Multi-frequency and multi-polarized SAR response to thin vegetation and scattered trees

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This communication highlights the results of a study carried out to understand the Synthetic Aperture Radar (SAR) response to thin vegetation volume at L, C and X bands as well as cross-polarizations at L and C bands, and the X band at VV polarization. The sensitivity of SAR backscatter to the vegetation volume varies with the frequency, polarization and incidence angle at which the canopy is illuminated. Multi-frequency, multi-polarized SAR response of thin linear vegetation along the roadside, small thorny hedges along the boundary of the farmers' fields and scattered cluster of trees was studied for this purpose. It was observed that cross-polarized signals were able to pick up signals better from a very thin vegetation volume among the polarization responses and the L band was the most sensitive among the frequencies.

Keywords: Cross-polarization, multi-frequency SAR, multi-polarized SAR data, scattered trees, vegetation.

A row of trees along the roadside or scattered trees in the farmers' fields or in any open space forms a good fraction of vegetation volume in the total vegetation of a given country. However, when it comes to accounting for the vegetation volume, the task seems impossible owing to difficulties involved in detecting and counting such thin vegetation volume. On the other hand, scattered trees in the farmers' fields or in waste-land areas also remain unnoticed mainly due to the scattered nature of such vegetation. Remote sensing comes handy in most of the applications where large geographical areas are to be surveyed. The task of detecting thin vegetation volume becomes challenging owing to the fact that it is required to have a sufficiently large, contiguous patch of uniform land cover in order to detect the same in a remotely sensed image. It is known that SAR signals are sensitive to tree canopy structure, size, orientation and moisture content of leaves, branches and trunk. Remote sensing using SAR has proved to be useful for many forest-related applications[1–4]. The interaction between SAR signal and tree canopy is volumetric in nature. Hence, the fraction of vegetation volume in a given resolution cell has significant impact on the SAR signal. Moreover, the amount of SAR signal that is attenuated due to vegetation volume is dependent on the frequency of operation, the polarization of transmit and receive signal, and incidence angle[5]. In this study, a comparative evaluation of the sensitivity of multi-frequency, multi-polarized SAR data to very thin vegetation volume has been made using data acquired at an angle of incidence of 36° from SIR-C/X-SAR mission. This communication highlights the results of a study carried out to understand the SAR response to thin vegetation volume at the L, C and X bands as well as cross-polarizations at the L and C bands, and the X band at VV polarization. The sensitivity of SAR backscatter to the vegetation volume varies with the frequency, polarization and the incidence angle at which the canopy is illuminated. Multifrequency, multi-polarized SAR signal of thin linear vegetation along the roadside, small thorny hedges along the boundary of the farmers' fields and scattered cluster of trees was studied for this purpose. It was observed that the cross-polarized signal was able to pick up very thin vegetation volume better among the linear polarization responses, and the L band was the most sensitive among the frequencies.

The total backscatter from forested terrain can include components from several backscatter mechanisms[6]. Total backscatter comprises of direct backscattering from the ground, trunk–ground backscattering, direct backscattering from the trunk, crown–ground backscattering and crown backscattering, including multiple scattering within the crown. The crown–ground and trunk–ground double bounces can be in both directions, i.e. from tree to ground or ground to tree. In the case of ground interaction, factors such as surface roughness and soil moisture have an important influence. The magnitude of each one of these backscatter components depends upon radar wavelength, polarization, angle of incidence and a myriad of terrain and canopy parameters. The contribution of the canopy layer in SAR backscatter is highly dependent on the orientation and size distribution of the scattering elements within the region being imaged. Due to their high moisture content, individual components of forest canopies (e.g. leaves, branches, trunks) represent discrete scattering and absorbing elements to the microwave power transmitted by the radar. Dobson *et al*.[7] observed that the depth of penetration of a signal into a forest canopy is governed by the degree of interaction that the field has with the canopy. C- and X-band microwave frequencies (5 and 3 cm wavelengths) interact more strongly with the leaves and branches of the upper canopy, while P- and L-band signals (68 and 24 cm wavelength) penetrate through the upper canopy of the forest. The L band penetrates mostly up to the trunk, whereas the P band interacts more strongly with the trunk as well as the ground[8]. Thus, at a given incidence angle, the frequency at which the vegetation volume is illuminated determines the depth of

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penetration within the vegetation canopy, which in turn determines the number of vegetation components with which the incoming SAR signal is interacting. Hence, the sensitivity of the SAR signal to plant density is strongly dependent on the frequency of illumination.

