DEMONSTRATION OF FREQUENCY-DEPENDENT PENETRATION DEPTH ESTIMATION USING SAR INTERFEROMETRY WITH WIDE FRACTIONAL BANDWIDTH

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ABSTRACT

Synthetic aperture radar (SAR) interferometry (InSAR) is a well-established remote sensing technique capable of providing accurate topographic information of an area. Multiple scattering occurring at different heights within a single resolution cell, however, cannot be resolved using a single baseline and results in a degradation of the height accuracy. A method was recently proposed to retrieve the three-dimensional structure of semi-transparent media using wide fractional bandwidth InSAR. The frequency dependency of the InSAR coherence was exploited to retrieve the three-dimensional structure, assuming that signals with wide fractional bandwidth are available, as it is the case for unmanned aerial vehicles (UAVs) or drones. This paper demonstrates the usage of wide-fractional bandwidth InSAR to estimate the frequency-dependent penetration depths using repeat-pass InSAR data acquired from a radar mounted on a drone platform.

***Index Terms*—** Synthetic aperture radar (SAR), SAR interferometry (InSAR), drones, unmanned aerial vehicle (UAV), wide fractional bandwidth, coherence

1. INTRODUCTION

Synthetic aperture radar (SAR) interferometry (InSAR) is a well-established technique capable of providing the topographic information of an illuminated scene using two SAR images acquired from vertically or horizontally separated positions [1, 2].

Acquiring topographic information using InSAR is adequate for surface scattering with backscatter occurring at a distinct height. In the case of semi-transparent media with multiple scattering from different heights in a resolution cell, volumetric decorrelation occurs, adversely affecting the InSAR phase and height measurements [3]. The decorrelation results in a decrease in the magnitude of the InSAR coherence, the complex correlation coefficient between the two SAR images, which can be used for further investigation of the specific area, e.g., to create a forest/non-forest map [4]. Attempts such as InSAR tomography were made to obtain more information on the vertical structure for use in digital terrain retrieval [5], measuring above ground biomass [6], radioglaciology [7], and agricultural monitoring [8].

Recently, we proposed a new method to retrieve the volume structure using InSAR data with wide fractional bandwidth [9, 10, 11]. The use of wide fractional bandwidth signals allows obtaining SAR data with a significant variation of the coherence over frequency. By applying a modified InSAR processing to the pair of SAR data, a coherence trend as a function of the frequency (or of the wavenumber) is obtained. The inversion can then be carried out by comparing different coherence models derived from vertical scattering profiles with the measured coherence trend.

This paper aims to provide preliminary results of the frequency-dependent coherence estimation. The modified InSAR processing is demonstrated on a repeat-pass InSAR data acquired from a drone-borne radar.

2. VOLUME STRUCTURE RETRIEVAL USING FREQUENCY-DEPENDENT INSAR COHERENCE

A high-level graphical representation of the proposed method to invert the three-dimensional structure of a semi-transparent medium using signals with wide fractional bandwidth is depicted in Fig. 1.

As shown in the top left-hand side of Fig. 1, the proposed method assumes an InSAR measurement from radars with wide fractional bandwidth, where the ratio between the transmit bandwidth and center frequency is larger than one, e.g., from 0.5 GHz to 5.5 GHz.

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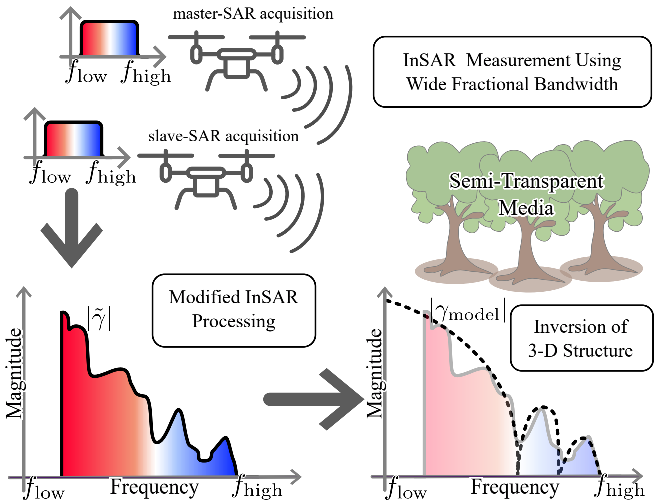

Fig. 1. High-level graphical representation of the proposed method, including data acquisition, coherence measurement, and inversion.

