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

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***Abstract*— This short paper details the current work for utilizing repeat-pass ALOS/PALSAR observations for characterizing vegetation in the Harvard Forest of Western Massachusetts. A significant number of repeat-pass measurements in both polarimetric and single/dual-polarization mode were made by PALSAR in the three years since its launch. To date, our team has been analyzing the co-polarized horizontal channel of the quad-pol mode over this region, and compared it to full waveform lidar data collected by the LVIS instrument in 2003. From these analyses, it has been possible to derive a lidar based estimates of biomass over a large geographic region, and to create relationships between the radar backscatter and the lidar derived biomass. Further, it is also possible to test the ability of the radar to estimate biomass directly, as well as to explore alternate observing scenarios, such as polarimetric interferometry and single-pol interferometry for estimating vegetation characteristics. This short paper summarizes these studies, and reinforces the well known association of backscatter power in the cross-pol L-band channel with biomass as well as showing the degree of temporal decorrelation over the PALSAR 46 day repeat cycle is sufficiently large to preclude the use of this observing mode for estimating height, or other structural characteristics, of vegetation.**

***Index Terms*—ALOS PALSAR, K&C Initiative, Forest Theme, above-ground biomass, etc. etc.**

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 Degredation) 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). The spaceborne instrument, ALOS/PALSAR [1,2], an L-band Synthetic Aperture Radar, and the Japanese Aerospace Agency's (JAXA) Kyoto and Carbon Cycle Initiative [3], 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 one study conducted by the University of Massachusetts, NASA's Jet Propulsion Laboratory, and the Japanese Aerospace Agency, scientists are using data from ALOS/PALSAR and an Airborne lidar (LVIS; from NASA's Goddard Space Flight Center) to image the vegetation structure over the Harvard Forest located in Western Massachusetts. The Harvard Forest [4] 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 (Figure 1).

Figure 1. Image of the forest cover type near the Quabbin reservoir in the ALOS/PALSAR image swath. This image gives an indication of the vegetation and landcover type for the region.

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 threedimensional structure in the Harvard region and to extrapolate the results as they would apply to similar observations worldwide.

II. Project Description

A. Relevance to the K&C drivers

One of the drivers of the JAXA's Carbon Cycle Program is for the quantification of carbon of the world's forested regions. In order to attain this far reaching goal, it is necessary to carry out focused studies on localized regions, so as to develop a better understanding of the types of accuracies and error sources involved in estimating carbon using a satellite based system.

To this end, this detailed study of the Harvard Forest provides a cornerstone for conducting further studies, as well as providing an important set of conclusions in its own right. Among the scientific findings that have been made as a result of this work are:

i.) we have derived a lidar based biomass map of the Harvard Forest region. This biomass is available to other scientists in JAXA's K&C program by request

ii.) a relationship of L-band cross-polarized backscatter to above ground biomass has been derived. This relationship is consistent with similar relationships published by other researchers in the field

iii.) it is demonstrated that the degree of temporal decorrelation over a 46 day repeat period makes it difficult to perform quantitative estimates of 3D vegetation structural characteristics based on the interferometric observations alone.

B. The Harvard Forest Region

Located near the Quabbin reservoir in Western Massachusetts, the Harvard Forest is a temperate zone mixed phase forest consisting of a variety of transition hardwood regrowth resulting from widespread disturbances that took place over 100 years ago. One of the nine NASA funded Bigfoot sites for connecting remote sensing measurements to ground process observations of carbon flux and net primary production, the Harvard Forest has been a resource for a wide variety of ecological studies on spatial scales extending from the microscopic to macroscopic. Typical characteristics of the region that are relevant to this study are an upper limit to carbon content range between 100 and 120 Mg/ha, an average tree height of 24m, a mean basal area of 40 m2/ha, and on the order of 1000 trees/ha [5].

