Application potentials of synthetic aperture radar interferometry for land-cover mapping and crop-height estimation

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Synthetic aperture radar (SAR) interferometry is widely used for applications like digital elevation map generation and studies related to surface movement. However, SAR interferometry can also be exploited in many other areas. Here a few of the potential applications of SAR interferometry have been demonstrated by exploring its use in delineation and density mapping of forested areas, delineation of surface water extent under adverse weather conditions, which is useful during flood-mapping; detection of human settlement and crop-height estimation. This has been achieved by exploiting interferometric coherence, which is inversely related to the magnitude of random dislocation of scatterers between the two passes. The study indicated that interferometric coherence decreases with increase in forest density or increase in crop height. It was also observed that interferometric coherence over stable targets like settlement is quite high compared to other land-cover classes. In contrast, interferometric coherence is always low for unstable surfaces like the water surface. The study suggested that interferometric coherence is a parameter that provides valuable information, which is completely different from that of SAR backscatter. It was also observed that synergic use of SAR backscatter with InSAR coherence enhances the application potential of a SAR system as a whole towards many land-cover features.

Keywords: Crop-height, forest density, human settlement, interferometric coherence, surface water extent.

IT is well known that microwave remote sensing has immense potential in general land-cover mapping, including forestry, agriculture, human settlement and wetland-related studies. It is not only due to the all-weather capability of microwave over optical remote sensing, but also due to its unique sensitivity towards the texture, surface roughness, canopy structure, canopy moisture, vegetation volume, shape, size and orientation of the target. However, land-cover mapping is difficult using single-frequency and single-polarization C-band intensity synthetic aperture radar (SAR) data as under certain conditions, the ranges of backscatter intensities over forests, wetlands and agricultural fields overlap with each other. Here, an attempt has been made to demonstrate the potential of SAR interferometry (InSAR) for land-cover mapping by exploiting the sensitivity of interferometric coherence for various land-cover features. Synergic use of interferometric coherence with SAR backscatter has also been attempted. The study indicated that interferometric coherence could be used as an additional tool along with backscatter data, to enhance the application potential of microwave remote sensing in the field of forestry, surface-water extent and human settlement. The feasibility of estimating crop height, which is an important information for various agricultural applications, has also been attempted using interferometric coherence.

SAR interferometry was introduced by Graham[1] for topographic mapping and it was widely used to generate digital elevation maps (DEM) and studies related to surface movements[2]. This is due to the fact that the height information can be related to the phase difference between two SAR images. However, there are some of the less explored potential applications of SAR interferometry[3–6]. Here an attempt has been made to demonstrate a few such potential applications. The applications demonstrated are in the field of forest density mapping, delineation of surface-water extent under adverse weather conditions (wetland, water body, flood, etc.), crop-height estimation and detection of human settlements. This has been achieved by exploiting the interferometric coherence, which is defined as the normalized complex cross-correlation of both complex signals S_1 and S_2 received from the first and second images. The coherence g is a quantitative measure that represents the amount of noise present in a SAR interferogram. Absolute value of coherence varies from 0 (incoherence) to 1 (perfect coherence). Coherence value 1 indicates that both the signals are identical, whereas zero coherence value indicates that both the signals do not correlate. Coherence (g) is defined as:

$$g = \frac{< S_1 S_2^* >}{\sqrt{(< S_1 S_1^* >< S_2 S_2^* >)}}, \qquad (1)$$

where S_1 and S_2 represent the two complex signals, $< >$ gives the expectation value and * represents the complex conjugation operator.

In the context of interferometry, coherence represents phase variance between two SAR images. The value of coherence indicates the level of changes in phase. Coherence provides information on temporal stability and is therefore an important feature for general land-cover mapping. Temporal decorrelation is caused by those features on the ground that produce random dislocation of scatterers between the two passes. Forest cover, vegetation/crop cover, water surfaces and human activities like ploughing, etc.