An interferometric coherence map with high range resolution can be obtained from the available measurements using conventional InSAR processing. A modified InSAR processing is introduced to estimate the coherence as a function of frequency for each range and azimuth pixel through bandpass filtering of the range compressed data in frequency. As a result, coherences over a wide range of vertical wavenumbers are obtained at the cost of a degraded range resolution of the coherence maps. The magnitude of the coherence trend varying with frequency is depicted in the bottom left-hand side of Fig. 1.

The inversion of the coherence trend is performed by searching for a coherence model that best fits the estimated coherence values, as shown in the bottom right-hand side of Fig. 1. A set of parameters that characterize the coherence model can be used to define the vertical scattering profile, which represents the amount of backscatter within a semi-transparent medium.

3. DATA ACQUISITION USING A DRONE-BORNE RADAR

A repeat-pass InSAR experiment was conducted in June, 2023. A ground-penetrating radar operating at L-, S-, and C-band was mounted on a hex-rotor UAV as shown in the top-side of Fig. 2 [12]. The experiment scene consisted of a flat ground with multiple triangular trihedral corner reflectors. The platform was flown in a straight trajectory using autopilot and predesignated waypoints at a constant height and speed of 10 m and 2 m/s, respectively. The antenna illuminated the ground at a 45° look angle with no squint.

The radar utilized frequency-modulated continuous-wave (FMCW) waveform with a center frequency, bandwidth, and

Fig. 2. Pictures of the data acquisition experiment, where a frequency-modulated continuous-wave radar is mounted on a hex-rotor drone (top) and the experiment scene with corner reflectors (bottom), are shown.

pulse duration of 2.5 GHz, 3 GHz, and 3.5 ms. The FMCW signal was digitized using a sampling frequency of 2.6 MHz which allowed maximum range of 90 m after range compression.

The experiment incorporated the use of real-time kinematic (RTK) system with a local RTK station on site. The positions were given in local East-North-up (ENU) coordinates referenced to the RTK station, which were used to form the SAR images using back-projection algorithm.

4. DATA PROCESSING FOR FREQUENCY-DEPENDENT COHERENCE ESTIMATION

The position measurements given by the RTK station were used to shift each pulses in time to form a linear trajectory assuming a flat ground plane. The range migration algorithm was applied to the range-compressed data upon motion compensation.

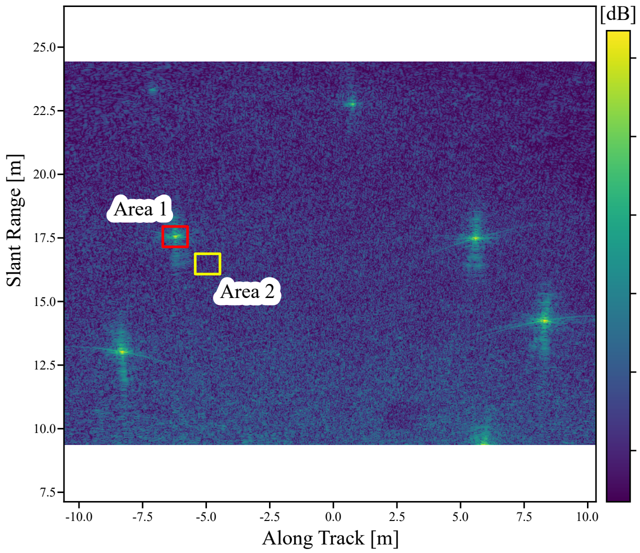

Fig. 3. SAR image from a scene including multiple corner reflectors and a grassy ground.

The synthesized SAR image is shown in Fig. 3, where the vertical and horizontal axes represent the slant range and along track, respectively. Multiple corner reflectors are visible within the SAR image, and the ground reflection are mostly from a flat ground with short grass. Data from another acquisition track can be used to form a pair of SAR images for interferometric processing.

