Subsurface Topography Mapping in Deserts using Two Frequency SAR Interferometry

Adel Elsherbini and Kamal Sarabandi

Radiation Laboratory, EECS Department, University of Michigan – Ann Arbor, MI 48109
{sherbini, saraband}@umich.edu

Abstract

The progress in the development of a new two frequency InSAR system for mapping the subsurface topography in deserts and arid regions is presented. The proposed system consists of a Ka-InSAR for mapping the top interface topography and a VHF-InSAR for mapping the subsurface topography. The required modifications in conventional InSAR inversion to allow for height estimation in the presence of the top layer are then presented. Some of the image distortions that occur in the SAR images are also presented. Scaled model measurements were performed to verify the operation of the proposed system.

1. Introduction

Mapping the sand layer thickness in deserts and arid areas can greatly increase the efficiency of oil field and ground water explorations and can have several other applications in environmental and archaeological studies, mine fields detection and planetary explorations [1, 2]. Current techniques for subsurface sensing are based on seismic and ground penetrating radars (GPRs) [3]. However, they are very time consuming and labor intensive for mapping large areas. On the other hand, conventional airborne or space-borne Interferometric Synthetic Aperture Radars (InSAR) [4] can generate the surface topography of vast areas with high resolution over a relatively short period of time. InSAR systems generate two SAR images of the same ground region using two slightly different flight passes (look angles). The two SAR images are then coregistered and cross correlated. The phase of the cross correlation (the phase interferogram) is unwrapped using a 2D unwrapping algorithm. The unwrapped phase is then used to calculate the ground topography.

However, conventional InSARs are not capable of estimating the subsurface topography since they cannot directly account for the propagation effects through the top layer [4]. Thus, we propose the use of two InSAR systems as shown in Fig. 1; the first is a conventional InSAR operating at Ka-band to obtain the topography of the top sand interface, since at this frequency the sand surface and volume scattering are dominant [5]. The second InSAR operates in the VHF band, which allows it to penetrate through the sand layer and provide information about the topography of the underlying bedrock since at these much lower frequencies, sand surface and volume scattering are negligible. This VHF InSAR will use the top surface map generated by the Ka-InSAR to correct for the propagation effects through the top layer and obtain an accurate estimation of the bedrock height.

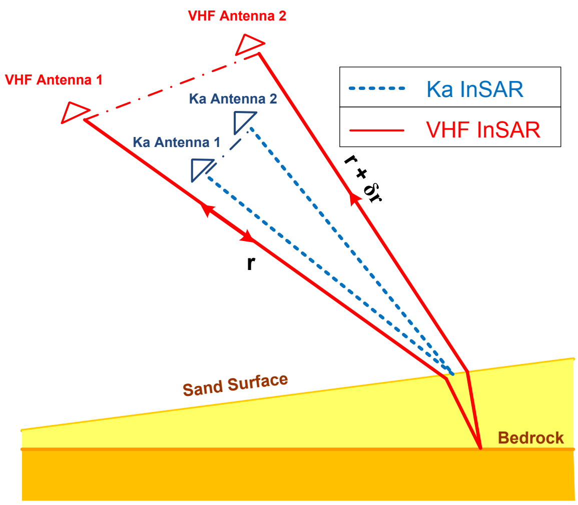

Figure 1: Proposed two frequency InSAR system.

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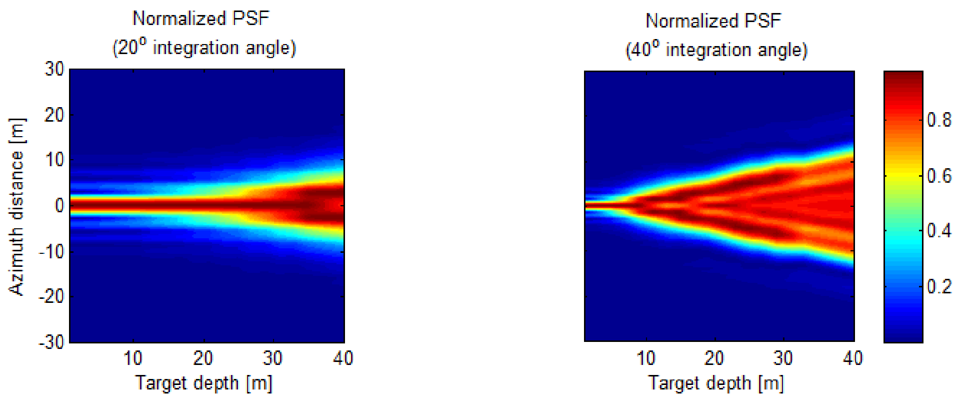
2. Image Distortion Effects

