and 20m tall trees. The image below confirms this fundamental lack of sensitivity to vegetation structure, in that there is no discernable trend in the image shown in Figure 13, which indicates that the observation is geographically varying in a manner consistent with the vegetation characteristics know to exist on the ground.

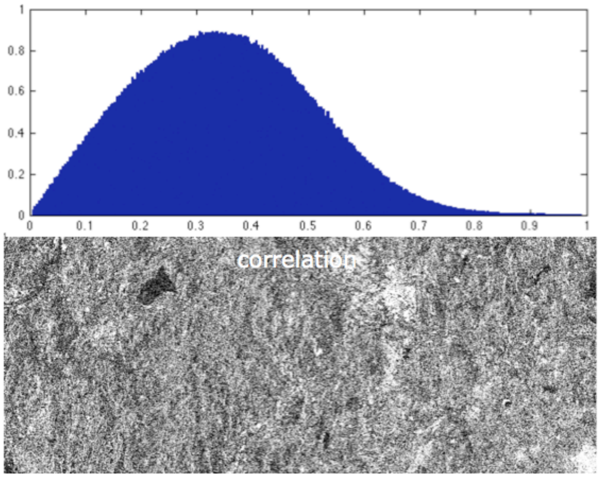

Figure 13. A histogram and image of the observed interferometric correlation over the Harvard Forest region.

C. Lidar Analysis

As a final part of our study, the full waveform lidar data described in Section IID was used to relate the observed lidar height to the ground validated biomass measurements made within the 225 subplots that made up the 15 one hectare regions, complete with 16 25x25m subplots. The resulting linear relationship that was used to relate the measured biomass to the LVIS measured height (rh100) is shown in Figure 14. While it can be seen in this figure that the relationship between biomass and the lidar measured height is somewhat loose, a trend does exist that can be explored further.

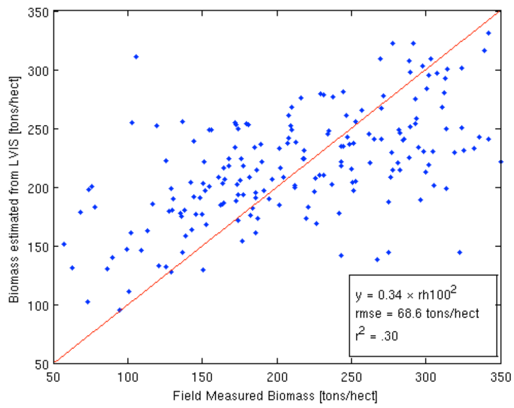

Figure 14. Plot of field measured biomass over the 225 subplots that make up the components of the 15 one hectare plots in the Harvard Forest, versus the lidar measured heights, known as the rh100 (height of 100% energy).

One way of using the data shown in Figure 14 is to extend the relationship between the field-measured biomass to the entire area covered by the lidar. A result of applying this relationship to the LVIS observed region over the Harvard Forest is shown in Figure 15.

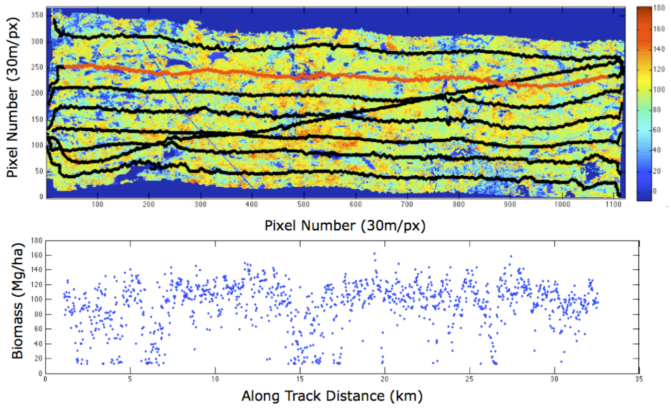

Figure 15. An LVIS-derived biomass map over the Harvard Forest. Shown in the above image is a plot of the biomass as a function of geographic location, measured in 30m pixels. The lines drawn on top of the image is the nadir track of the LVIS instrument, with the red track being shown as a plot in the lower part of the figure.