To perform interferometry with respect to a specific center frequency and bandwidth other than that of the transmitted one, the signal can be filtered prior to SAR processing [11]. To accommodate the equivalent subsequent to the image formation, the SAR image is first Fourier-transformed into the spatial frequency as shown in Fig. 4. The spectrum of the SAR image is depicted pn the left-hand side of Fig. 4 (a) and (b), where the vertical and horizontal axis represent the wavenumber in slant range and along track, respectively.

The spectrum are depicted with a two-dimensional passband filter which represent the reflection from different frequencies. Due to the non-linear transformations within the SAR image processing, where the raw data is represented by fast-time and slow time and the SAR image is represented by slant range and azimuth, the response representing a specific fast-time frequency is within a region specified by two arcs of a circle.

An example of the response from a lower and higher fast-time frequency is shown as the shades in Fig. 4 (a) and (b), respectively. The center frequencies of the lower and higher band was assumed to be 1250 MHz and 3750 MHz, respectively. The SAR image can be recovered by a two-dimensional inverse Fourier transform upon filtering, which is shown in the right-hand side of Fig. 4, where the SAR image from lower and higher frequency is shown in (a) and (b), respectively.

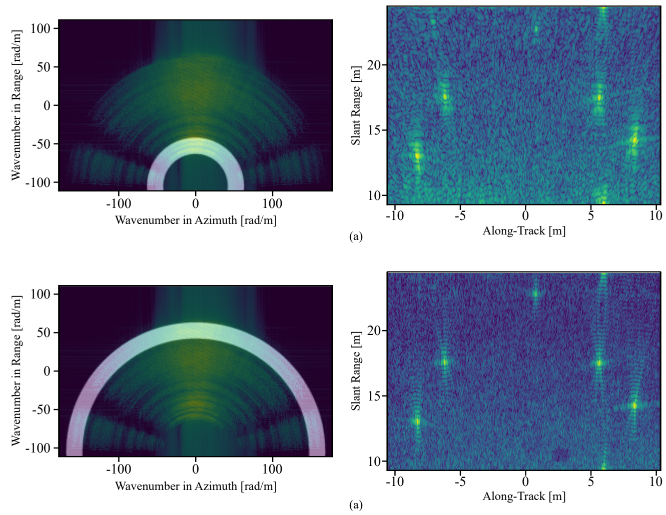

Fig. 4. The spectrum and SAR image filtered in low frequency (a) and in high frequency (b).

The InSAR coherence varying with frequency can be estimated by generating multiple filters in the spatial frequency domain representing the response from multiple center frequencies and a specified filter width, which can effectively perform the modified InSAR processing in Fig. 1.

5. EXPERIMENT RESULTS

Fig. 5 depicts the magnitude and phase of the coherence trend measured from two different areas. The coherence in Fig. 5 (a) and (b) are obtained from the areas marked in Fig. 3 with red (Area 1) and yellow (Area 2), respectively. Area 1 includes a corner reflector, and Area 2 includes a flat ground near the corner reflector.

The two tracks are highly overlapped, and therefore the coherence from Area 1, where the reflection is similar to a response from a point target, is expected to have a constant coherence trend. Due to the unknown ground topography, there exists linear phase in Fig. 5 (a) which is not compensated. The trend is also noticeable from the coherence trend of the clutter in the right-hand side of Fig. 5 (b).

The coherence trend from the clutter can be calibrated using the response from the corner reflector. Fig. 5 (c) shows the magnitude and phase of the coherence trend of the clutter multiplied by the complex conjugate of the coherence trend obtained from the corner reflector. The phase of the coherence trend on the right-hand side of Fig. 5 (c) reflects difference in the backscatter depth between the corner reflector and the clutter. The phase near 1.5 GHz and 3.0 GHz constant with regards to frequency implies that the backscatter occurred from the same height. The phase between 2.0 GHz