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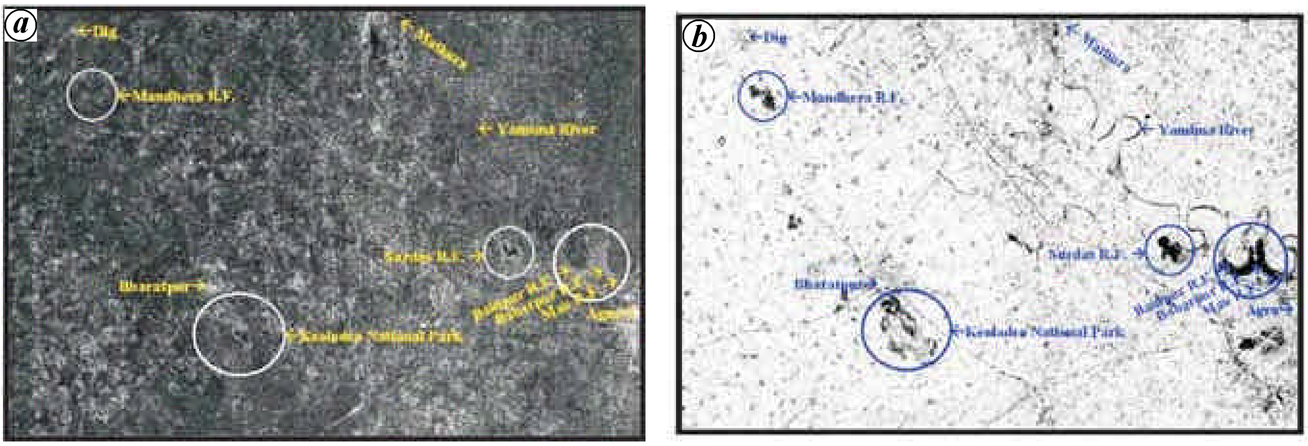

Figure 1. ERS SAR backscatter image (***a***) and Interferometric coherence image (***b***) over parts of Agra, Mathura and Bharatpur districts.

are good sources of random dislocation of scatterers between the two passes. All these phenomena cause random change in the location of scatterers, between the two passes. These changes can be observed over periods of hours to months. However, for some features like water surfaces and dense forests, changes can occur in a matter of seconds.

For the purpose of exploring the potential applications of InSAR technique, it was required to monitor the random dislocation of scatterers between the two passes. Best results can be obtained by minimizing the time difference between the two passes. For this purpose, the interferometric data pair from ERS-1/ERS-2 (tandem mission) over parts of Agra, Mathura and Bharatpur districts has been acquired. In tandem mission, ERS-2 followed ERS-1 with a time lag of 24 h. It means that the same area had been viewed by ERS-2 after 24 h. ERS-1/ERS-2 tandem mode data provided the interferometric pairs highly suited for land-cover mapping, as little human activity is expected between the two passes and therefore any decorrelation in the interferogram is expected due to the random dislocation of the scatterers from vegetation covered soils and water bodies. Three InSAR pairs (26-Mar-96 and 27-Mar-96; 14-Apr-96 and 15-Apr-96; 30-Apr-96 and 01-May-96) have been used in the analysis. In order to explore and demonstrate the potential of InSAR coherence in the field of forestry, agriculture, wetland studies, urban area and crop-height estimation, a study area has been selected over parts of Agra, Mathura and Bharatpur districts. The area is mostly a flat-level terrain with little/gentle undulation at few places. Major crops during Rabi season are wheat, mustard and potato. However, during data acquisition in late April and early May, almost all the fields were harvested, whereas during the March pass only wheat crop was present and mustard and potato had been harvested. The study area also covers major reserve forests, including the famous Keoladeo National Park (a world heritage and Ramsar site). Other land cover features like lakes, rivers and settlements are also present in the study area.

InSAR analysis has been performed using the SARDA (SAR DEM and Applications) software developed at Space Applications Centre (Indian Space Research Organization), Ahmedabad, India[7]. With the help of the SARDA software, interferometric coherence images and SAR backscatter images for all the three image pairs (viz. 26-Mar-96 and 27-Mar-96; 14-Apr-96 and 15-Apr-96; 30-Apr-96 and 01-May-96) have been generated. Figure 1 *a* and *b* shows sub-images of SAR backscatter of 30-Apr-96 and corresponding interferometric coherence for 30-Apr-96 and 01-May-96 image pair.