In July of 2003, the Laser Vegetation Imaging Sensor (LVIS) overflew the Harvard region, collecting full waveform lidar data for determining the true ground elevation and the vertical extent of the canopy over a 30 kha area (9 km x 30 km). These data are used for comparison to the PALSAR backscatter and INSAR data (Figure 2).

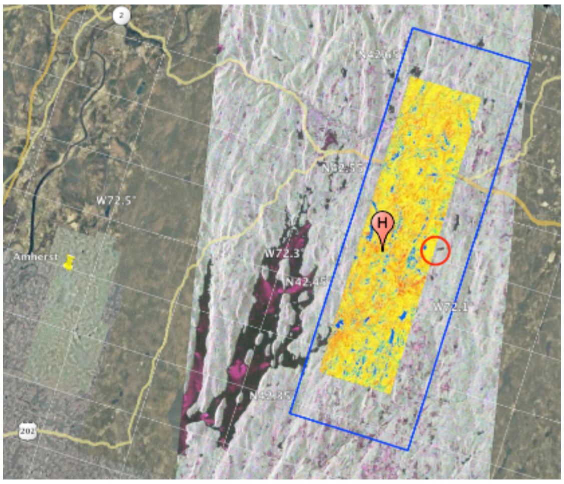

Figure 2. Location of the Harvard Forest (balloon-H) in relation to Amherst (yellow push-pin), the LVIS swath (yellow rectangle representing tree heights), the ALOS swath (white region). ALOS K&C © JAXA/METI.

C. ALOS/PALSAR Observations

Since its launch in early 2006, ALOS has made multiple observations of western Massachusetts using various observing modes, among them, fully polarimetric, single- and dual-pol, and wide beam scansar. The initial focus of this work has been on the processing of the fully polarimetric data. To date, only the co-polarized horizontal polarization has been processed. A summary of the fully polarimetric (PLR) observations (cycle number, date and season) are given in Table 1. Note that not all cycles included observations (letters monikers indicate the observations), yet some nine data collections have already been made. Each observation offers a new scene that can be interfered with the others, thus creating a matrix of possible interferograms. Table 2 provides details of the interferometric baselines between all possible pairings of these nine observations. The critical baseline being 4.5 km for this observing mode.

The sum total of all ALOS observations covers multiple years and multiple seasons. Many are in adjacent observing periods (46 days long). Hence the rich data set, especially over the Harvard Forest region, is ideal for exploring a variety of relationships relating to phenology of different target types, and repeatability of measurements over multiyear periods. All important characteristics for maximizing the utility of the existing dataset as well as for planning future ones.

Table 1. Summary of available fully polarimetric PALSAR scenes over the Harvard Forest. A letter code is given for easy reference to the different scenes.

cal	1	27-May-06	early summer
A	2	12-Jul-06	mid summer
B	3	27-Aug-06	late summer
C	4	12-Oct-06	mid fall
D	5	27-Nov-06	early winter
E	6	12-Jan-07	mid winter
	7	27-Feb-07	mid winter
F	8	14-Apr-07	early spring
G	9	30-May-07	early summer
	10	15-Jul-07	mid summer
	11	30-Aug-07	late summer
H	12	15-Oct-07	mid fall
I	13	30-Nov-07	early winter

Table 2. Interferometric perpendicular baselines (m) over the Harvard region (see table 1 for observation dates). The critical baseline for this observing mode is 4.5 km. Highlighted are those baselines of interest. Dark highlights indicate those that have baselines that are likely too large for their intended purpose.

	A	B	C	D	E	F	G	H	I
A	0	4250	3800	4500	2450	5160	4600	6180	6200
B		0	460	240	1800	910	340	1900	1970
C			0	705	1350	1360	800	2380	2460
D				0	2070	660	70	1670	1720
E					0	2730	2160	3750	3800
F						0	570	1020	1080
G							0	55	1640
H								0	52
I									0

Figure 3. Optical image (from Google Earth) of a small region covered by both LVIS and PALSAR observations. Note a variety of landcover types, ranging from open fields, open water and mixed (coniferous and deciduous hardwood) vegetation types. The size of the above image is 3 km by 5 km.