The proportion of horizontally and vertically polarized components in the received backscatter is dependent on the polarization of the transmitted microwave signal and the relative orientation of the scattering elements present in the vegetation[9]. Compared to the like-polarized SAR signal, the cross-polarized SAR signal is likely to be more sensitive to vegetation volume owing to the depolarization of the signal that takes place during the multiple reflection of the incoming signal inside the vegetation volume[10]. Due to the characteristic interaction of the SAR signal with the vegetation volume, it is expected that longer wavelength, cross-polarized radar data would be able to detect thin vegetation volume in a better way.

A limited number of SAR missions was flown, from which multi-frequency data have been collected. The only space-borne missions are those flown on the NASA shuttle, which have collected data over a number of preselected sites. The SIR-C/X-SAR system was flown as a science experiment on the space shuttle Endeavour in April (SRL-1) and October 1994 (SRL-2), collecting SAR data over many sites around the world, including India. SIR-C/X-SAR operated in multi-polarization mode for the L and C bands, whereas at the X band it operated at a single polarization[11]. The SIR-C/X-SAR system was able to provide data in the incidence angle varying from 15° to 60°. Imaging resolution varied from about 10 to 50 m depending upon the geometry. Additional information about SIR-C is available at http://southport.jpl.nasa.gov/. In the present study, SIR-C/X-SAR L- and C-band data at VV, HH and VH polarization, and X-band data at VV polarization at 36° angle of incidence acquired on 12 April 1994 have been analysed for understanding the detection capability of SAR backscatter to thin vegetation.

The study area falls near village Velavadar, Bhavnagar District, Gujarat, India. The study area is dominated by deltaic alluvium soils. *Prosopis juliflora* is the dominant plant type found in the area. Thin, linear vegetation along the roadside, small thorny hedges along the boundary of the farmers' fields and scattered cluster of trees present in the study area were investigated. Ground surveys were carried out in synchrony with the SIR-C/X-SAR flight during April 1994. Topographic map, previous ERS-1 SAR image and optical remote sensing data of IRS-LISS II were also used as support data for the purpose of carrying out ground truth and data analysis. The following are the major steps involved in data analysis.

At the time of data taken in April 1994, the study area was dominated by fallow agricultural areas, scrubland and grassland. The area is under dry-land farming and has no means of irrigation. Hence there were no agricultural crops during April 1994. The moisture status of the agricultural fallow fields was mostly dry to very dry. Scrubland consisted of *P. juliflora* plantation and grassland consisted of dry grass. Other land-cover classes like creeks, barren land and habitation were also present in the study area. For the purpose of ground truth and data analysis, support data like topographic map, ERS-1 SAR image and optical data from Indian Remote Sensing Satellite were also used. Areas showing peculiar signatures were marked on ERS-1 images. These sites were visited to understand the SAR response at various polarizations and frequencies to different ground covers. Most of the area had very dry soil conditions, except for the creek areas where sea water flows back and forth. Areas having thin linear vegetation along the roadside, small thorny hedges along the boundary of the farmers' fields and scattered cluster of trees were taken as the ground-truth locations for this purpose. Ground-truth locations were identified with the help of GPS.

The data were provided as a compressed scattering matrix of complex numbers with real and imaginary components. These single-look complex images of SIR-C SAR were converted to backscatter images using RAVEN software[12]. Six backscatter images, comprising the L-band HH, VV and VH polarization and C band HH, VV and VH polarization were generated.