Signatures of major land-cover classes like water bodies, very dense forest, dense forest, open forest, dry bare fields, wet bare fields and human settlements have been extracted from the SAR backscatter image and corresponding interferometric coherence image for 14-Apr-96 and 15-Apr-96 as well as the 30-Apr-96 and 01-May-96 pairs. As the wheat crop was harvested up to the second week of April, only the interferometric pair for the month of March (26-Mar-96 and 27-Mar-96) was used to extract the signature of wheat crop at different heights.

In order to explore the application potential of InSAR coherence, for various land-cover mappings, a scatterplot showing variation of interferometric coherence with SAR backscatter for various land-cover classes, extracted from the interferometric coherence and SAR backscatter images was generated from 14-Apr-96 and 15-Apr-96 as well as the 30-Apr-96 and 01-May-96 image pairs (Figure 2). Figure 2 clearly indicates that certain land-cover classes that have poor separability on the SAR backscatter image, are clearly separable on the coherence image. For example, SAR backscatter images of three categories of forest densities overlap with each other and water with surface waves mixes with agricultural land, but they are separable on the coherence axis. Similarly, certain land-cover classes that have poor contrast on the interferometric coherence image, are clearly separable on SAR backscatter image. For example, various categories of agricultural fields, which overlap with each other on the coherence axis, have distinct SAR backscatter values.

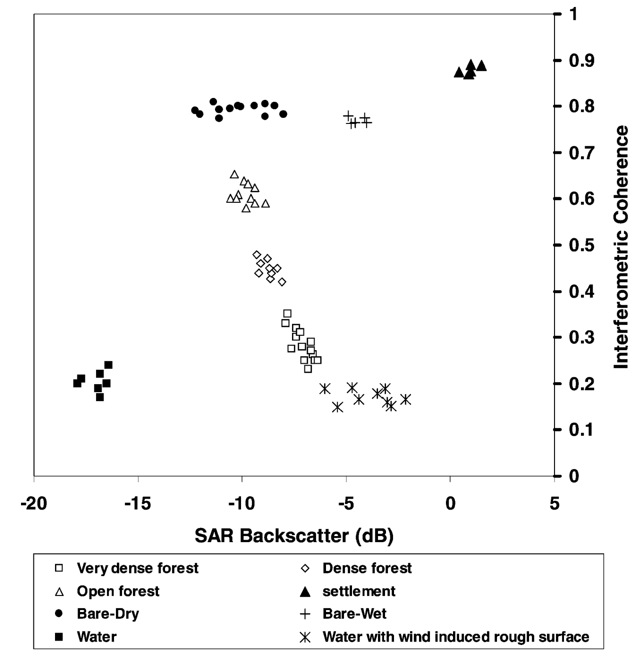

Figure 2. Scatter plot showing variation of interferometric coherence with SAR backscatter for various land-cover classes.

A close observation of variation of backscattering coefficient with interferometric coherence indicates that most of the land-cover classes give distinct signatures when SAR backscatter and coherence images are used. However, there are a few land-cover classes that produce overlapping signatures in both backscatter image as well as coherence image with some other land cover class. For example, the water signatures under calm and rough surface conditions overlap with each other and water also merges with dense forest depending upon its surface roughness conditions on the coherence axis, whereas it merges with different categories of bare agricultural fields on the backscatter axis. Hence it is difficult to map these land-cover classes using either backscatter image or coherence image alone. It is required to make synergic use of one of the SAR backscatter images (say s_A°), the difference of both the SAR images ($s_A^\circ - s_B^\circ$) as well as coherence (g) to separate this particular category. Now we describe at length, the potential applications of InSAR coherence explored for forest density mapping, surface water extent and for detection of human settlements.