Conventional SAR processing assumes that the wave path between the radar and the target is a straight line with a propagation constant equal to that of free space. For subsurface targets with top surface undulations, this results in two types of image artifacts: defocusing and geometrical distortion. In this section, we present these effects on two sample scenarios. In the following simulations, the center frequency is 150 MHz, the bandwidth is 60MHz and the platform height is 5 Km.

The first problem with subsurface SAR images are defocusing effects which can be separated into range defocusing and azimuth defocusing. Simulation results shows that range defocusing is much less significant than azimuth defocusing since dry sand dispersion is very small for the frequency range considered for this application [1]. However, azimuth defocusing is very significant and poses significant limitation on the achievable azimuth resolution. An example is shown in Fig. 2 where a target was placed under a sand layer with flat interface at a ground range of 2km and a depth that is varied from 0 - 40m. The target image was generated using conventional back-projection with focusing plane at the surface. Fig. 2 (a) shows that for small integration angle, the azimuth target point spread function (APSF) maintains its form up to a depth of approximately 20m (corresponding to long depth of focus) but has poor ground resolution. On the other hand, for larger integration angles (Fig. 2 (b)), the APSF has much better ground resolution but keeps its form over much shorter distance of about 5m beyond which the resolution degrades rapidly (short depth of focus). Since for VHF SARs even larger integration angles are typically required to achieve reasonable ground resolution, accurate focusing is extremely important.



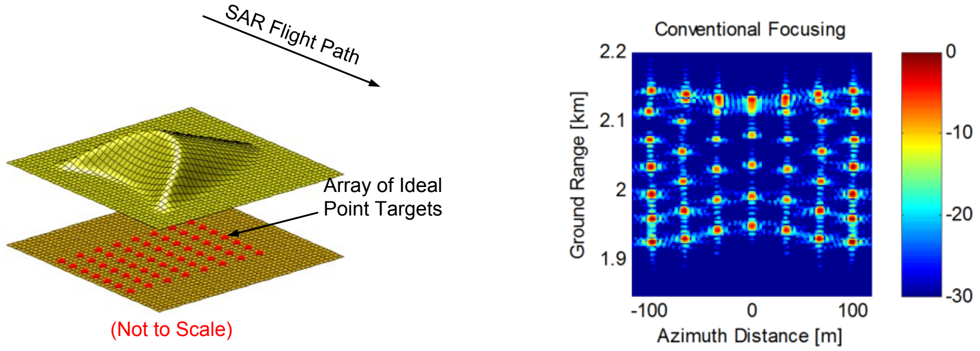
(a) (b)

Figure 2: Azimuth Point Spread Function (APSF) of a point target vs. the target depth when using conventional focusing with focusing plane at the surface with (a) 20o integration angle and (b) 40o integration angle.

The second issue with conventional focusing is geometric distortion due to refraction effects through the top surface topography. A sample scenario is shown in Fig. 3 (a), where an array of 49 (7x7) point targets arranged uniformly over an azimuth range of 200m and ground range of 200m centered at (0, 2Km) is placed at a depth of 5 m under a barchan sand dune with crest height of 30m and length of 200m. The integration angle was limited to 10^o to avoid defocusing. From Fig. 3 (b), we can see that the point target locations got shifted due to the refraction through the top layer. This limits the use of the subsurface InSAR in some applications such as mine detection and also affects the image coregistration accuracy. An interesting phenomenon is the geometric distortion near (0, 2.12km) where the refracted rays made two targets appear at almost the same range. This is very similar to forshortening and layover in conventional SAR imaging when two targets share the same range bin due to surface topography. Unfortunately, this can only be fixed by increasing the bandwidth or adjusting the radar look angle and cannot be fixed by refocusing.