For speckle suppression, SAR data were subjected to enhanced Lee filter[13] with a moving window of 3×3. The L-band HH image was geo-referenced with the help of GPS and 1 : 50,000 scale, Survey of India (SOI) topographic map. The remaining SAR images were co-registered with this master image. The road network and ground-truth locations were digitized and transferred on the image. Ground-truth locations were identified with the help of their latitude and longitude positions. $\sigma°$ (SAR backscatter) was extracted for a strip of 40 pixels for each of the ground-truth sites in such a way that the location of the target was centred. $\sigma°$ extracted from the L- and C-band SAR for HH, VH and VV polarization, and the X band VV polarization was termed as $\sigma^{\circ}_{\mathrm{fpp}}$ dB, i.e. $\sigma°$ at frequency *f* (either L, C or X in our case) and polarization state pp (i.e. HH, VH or VV in our case). Thus backscattering coefficients for the L, C and X band at HH, VH and VV polarization are $\sigma^{\circ}_{\mathrm{Lhh}}$ dB, $\sigma^{\circ}_{\mathrm{Lvh}}$ dB, $\sigma^{\circ}_{\mathrm{Lvv}}$ dB, $\sigma^{\circ}_{\mathrm{Chh}}$ dB, $\sigma^{\circ}_{\mathrm{Cvh}}$ dB, $\sigma^{\circ}_{\mathrm{Cvv}}$ dB and $\sigma^{\circ}_{\mathrm{Xvv}}$ dB respectively. Unit of backscattering coefficient or SAR backscatter is decibel and is represented by dB.

The study aims at understanding the detection capability of SAR backscatter to the thin vegetation at different polarizations at the L and C bands as well as at the X-band VV polarization. For this purpose, the following three features were studied:

1. Areas having thin linear vegetation along the roadside.
2. Small thorny hedges along the boundary of the farmers' fields.
3. Scattered cluster of trees.

Field photographs showing the ground condition of these features, namely thin vegetation along the roadside, small thorny hedges along the boundary of the farmers' fields and scattered cluster of trees are given in Figures 1 *a*, 2 *a* and 3 *a* respectively. We now describe the feasibility of detecting each of these features in multi-polarized and multi-frequency SAR images.

The thin vegetation of *P. juliflora* was around 1–2 m high and a row of single plants run parallel alongside the road (Figure 1 *a*). The corresponding sub-images were extracted from the L and C bands at like as well as cross-polarizations and the X band at VV polarization. Backscattering coefficient ($\sigma°$) values were extracted for all the seven SAR images for a strip of 40 pixels for each of the ground-truth sites in such a way that the location of the target was centred. The profile of SAR backscatter observed across the thin vegetation along the roadside is shown in Figure 1 *b* for the L band at VV, VH and HH polarization, for C band at VV, VH and HH polarization and for X band at VV polarization. In order to highlight the effect of thin vegetation on multi-parametric SAR image, the profile of SAR backscatter across the road without thin vegetation is also shown in Figure 1 *c*. It is interesting to note the cross-polarization response for the thin vegetation at the C as well as L bands. A peak in the SAR backscatter was observed for L_{VH}, C_{VH} and L_{HH}, whereas for L_{vv}, C_{vv}, C_{hh} and X_{vv} there was no difference between the response of the thin vegetation and the surrounding rough fields. The peak to background difference was 20 dB for the L band VH polarization, and for the C band VH polarization the peak was 10 dB higher than that of the background. Whereas, for the like-polarized L-band HH, peak to background difference was 4 dB. Thus the L-band cross-polarization is most sensitive to thin vegetation followed by C-band cross polarization and L-band HH polarization. The thinly vegetated areas are surrounded by dry, rough agricultural land. Hence the background happens to be relatively smoother for L band in comparison to the C-band. This leads to poor background-to-peak ratio for C band like polarized backscatter images. The impact of the vegetation volume on the C-band cross-polarized backscatter was higher compared