While studying the forest signatures in SAR backscatter (s°) image, it was observed that there is poor contrast between various forests with the surrounding areas as seen in Figure 1 *a*. For example, Mandhera Reserve Forest near Dig is not visible on the backscatter image, whereas other forests like Keoladeo National Park and Surdas Reserve Forest (RF) show poor contrast with the surrounding areas. Although Bainpur, Babar and Mau RFs near Agra are visible on the backscatter image, the boundaries of these forests are not sharp. In contrast, Mandhera RF is clearly seen on the interferometric coherence image generated from the same image pair as shown in Figure 1 *b*. Moreover, the boundaries of other RFs are also clearly seen in Figure 1 *b* compared to the SAR backscatter image. Figure 1 *b* also reveals that Keoladeo National Park, which shows poor contrast with its surroundings on SAR backscatter (s°) image, appears distinct on the interferometric coherence image showing excellent contrast with its surroundings. These observations clearly suggest that interferometric coherence is an important tool for forest mapping using SAR data.

Figure 2 further reveals that all the three density classes of forests (ranging from –10.56 to –6.4 dB) overlap with their surrounding areas comprising bare fields with varying surface roughness and soil moisture conditions, occupying maximum value of –4 dB and minimum value of –12.23 dB on the backscatter axis. In contrast, all the forest density classes represented by coherence values ranging from 0.23 to 0.65 are clearly separated from coherence values of all types of bare fields having varying surface roughness and soil moisture values, and with coherence value of around 0.79. However, Figure 2 indicates that the minimum value of interferometric coherence of very dense forest (0.23) mixes with the maximum value of interferometric coherence of water depending on the surface roughness conditions of water.

It should be noted that InSAR coherence that has the capability to delineate all the three densities of forested land along with the potential to discriminate forested land with surrounding agricultural areas, requires the knowledge of SAR backscatter as well as difference of both the SAR images to delineate very dense forest class with water having varying wind-induced surface roughness conditions. Similarly, SAR backscatter which shows clear-cut delineation between calm water and very dense forest requires InSAR coherence values for delineation and density mapping of forested land. The above observations suggest that synergic use of SAR backscatter and InSAR coherence is more useful for delineation and density mapping of forested areas.

It is well understood that radar imagery is a potential data source for the identification, mapping and measurement of hydrologic phenomena such as streams, lakes, extent of flood cover and various types of wetlands. Moreover, in the case of floods, which occur mostly under cloudy conditions, surface water extent is a critical parameter. Potential of radar data for the delineation of surface-water extent, when coupled with the all-weather capability and ability to acquire data during day/night, makes the radar a unique choice for mapping of surface-water extent, particularly during floods. However, in order to use SAR data for surface water delineation, it is required to understand the basic interaction that takes place between the SAR signal and areas under open water. Surface-water features are detectable on radar amplitude imagery due to the high contrast between the smooth water surface and rough

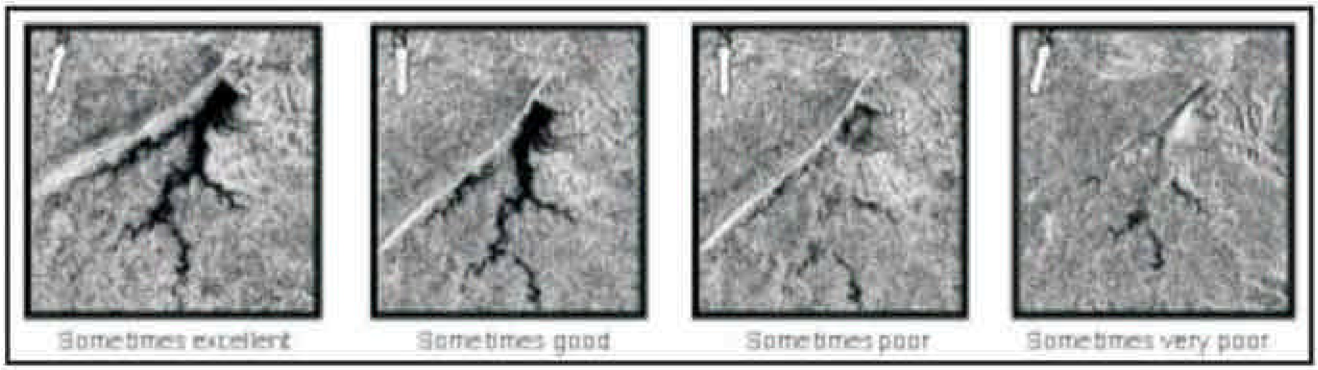

Figure 3. Surface-water extent as seen on SAR imagery.