D. Work approach

The approach for performing the study has taken place in three basic steps. These are: i.) processing of the full waveform lidar data into estimates of above ground biomass based on available ground validation measurements over 43 sites within the region, ii.) processing of the ALOS data from level 1.0 into ground referenced data suitable for PolInSAR processing as well as radiometrically calibrated backscatter measurements, and iii.) investigation of relationships between the lidar derived parameters of height and biomass, and those observed with ALOS/PALSAR. First however, it is important to consider the region being studied.

Lidar data and Processing

Full waveform data from the LVIS instrument is available over a 10 by 30 km region over the Harvard Forest (see Figure 1). In addition, some 43 ground validation sites have been established [5] for studying biomass and vegetation structural characteristics. Full waveforms, like those shown in Figure 4, provide measures such as the height of mean energy (or HOME) which can be used for forming empirical relationships between vegetation characteristics of interest and the lidar measures. Several such relationships are shown in Figure 5, which relates lidar derived biomass to the biomass measured at the ground validation sites. Note that in determining the biomass relationships that make up the plot of Figure 5, the ground validation data is used two times, first to fit the data, and second, to demonstrate the quality of the fit. Given the very small sample size (43 plots, 30m in diameter), this is an acceptable approach.

Further, Figure 5 also demonstrates the goodness of fit for two different types of polynomials. One, a linear fit to the lidar measure of HOME (equivalently rh50) and the other, proportional to HOME, the square of HOME, and the variance of the HOME measure. In all, the improvement attained by the more complicated model is only 5 Mg/ha for the root mean square error, or RMSE. Because of the minor improvement, it is generally preferred to rely on the simpler model, to avoid overfitting of the ground validation data.

A last step of preprocessing for the lidar data was necessary. This involved in examining the lidar waveforms over the ground validation sites in a 3-dimensional framework to assure that the lidar waveforms were correctly aligned with respect to the true ground surface. That is, it was found that a significant number of waveforms were mis-registered in the vertical direction and had to be corrected so as not to provide false signatures related to the vegetation height. An example of a successful set of lidar waveforms over the 85th Harvard Forest Site is shown in Figure 6.

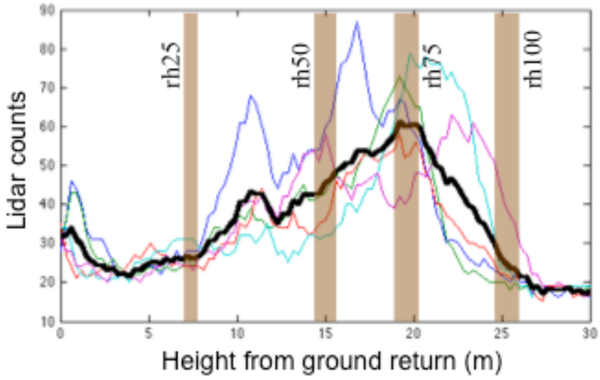

Figure 4. An LVIS waveform plot over a 700 m^2 Bigfoot test plot (#85) located at the Harvard Forest. The biomass for this area was measured to be 92 ± 10 Mg/ha. Shown are five waveforms (thin lines) and the average waveform (thick black line) and the radar metrics of rh25, rh50, rh75 and rh100, which can be used for forming empirical relationships between height and vegetation structural characteristics or biomass.