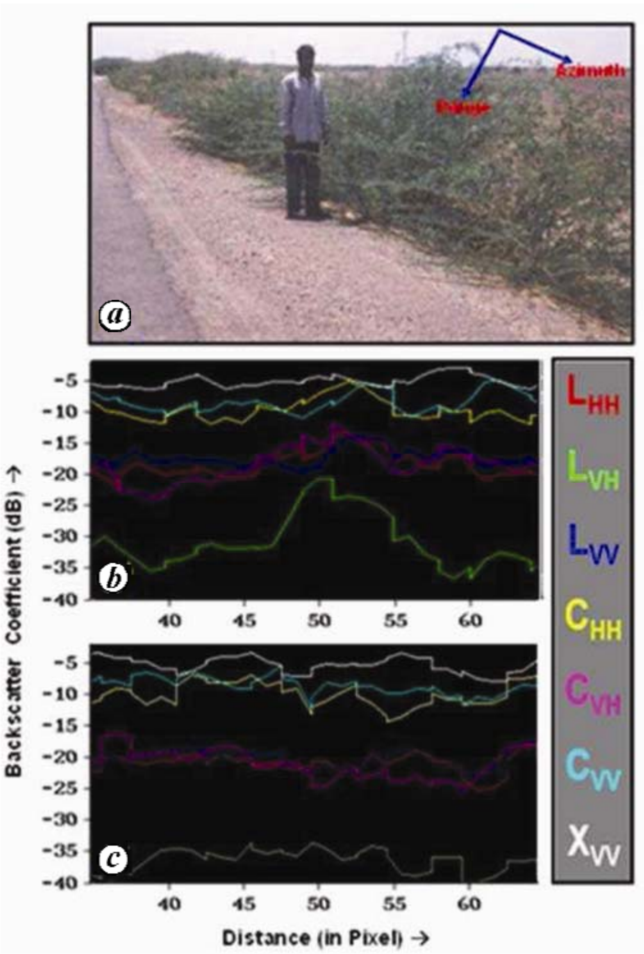

Figure 1. Field photograph and response of multi-frequency and multi-polarized SAR backscatter towards thin vegetation along the roadside. (Location of thin vegetation is at pixel position 50 and response without thin vegetation is shown in ***c***.)

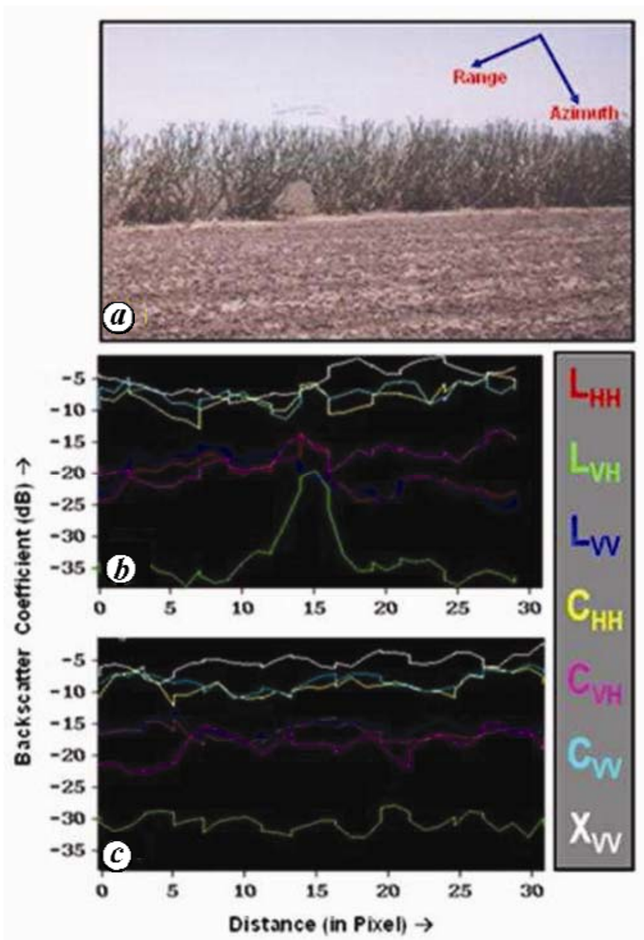

Figure 2. Field photograph and response of multi-frequency and multi-polarized SAR backscatter towards small thorny hedges along the boundaries of the farmers' fields. (Location of hedges is at pixel position 15 and response without hedges is shown in ***c***.)