land surface. This fact indicates that in case of roughness introduced by wind, the SAR backscattered energy from a wind-induced rough water surface could be the same as that of a rough (land) surface. This makes it difficult to map surface-water extent with high accuracy and in the case of strong winds, it becomes impossible to detect the surface water extent. The effect of wind on sensitivity of SAR backscatter towards surface water is clearly visible in Figure 3. The figure clearly indicates that the potential of SAR backscatter to delineate water bodies largely depends on the presence or absence of surface waves induced due to the wind. Hence surface-water extent may appear as excellent, good, poor or very poor compared to the ground reality depending upon wind conditions. Delineation of surface water on SAR backscatter image largely depends upon the difference in roughness between the smooth water body and surrounding (rough) land surface. It implies that identification of water bodies with higher accuracies using SAR backscatter image, holds good only for calm (smooth) water surfaces, which is always not possible under natural conditions.

This calls for using a more accurate tool that holds good for smooth (calm) water surfaces as well as for wind-induced rough water surfaces having surface waves. Interferometric coherence is one such tool for delineation of surface-water bodies. Interferometric coherence relies on the random dislocation of scatterers between two passes rather than actual surface roughness conditions. Since no water surface can remain steady between any given passes, random dislocation of scatterers is considerably high in the case of water bodies compared to land features. This leads to better identification and mapping of surface-water bodies and surface-water extent.

Figure 4 *a*, *b*, *d* and *e* shows the intensity images of both the interferometric pairs (14-Apr-1996 and 15-Apr-1996 as well as 30-Apr-1996 and 01-May-1996). It is clear from intensity images shown in Figure 4 *a* and *b*, that at few places delineation of boundary between water body and land is not clear (marked in red circle) due to surface waves, whereas the coherence image (Figure 4 *c*) generated with the help of phase information of the same image pair clearly delineates the boundary of a lake. Similarly, in Figure 4 *d* and *e*, at a few places smooth (dry) river sand and rough river water create confusion (marked in red circle). However, the coherence image (Figure 4 *f*) generated with the help of phase information of the same image pair clearly delineates the river water and river sand. Study of scatter plot shown in Figure 2 indicates that there is a possibility of mixing of coherence values of water with that of very dense forest in a case where water is surrounded by dense forest, depending upon the surface roughness conditions of water. At the same time, on the backscatter axis, water with varying surface roughness may even give overlapping signature with that of very dense forest. In such cases, one needs to make conjunctive use of InSAR coherence, SAR backscatter of one of the dates and difference of SAR backscatter from both the dates. Since for the case of water with varying degree of surface roughness, the difference of SAR backscatter is very high, difference of SAR backscatter from both the passes ensures that water with varying degree of surface roughness is delineated even from surrounding very dense forest class. Thus this study indicates that the InSAR technique is a promising tool, in particular for flood mapping, which normally occurs with associated cloudy and rough weather conditions.

Identification of human settlements is not a problem on SAR backscatter image as such settlements always give high returns on SAR backscatter image due to the presence of dihedral and trihedral corner reflector effect. However, under certain conditions, features adjacent to human settlements may also give high return to create confusion between human settlements and land-cover classes. Interferometric coherence comes handy again to resolve this problem.