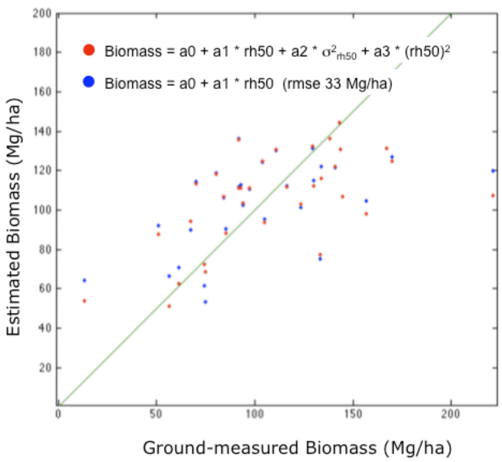

Figure 5. Results from forming a polynomial fit between full waveform derived lidar moments and measured biomass. There is a preference for the least complicated model, shown in blue, which gives a mean error of 33 Mg/hectare. ALOS K&C © *JAXA/METI.*

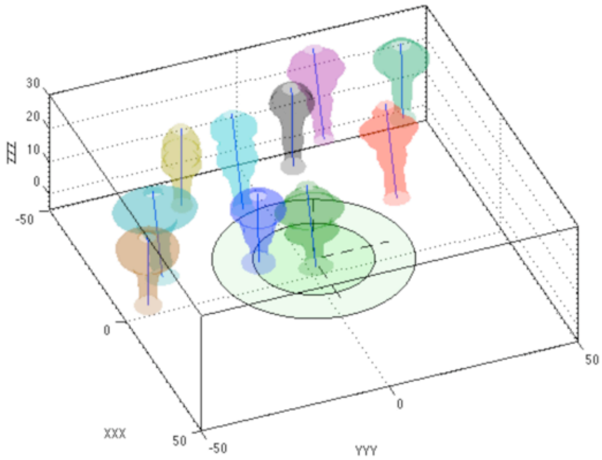

Figure 6. A 3-dimensional plot of lidar waveforms associated with the site #85 of the Harvard Forest ground validation data. Shown at center are 15m and 25m radii around the area where data were taken on the ground. Ten lidar waveforms closest to the site (shown in different colors), are plotted with different aspect angles due to the changing position of the lidar platform, and the power as a function of height, shown as a vertical cylinder with varying radius, for each lidar return. It was determined that individual lidar waveforms had to be adjusted to assure that all were correctly registered to the true ground surface for the region.

Figure 7. A close-up optical image of site #85 at the Harvard Forest. Images such as these were used to interpret the observed lidar returns for each site.

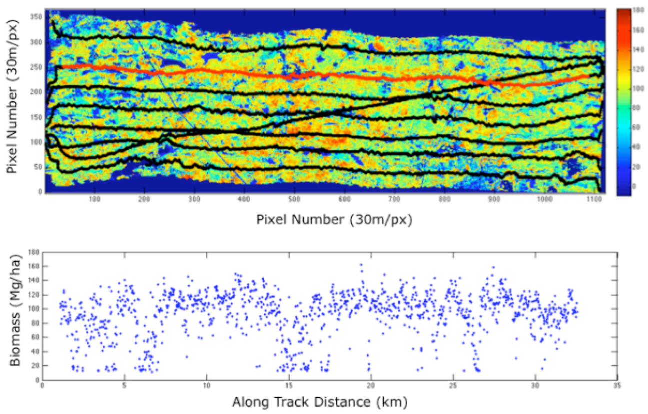

Figure 8. Image of the lidar-derived biomass map of the Harvard Forest region overlain with the nadir track of the LVIS lidar. The part of the track highlighted in red was used to extract a plot of biomass which could be compared to radar observations of backscatter power and interferometric correlation. The lower plot shows the resulting biomass estimates calculated along the highlighted LVIS nadir track.

Once the relationship between lidar and ground validation data (shown in Figure 7) was established, a full biomass map based on the observed LVIS lidar data set was derived. This is shown in Figure 8 and Figure 10. In Figure 8, this biomass map is overlain with the nadir track of the LVIS sensor. The nadir track tends to be more accurate because of the simpler viewing geometry and better ground return for the lidar in the nadir direction.