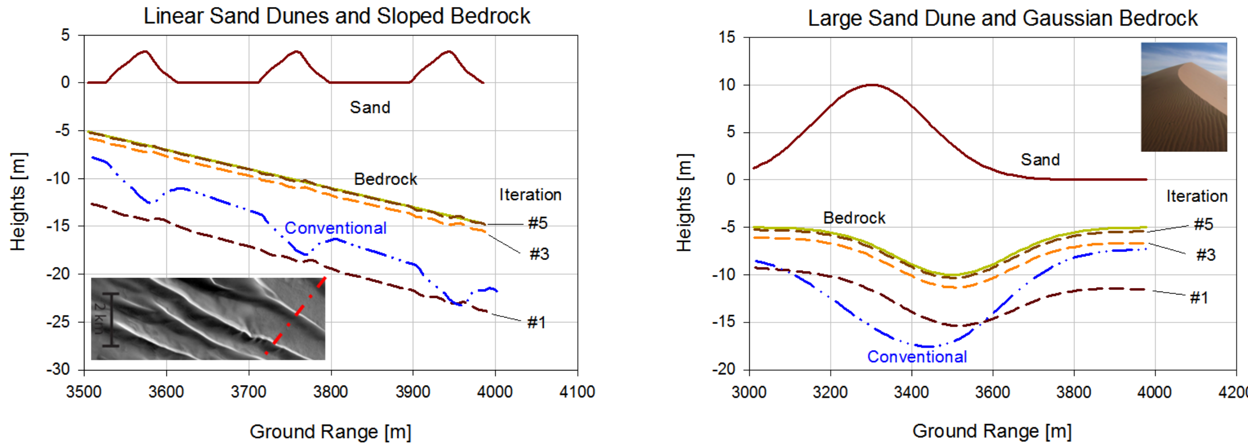
3. Inversion Algorithm

Even though the VHF InSAR is able to penetrate the top sand layer and obtain information about the bedrock height, this height information is distorted by the refraction through the top surface. An example is shown in Fig. 4 where conventional InSAR processing was used to estimate the topography of flat sloped bedrock underneath 1D sand undulations representing linear sand dunes. As shown from the blue curve in the figure, the resulting height estimation includes artificial undulations due to the electromagnetic waves refraction through the top interface. Due to the fact that the top undulations are in the order of many wavelengths at VHF frequencies, geometrical optics can be used to model the propagation effects through the top layer. Thus, we developed a fast physics based iterative inversion algorithm that employs geometrical optics and is able to estimate the subsurface topography [1, 2]. The algorithm was tested on several simulated sand and bedrock scenarios and was found to converge within a few iterations as shown in Fig. 2 (a) and (b).



(a) (b)

Figure 3: Sample scenario to illustrate geometric distortion in subsurface SAR images due to top layer propagation effects, (a) the simulation scenario and (b) the conventionally focused SAR image.



(a) (b)

Figure 4: Two simulated sample scenario for using conventional InSAR for mapping the subsurface showing the results of applying conventional InSAR processing and the results of the different iterations of the inversion algorithm (a) linear sand dune and (b) barchan sand dune.

4. Scaled Model Measurements

To verify the performance of the proposed algorithm, we used a scaled model in the lab as shown in Fig 5 (a) [1]. It consists of two horn antennas mounted on an XY table and connected to an Agilent 8720D network analyzer. The center frequency is chosen to be 10GHz and the bandwidth is 4GHz. An ideal equivalent model would require antennas heights close to 75m which is not feasible. Instead, the two paths were at heights of 1.21m and 1.46m and the sand layer thickness was reduced to account for that. The scene consisted of a flat sand layer of thickness 7.8cm on top of a metallic rough surface with an rms roughness of about 1.5mm. We used fine silica sand which has minimal volume scattering at 10GHz and a relative dielectric constant of 2.8+i0.01 which is reasonably close to that of dry sand at 150MHz (2.9+i0.018). Six corner reflectors were used for calibration and coregistration purposes. The resulting SAR image for one of the passes is shown in Fig 5 (b). Conventional InSAR processing was then applied to the data. Then different constant azimuth sections in the generated 2D map were plotted in Fig. 5 (c) for easy comparison. From the figure, we can see that conventional InSAR could accurately predict the height of the corner reflectors as expected, but it showed significant height error (up to 25%) and an artificial ramp in the bedrock height. The proposed algorithm was then applied to the data and the results are shown in Fig. 5 (d). As we can see, both the corner reflectors and bedrock heights were accurately estimated with very small average error. The RMS error is 4mm. It is in part due to the moderate defocusing through the sand layer, the coregistration errors and the geometrical decorrelation due to the baseline.