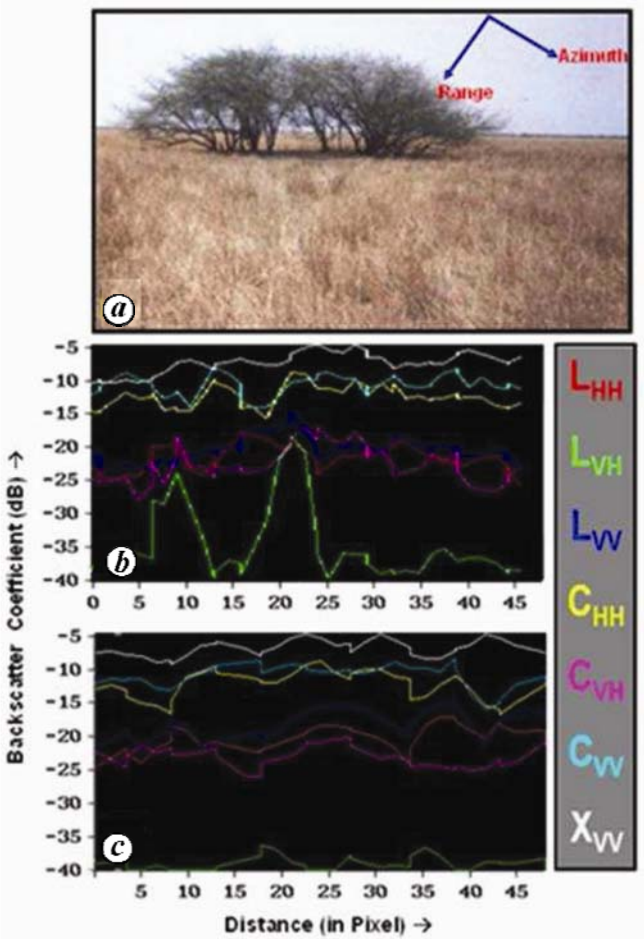

Figure 3. Field photograph and response of multi-frequency and multi-polarized SAR backscatter towards two closely spaced clusters of *Prosopis juliflora* over the background of uniform dry grasses. (Location of first and second clusters is at pixel positions 9 and 21 respectively and response of uniform dry grasses without clusters is shown in ***c***.)

to that of surrounding bare dry rough fields due to multiple scattering that takes place within the vegetation volume. This makes the thin vegetation along the roadside discernible from the surrounding dry rough fields in both the cross-polarized SAR channels. Whereas for the C-band like-polarized SAR, the return signal strength for the dry bare rough fields was comparable to the return signal strength from the thin vegetation volume along the roadside. This leads to poor discrimination between the vegetation and agricultural fields. However, one must note that when there is contiguous vegetation, the same is not true. A patch of dense vegetation is clearly picked up even in the C-band like-polarized backscatter image. This indicates that the vegetation density also plays an important role in determining the SAR return signal.

Similar observations were made for small thorny hedges along the boundary of the farmers' fields (Figure 2 *a*). Figure 2 *b* shows the extracted SAR backscatter values across the hedges for all the seven $\sigma^{\circ}_{\mathrm{fpp}}$ dB values, whereas Figure 2 *c* shows the extracted SAR values across the farmers' fields without hedges. The distinct signature of small thorny hedges at cross-polarized L-band SAR indicated the sensitivity of cross-polarized L-band SAR to such a sparse vegetation volume available within small thorny hedges. The hedges did not give any distinct signature at the L-band VV polarization. However, the SAR return at the L-band HH polarization for the hedges was observed to be slightly higher compared to the surrounding background of dry rough agricultural fields. Figure 2 *a* also indicates that the higher sensitivity of HH polarized backscattering to hedges can be attributed to the structure of the hedges that is responsible for higher coupling of the incoming HH polarized signal with the hedges.