Data from this nadir track was extracted and used for comparison against radar derived measures of correlation and backscatter, thus providing a pathway for determining how well the radar can estimate the vegetation structural characteristics across the lidar swath and over wider regions where lidar data might not be available. The biomass as a function of position along one of the LVIS nadir tracks is shown in the lower half of Figure 8. The full biomass map, expanded in size to show greater detail, is shown in Figure 10.

SAR and InSAR data and Processing

SAR and repeat-pass InSAR data were collected over the Harvard Forest using multiple observing modes of the ALOS/PALSAR instrument. For the work described in this paper, we show only those results relating to the polarimetric observing mode known as PLR 21.5.

Data was requested from JAXA in level 1.0 format so that all scenes could be processed by gamma remote sensing software to the same Doppler centroid (necessary for interferometric processing). Further, data were coregistered to the SRTM DEM, using a simulated backscatter image derived from the DEM. This process allows easy exchange between radar data coordinates and map coordinates, as well as the extraction of the known DEM (C-band) from the interferometric data.

Because the processed SAR data is effectively co-registered to the SRTM DEM map-level data to the sub-pixel level, both in radar and map coordinates, the task of making comparisons between the lidar (in map coordinates) and radar data sets is a straight-forward task. An illustration of this relationship is shown in Figure 9.

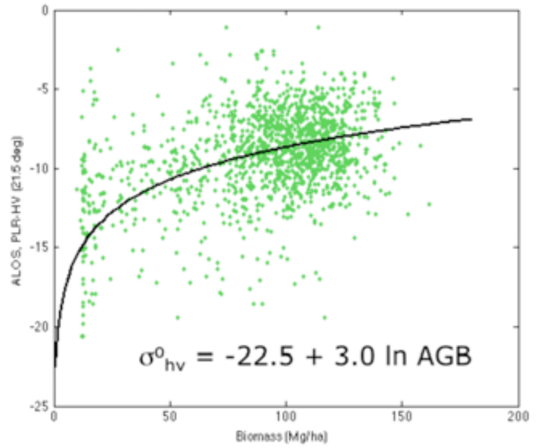

Figure 9. A relationship between ALOS measured backscatter cross-pol power (21.5 degree look angle) and lidar derived biomass. The black curve shows the equation for above ground biomass (ABS) and the backscatter power. ALOS K&C © JAXA/METI.

Processing for interferometry and polarimetric interferometry is a bit more involved (see Figure 11). It requires careful calibration of the data and processing all polarizations for the two (or more) passes of the instrument to a common Doppler centroid, nominally zero, or in the broadside direction to the flight path. After processing scenes, they are coregistered (if not already) and the coherence matrix is formed from the multiple polarizations. Based on the observing geometry and the SRTM DEM, the interferometric phase due to topography is removed, thus leaving only that phase that is associated with the difference in topography seen between the SRTM C-band observations and those from ALOS/PALSAR's L-band SAR.

The resulting interferogram for any one combination of two polarizations is a complex number. The phase, relating to the differential topography discussed in the previous paragraph, and the amplitude, which is relate to the standard deviation of the phase. For volume scatterers, this standard deviation is proportional to the vertical depth of the volume, and thus can provide a method for estimating the vegetation height.

There are other signals that affect both the volume and phase of the interferometric signature however. Related to the phase, things like a differential path length through the atmosphere (due to weather etc.) can distort the phase across the observed swath. For the correlation magnitude, the primary error source for repeat-pass systems is related to a changing electromagnetic signature of the target in the time period between observations. This signature can be altered by simple things such as active weather (wind and rain [6]), as well as long term effects related to seasonal differences in the target. Because of the 46 day repeat period of ALOS, it would be expected that this might be a dominant error source, and indeed it is. While correlation magnitudes are large enough to provide sufficient signature for estimating phase, they are large enough to preclude the use of the instrument for using the correlation magnitude signature to perform vegetation height estimation.