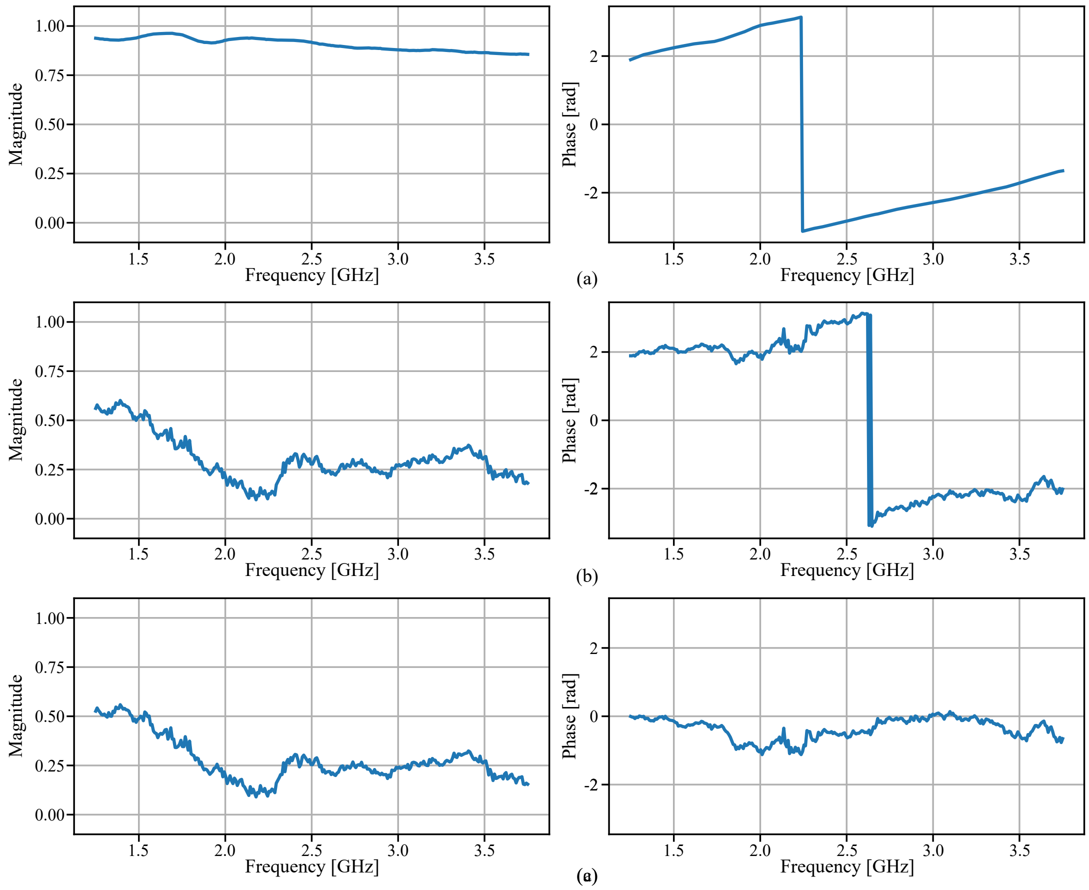

Fig. 5. The magnitude and phase of the coherence with respect to frequency measured from the corner reflector (in Area 1) and the clutter (in Area 2) is depicted depicted in (a) and (b), respectively. The magnitude and phase of the product between the coherence from the clutter and the complex conjugate of the coherence from the corner reflector is depicted in (c).

and 2.5 GHz have slightly different phase values, which implies that the backscatter occurred from a different height.

6. CONCLUSION

A recent study presents a novel method to invert the three-dimensional structure using InSAR data with wide fractional bandwidth. The use of signals with wide fractional bandwidth allows estimating the coherence over a wide range of vertical wavenumbers using a single or a small number of baselines. The proposed method incorporates a modified InSAR processing to estimate the InSAR coherence with regards to a varying wavenumber. The measured coherence is inverted to the vertical scattering profile, and the three-dimensional structure is retrieved.

In this paper, the modified InSAR processing is demonstrated on SAR data measured using a FMCW radar mounted on a drone platform. A patch of data from a SAR image is extracted which represents a flat ground to estimate the penetration depth with regards to frequency. The phase was calibrated with the response from a corner reflector, and deviations in the phase imply that there may be backscatter occurring from several heights for different frequencies.

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