IV. Results and Summary

The work carried out in this phase of JAXA's K&C Initiative has produced number of important results. While it could be argued that these results are specific to the Harvad Forest region, the methodology employed is applicable to a number of other regions in the Northeastern United States and in the Queensland region of Australia. Indeed, our group is actively in the process of producing these additional analyses, and it is expected that this will be forthcoming over time.

In summary however, the important conclusions and summary of work that have been reached as a result of this study are:

- A total of fifteen one-hectare ground validation sites were established at the Harvard Forest. The one hectare plots were split into sixteen 25x25m subplots, and the vegetation was characterized in terms of diameter at breast height, species, and live or dead. In addition, UAVSAR, ALOS/PALSAR, and LVIS lidar data was collected over the larger Harvard Forest geographic region.
- The inherent resolution of the ALOS sensor (28 MHz) requires that a minimum number of independent samples (i.e. looks) be used in relating the backscatter measurements to biomass. This number of looks makes the minimum resolution for the biomass estimate to be on the order of one hectare or greater.
- Our comparison between co-polarized and cross-polarized backscatter over one hectare regions, indicates that there is some improved sensitivity to biomass using the cross-polarized measure, but that this sensitivity masked by other variables associated with the observed backscatter response.
- The use of repeat-pass interferometric observations (either interferometric phase or correlation magnitude) available from ALOS/PALSAR for characterizing the vegetation structure, is limited because of the effect of temporal decorrelation on the observations.

- A relationship was established between the lidar measured vegetation height (rh100) and the field-measured biomass. This relationship was extended over the full coverage area of the lidar data, and a biomass map of the region was created.

ACKNOWLEDGEMENTS

This work has been undertaken within the framework of the JAXA Kyoto & Carbon Initiative. ALOS PALSAR data have been provided by JAXA EORC. Funding for performing the work described here was provided under Grant #: NNX09AI18G, as part of NASA's Terrestrial Ecology program for Remote Sensing Science. The authors would also like to thank Drs. Shimada and Rosenqvist for their continued leadership at JAXA and the K&C program initiative.

REFERENCES

[1] Ahmed, R., P. Siqueira, K. Bergen, B. Chapman and S. Hensley, "A Biomass Estimate over the Harvard Forest Using Field Measurements with Radar and Lidar data," IEEE Geosci. and Rem. Sens. Symp., Hawaii 2010.

[2] Ahmed, R., P. Siqueira, S. Hensley, B. Chapman and K. Bergen, "A survey of temporal decorrelation from spaceborne repeat-pass InSAR," Rem. Sens. Env., 9pp, accepted for publication, April 2010.

[3] Jenkins, J.C., D. C. Chojnacky, L.S. Heath, and R.A. Birdsey "Comprehensive database of diameter-based biomass regressions for North Amer- ican tree species," Gen. Tech. Rep. NE-319, U.S. Department of Agriculture, Forest Service, Northeastern Research Station, 45 pp., 2004.

[4] Rosen, P., S. Hensley, I. R. Joughin, F. K. Li, S. N. Madsen, E. Ro-driguez, and R. M. Goldstein, "Synthetic aperture radar interferometry," Proc. of Inst. Elect. Eng., 88(3), 333–382, 2000.

[5] Treuhaft, R., and P. Siqueira, "Vertical structure of vegetated land surfaces from interferometric and polarimetric radar," Radio Science, 35(1), 141–177, 2000.

Paul Siqueira is an associate professor of Electrical and Computer Engineering at the University of Massachusetts in Amherst. Prof. Siqueira received his PhD from the Radiation Laboratory at the University of Michigan in Ann Arbor in 1996, and has worked as a senior engineer at NASA's Jet Propulsion Laboratory and as a visiting scientist in the Space Applicatons Institute at the European Commission's Joint Research Centre in Ispra, Italy. His early work with the Japanese Aerospace Exploration Agency has been with the JERS-1 satellite where he worked on the coregistration and mosaicking of JERS-1 data over the Amazon rainforest. His most current interests are in the use of SAR, InSAR and lidar for studying vegetation structure, and in the engineering and construction of millimeterwave interferometric systems.