The reason for high contrast between human settlements and their surrounding areas can be explained by the fact that random dislocation of scatterers between the two passes over an urban area is least (nearly zero) and it leads to high values of interferometric coherence, as shown in

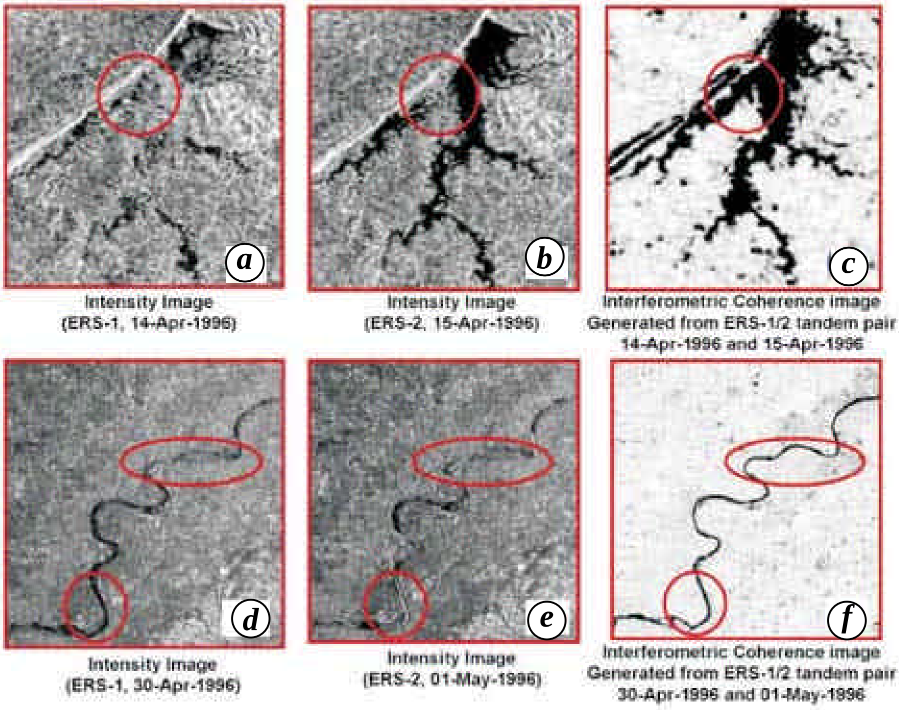

Figure 4. Coherence image and corresponding SAR backscatter image showing better delineation of water bodies in coherence images compared to backscatter images.

scatter plot in Figure 2. The scatter plot indicates that interferometric coherence over urban areas can go up to 0.9, which is the highest value amongst all other categories. Moreover, human settlements always cause high backscatter on SAR imagery leading to almost zero value for difference image of SAR backscatter. In order to get a visual impact of this, when a false colour composite (FCC) is generated[8], human settlements yield a unique yellow shade as explained below.

Red: Interferometric coherence → high value;
Green: SAR backscatter → high value;
Blue: Difference of SAR backscatter of two images $(s^{\circ}_{\mathrm{HIGH}} - s^{\circ}_{\mathrm{HIGH}})$ → very low value.

High value of interferometric coherence (high red) coupled with high value of SAR backscatter (high green) and very low difference between the pair of backscattered images (negligible blue) results in yellow colour in the FCC ({high red + high green + negligible blue} → yellow). Thus, as seen from the scatter plot in Figure 2 and the discussion on interferometric coherence, human settlements can be delineated accurately by the combined use of InSAR coherence and SAR backscatter images.

Crop height is an important parameter for crop-growth monitoring, crop discrimination and crop-production estimation. Though optical remote sensing has long proven to be an efficient means for various agricultural applications, estimation of crop height is difficult using optical remote sensing. In contrast, radar remote sensing, which is sensitive to shape, size, orientation and structure of the crop canopy can play an important role in estimation of crop height. However, it was observed that variation of backscattering coefficient with crop height could not always be explained. It is due to the fact that besides crop height, radar backscatter also depends upon a number of other parameters like canopy structure, canopy moisture, soil moisture and surface roughness conditions of the underlying soil. Since interferometric coherence relies on the random dislocation of scatterers between the two passes rather than actual backscattering from the target, one can attempt to resolve this problem using interferometric coherence for crop-height estimation. Since it is the number of scatters that governs the random dislocation of scatters, it is expected that random dislocation of scatterers for taller crop is considerably high compared to shorter crop. This phenomenon leads to better estimation of crop height from SAR data.