III. Results and Summary

In all, the detailed work has yielded a lidar-derived biomass map of the Harvard Forest region. This map was used to develop and test relationships between the L-band SAR backscatter and interferometric signature against the biomass or other forest structural characteristics. In all, it was shown that a basic signature exists between backscatter and biomass, but that the variation is a bit large (Figure 9). This would make inverting the model prone to large uncertainty. Further, interferometric correlation magnitude was studied with the intent that it might be useful for vegetation height extraction. Temporal decorrelation however proved to be a dominant error source, and hence for the PLR 21.5 observing mode over the Harvard Forest at least, it is unlikely that the correlation magnitude can be used for quantitative estimation of vegetation height or other physical characteristics.

Future work will entail the investigation of other ALOS observing modes (such as the dual-pol FBD 34.3) for estimation of vegetation characteristics. The dual-pol observing mode will have a larger cross-track swath (and thus better for mapping) as well as a larger incidence angle, which will likely amplify the polarimetric signature of the vegetation. Figure 12 provides an illustration of the breadth and depth available from these other observing modes. Shown are the LVIS observing swath, a SRTM derived DEM corigistered to PALSAR polarimetric data (FBS 21.5) and PALSAR FBD differential interferometry data.

Acknowledgement

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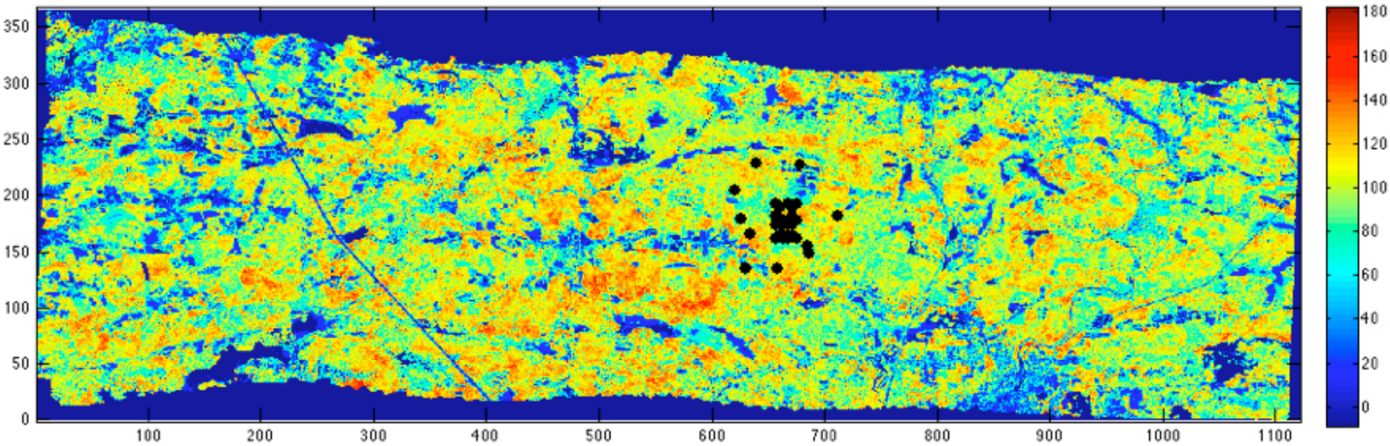
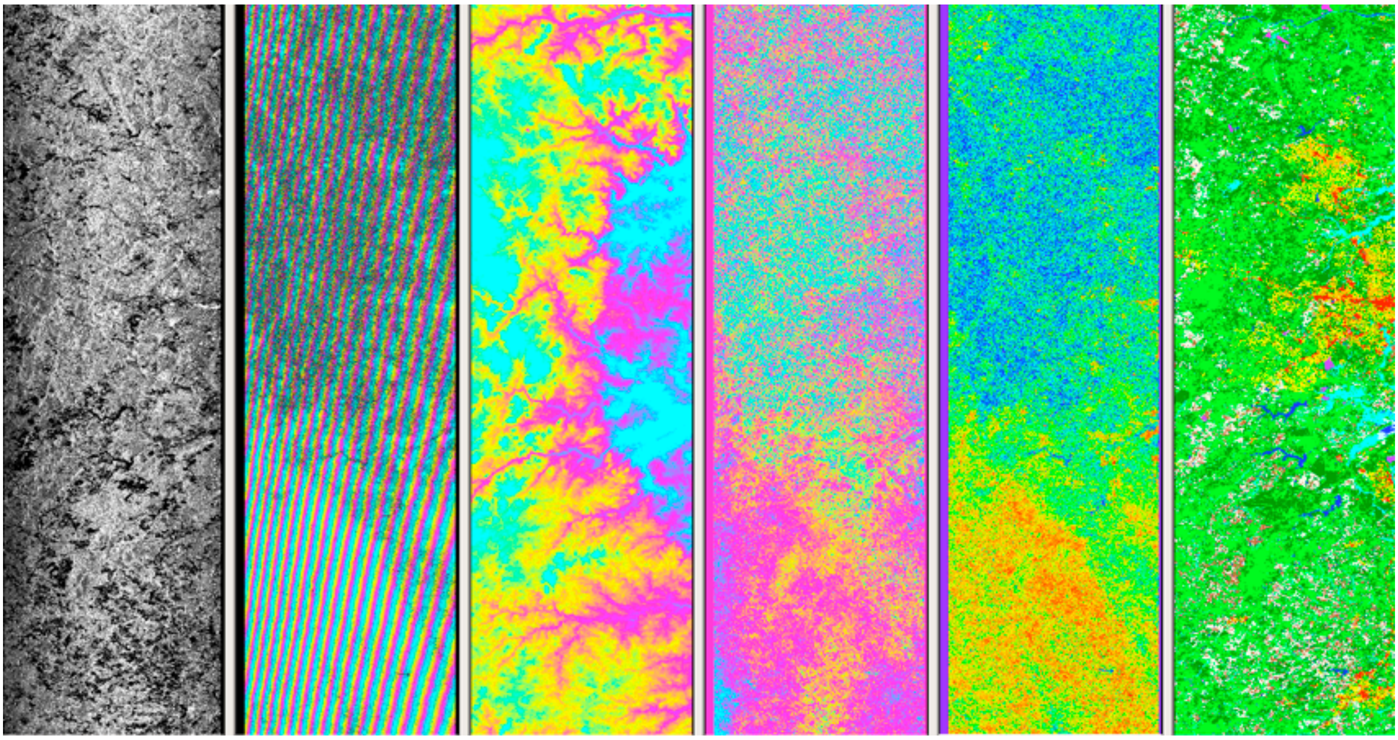


Figure 10. A biomass map of the Harvard Forest region using Goddard Space-Flight Center's LVIS (Laser Vegetation Imaging Sensor). Black dots near the center of the image indicate the locations of the 700m2 plots were biomass and other vegetation physical characteristics were measured on the ground. Horizontal and vertical (inverted) scales are in units of meters with respect to the SoutH-East corner. A depiction of the location of the LVIS swath with respect to larger geographic features and other data sets is shown in Figure ZZZ. Biomass units are in kilotons per hectare.



(a) (b) (c) (d) (e) (f)

Figure 11. Illustration of the various steps along the SAR processing chain. Shown is (a) the backscatter image, (b) interferometric correlation and fringes, (c) the SRTM DEM, (d) the differential interferogram, (e) the interferometric correlation magnitude and (f) a map of the national land cover data base (NLCD) from 2006.