The study of SAR response to two closely spaced clusters of *P. juliflora* plants as shown in Figure 3 *a*, leads to an interesting observation. The study of SAR responses shown in Figure 3 *b* indicates that the L-band cross-polarized SAR could detect two distinct clusters, whereas the C-band cross-polarized SAR could not give distinct signatures for two clusters; it appeared more or less as a single cluster. In order to highlight the effect of clusters of trees against the uniform background of dry grasses, the profile of SAR response over uniform dry grasses without tree cluster is shown in Figure 3 *c*. The background-to-peak ratios for L-band cross-polarized SAR was 20 dB for the first cluster and 15 dB for the second cluster, whereas for the C-band cross-polarized SAR, the background-to-peak ratio for the merged cluster was of the order of 7 dB. This once again confirms the high sensitivity of cross-polarized longer wavelengths to the vegetation, as described earlier. The L-band cross polarization interacts with factors affecting SAR response to various components of trees, whereas the C-band SAR interacts only with the top canopy of the cluster, resulting in a single peak.

In this communication multi-frequency, multi-polarized SAR data from SIR-C/X-SAR mission were studied for sensitivity towards detecting the presence of thin vegetation along the roadside, and hedges around the farmers' fields. Feasibility of detecting two spatially separated clusters of *P. juliflora* at L and C bands was also studied. The analysis of signatures for these features at multi-frequency and multi-polarization SAR in comparison to the background SAR backscatter values leads to interesting results. It has been observed that longer wavelength is in general more capable of detecting thin vegetation, which is attributed mostly to the increased path length within vegetation volume. In the polarization response, cross-polarization was found to be better suited for detecting the presence of scattered isolated thin vegetation, mostly owing to the multiple scattering of SAR signal occurring within vegetation volume. Cross-polarized SAR even at the C band was found to be useful in detecting the presence of thin vegetation. However, with regard to detecting two spatially separated clusters of *P. juliflora*, the L-band cross-polarized SAR was found to be best suited as two distinct peaks were observed for it. Whereas the C-band cross-polarized SAR could not give two distinct peaks corresponding to two tree clusters. Instead the two clusters appeared as more or less as a single cluster on the C-band cross-polarized SAR image. The X band could not detect the presence of thin vegetation volume for any of the three cases taken up in this study, as the thin vegetation failed to have any impact on the X band SAR in comparison to its surrounding features. Thus the overall L-band cross-polarized SAR was found to be the most suitable for detecting thin vegetation volume in the present study.

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The Great avulsion of Kosi on 18 August 2008

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The 18 August 2008 avulsion of the Kosi River draining the parts of north Bihar in eastern India may well be regarded as one of the greatest avulsions in a large river in recent years. The Kosi River shifted by ~120 km eastward, triggered by the breach of the eastern afflux bund at Kusaha in Nepal at a location 12 km upstream of the Kosi barrage. This event was widely perceived as a major flood in the media and scientific circles. Although a large area was indeed inundated after this event, it is important to appreciate that this inundation was different from a regular flooding event.

Keywords: Floods, Ganga plains, Kosi barrage, river dynamics, river management.

RIVERS play a critical role in human society and history as they are the major source of fresh water, transportation, and resources. However, this relationship is often 'troubled' because changes in river discharge (floods or droughts) or position can play havoc with permanent settlements. Such changes can be caused by natural forcing as well as human interventions, or a combination of both. Natural processes may include short-term changes in sediment load or water volume as well as long-term changes in relative sea level or climate change. The human interventions impact changes in sediment load or run-off through water resource management schemes such as dams, barrages and embankments. Human alterations of river systems can have many important consequences, primarily because river systems are dynamic and highly integrated systems and, any change in any part of the river can easily propagate and affect the whole system.

The Kosi River is an important tributary of the Ganga in the eastern India (Figure 1 *a*) and has distinctive hydro-

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