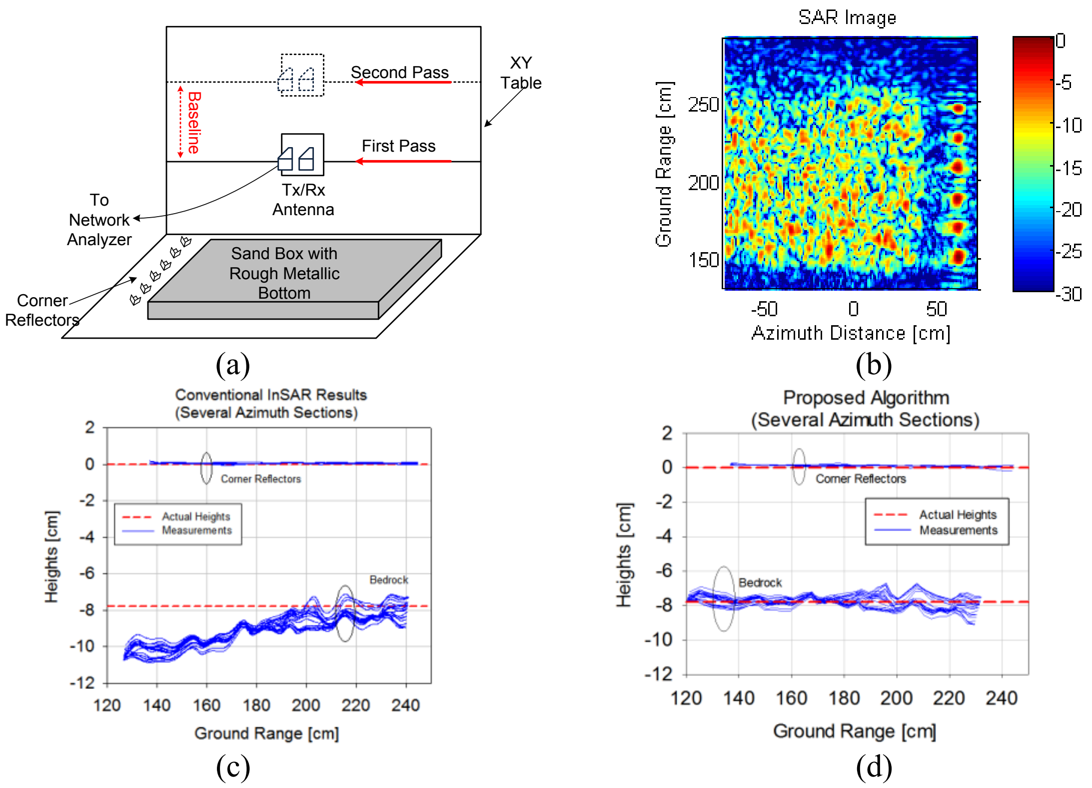


Figure 5: (a) Scaled model setup, (b) conventionally focused SAR image of the scene, (c) coherence map using conventional SAR focusing and (d) coherence map using subsurface SAR focusing.

5. Conclusion

We investigated the problem of estimating the topography of sand covered bedrock in arid and desert areas. We discussed the usage of a dual frequency InSAR composed of a conventional Ka InSAR responsible for mapping the sand surface topography and a VHF InSAR which can estimate the bedrock topography using this generated sand surface map. The different imaging issues associated with subsurface SAR focusing were presented with methods to overcome their effects. It is shown that conventional InSAR processing cannot be used since it does not account for the refraction effects through the top layer and thus a new physics based approach was used and was found to give accurate results and converge relatively fast. Measurements of a scaled model was presented to verify the proposed algorithm. The RMS errors for the measurements was reasonably small and showed the accuracy of the proposed algorithm.

6. References

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