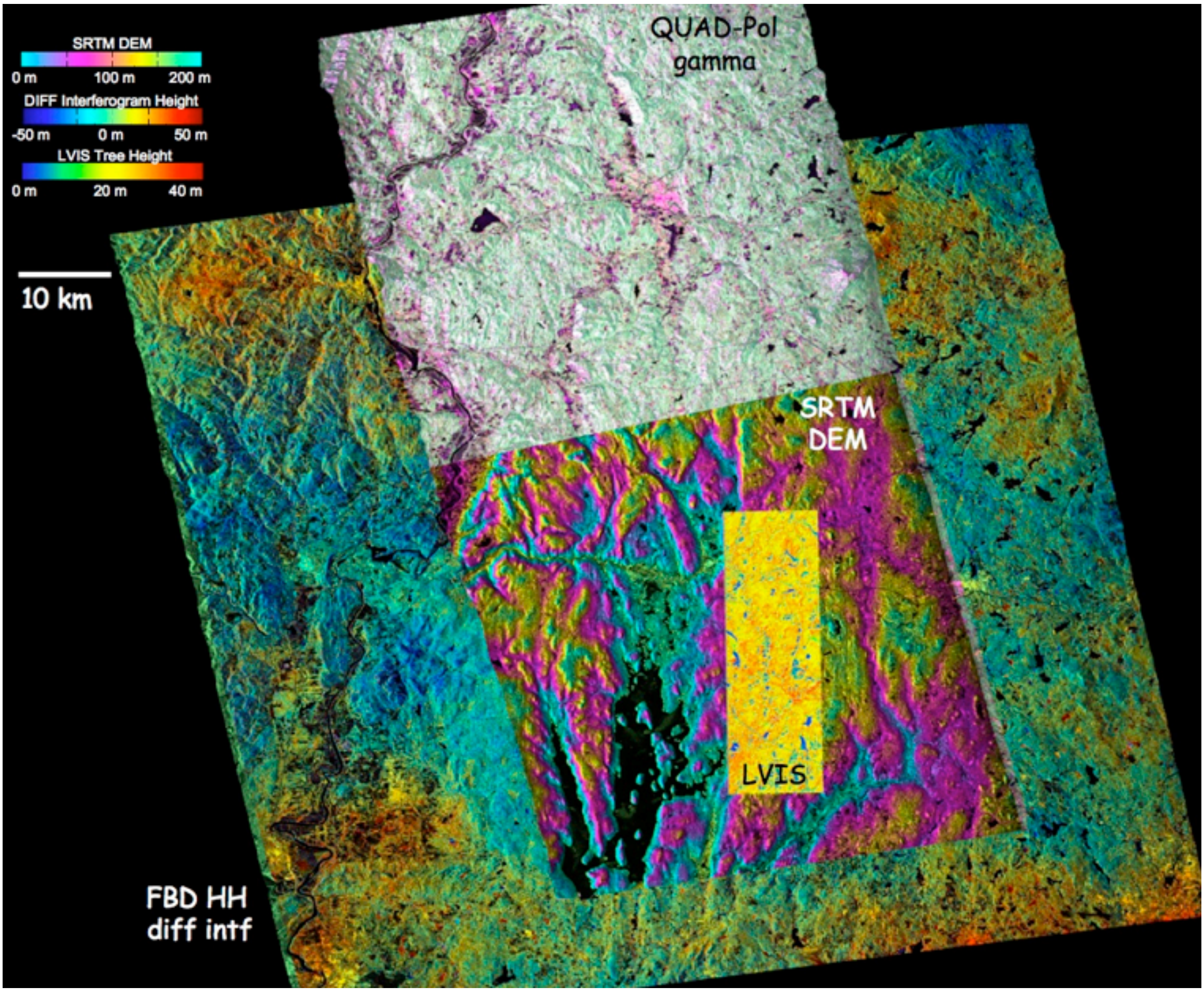


Figure 12. Image of the PALSAR coverage area over the Harvard Forest. Shown are the FBD differential interferogram, the Quad-pol, terrain corrected backscatter, a sample of the DEM derived from SRTM, and the tree height data derived from full-waveform lidar (LVIS). ALOS K&C © JAXA/METI