In order to explore the feasibility of use of interferometric coherence for crop-height estimation, only the 26-Mar-1996/27-Mar-1996 pair of ERS-1/ERS-2 tandem mission was used as wheat crop was harvested for the April and May data pairs. During data acquisition in late March, the only cropped fields were that of wheat. Measurements from soil surface to tip of the crop were made to arrive at crop height above ground using a measuring tape. Above-ground height of wheat varied from 0.87 to 1.14 m. A scatter plot between InSAR coherence and observed crop height is shown in Figure 5. It can be seen that crop height is inversely related to interferometric coherence. As the crop height increases, there is higher random dislocation of the scatterers leading to a decrease in InSAR coherence. In order to retrieve crop height, a linear regression analysis was performed between measured crop height and corresponding interferometric coherence values extracted from the interferometric coherence image, as given in eq. (2).

$$\text{Crop height} = A + B^* \text{ (interferometric coherence)} \quad (2)$$

Estimated coefficients are:

$$\text{Crop height} = 1.6396–1.268^* \text{ (interferometric coherence)}.$$

Results of regression analysis between crop height and interferometric coherence yielded a correlation coefficient (r) of 0.74 with 0.05 level of significance. Standard error of Y estimate was found to be 0.057. Validation of the crop-height estimates was also carried out on a validation dataset consisting of five randomly selected validation points. The root mean square error between measured crop height from field and estimated crop height from the model given by eq. (2) was observed to be 0.041 m. The present study indicates the feasibility to estimate crop height using interferometric coherence. It should be noted that although the results are encouraging for a given crop, i.e. wheat in this case, in a multi-crop scenario one must have knowledge of crop type to adopt this approach, since apart from crop height, InSAR coherence would also be affected by crop structure.

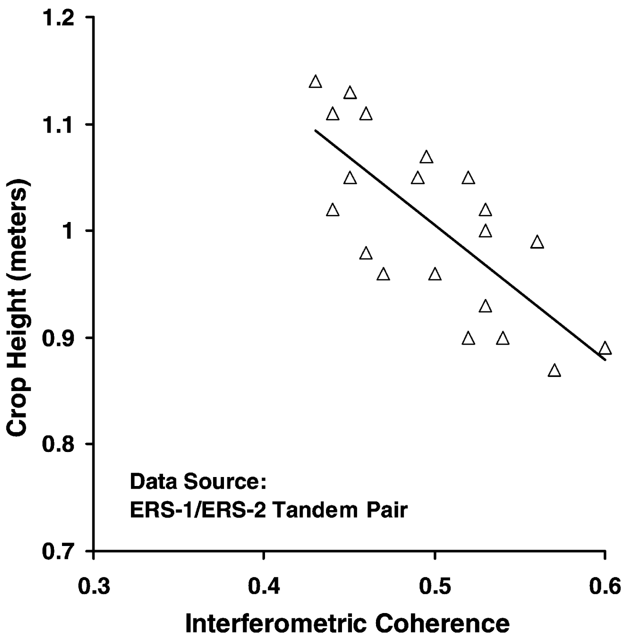

Figure 5. Variation of interferometric coherence with height of wheat crop.

The present study clearly indicates that SAR interferometry, which is widely used for mapping of scene topography (DEM) and surface displacement, has applications in forestry, wetlands, flood mapping, urban studies and crop height estimation. The study further indicates that interferometric coherence can be used as an additional channel with the backscatter channel to enhance the capabilities of SAR data for various applications in forestry, delineation of surface-water extent and urban studies. The fact that interferometric coherence does not rely on actual backscatter from the target but random dislocation of the scatterers between the two passes, makes it an independent physical parameter that is different from the SAR backscatter. The potential of these two independent parameters enhances the capabilities of SAR data manifold for various applications, as many objects that give high backscatter on SAR image give low interferometric coherence values and vice versa. Similarly, most of the targets that give similar interferometric coherence values give different backscatter values resulting in clear-cut separation of various land-cover features in 3D plane of InSAR coherence, SAR backscatter of one of the dates and difference between the SAR backscatter of the two dates. The significant outcome of the present study is that it has successfully demonstrated the potential of InSAR technique for relatively less explored applications.

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