CASE STUDY OF FACTORS AFFECTING TREE HEIGHT INVERSION PERFORMANCE USING SIR-C/X POLARIMETRIC INTERFEROMETRIC SAR DATA OF HETIAN TEST SITE IN CHINA

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ABSTRACT
In order to evaluate and study polarimetric SAR interferometry tree height inversion algorithm, three passes of SIR-C/X SAR L band full polarization SLC data were acquired for the same imaging area in the western region of Hetian district, Xinjiang Vygur Autonomous Region of PRC, China. The three images acquired in separate days of Oct. 7, Oct. 8 and Oct. 9 of 1994 makes the study of the factors affecting performance of three-stage tree height inversion methodology possible. In addition to the SAR data, two scenes of Landsat TM/ETM+ data, one Land cover map and some sheets of 1:50000 topographic maps covering the test site were collected. Firstly, the INSAR preprocessing methods, such as sub-pixel accuracy co-registration, baseline estimation, flatten phase removal, effective wave number and incidence angle images generation, and the three-stage inversion method were outlined. Then data processing and tree height inversion results were analyzed. Some points established from physics theory and simulation POLInSAR data in some publications were confirmed by the primary results of the case study: It has been observed that the tree height image generated from full model inversion (FMI) is much noisy, and better inversion result was observed with vegetation bias removal (VBR) method; The maximum DEM difference (MDD) method can underestimate forest height. Some possible error sources that can lead to worse inversion result have been analyzed and the way to solve this problem has been suggested.

Keywords: POLInSAR, tree height, three-stage inversion, volumetric decorrelation

1. INTRODUCTION
As one of the approved DRAGON cooperation project between Chinese and European scientists, “Technique for deriving forest information from polarimetric SAR interferometry” aimed to study the potential impact of the POLInSAR technique on forestry application in China; to review the current status of POLInSAR research in China and Europe and enable technology transfer where required; to establish possibilities for future collaborative research aimed at development and validation of quantitative forestry remote sensing applications using POLInSAR techniques. The project has been formally started since the DRAGON programme kick off symposium hold from 27 to 30 April in Xiamen, Fujian Province, China. This project need POLInSAR data as inputs, but there is still no established test sites in China because of lacking of airborne full-polarization InSAR systems in China. But space-borne SIR-C multi-temporal InSAR images with full-polarization have been acquired from NASA to support this project by Chinese experts. This

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paper summarized the primary achievements for the established SIR-C/X SAR POLinSAR Hetian test site in Xinjiang Autonomous Region of PRC, China.

Successfully tree height inversion result using SIR-C/X repeat pass POLinSAR dataset was published in 1998[1]. One generalized tree height inversion frame proposed for single baseline polarimetric interferometry was published in 2001[2]. A simplified three-stage inversion method for the estimation of underlying ground topography, vegetation height and mean extinction from single baseline polarimetric interferometric SAR data has been developed in 2003[3]. In this paper the tree high inversion methods developed in [3] were applied in order to evaluate their performance using the SIR-C/X POLinSAR datasets acquired in the Hetian test site. Some error sources were analyzed to explain the tree height estimate results obtained.

2. TEST SITE AND EO DATA

The test site is located in Hetian District of the Xinjiang Autonomous Region in the west of China. The geographical location of the test site is from 79°14´E~79°44´E and 36°48~37°14´. Fig.1 shows the location of Hetian in the County and city-boundary vector map of China. Totally 6 scenes of SIR-C/X SAR data have been acquired for this test site: three in L band and three in C band. All the images were covering almost the same region in the western part of Hetian district. Tab. 1 shows the two L band SLC images have been investigated and analyzed in this paper.

One scene of Landsat TM data and one scene of Landsat ETM+ data were collected. The Landsat TM data was acquired in Oct. 15, 1990; the Landsat ETM+ data was acquired in Oct. 24, 2000. Both of them were taken in the same month but with 4 years ahead and 6 years late to SIR-C/X SAR data respectively. Fig.2 shows the location of SIR-C/X SAR data coverage in the geo-referenced TM image (1990.10.15, R: band 5; G: band4; B: band3). Red box is the SIR-C/X SAR coverage, where the major land cover is agriculture filed, some forest stands (fruit orchard), grass land and farm houses.

One land cover map in vector format shown in Fig.3 has been collected for understanding of the ground cover in this region. The map was generated in 1996 through manual interpretation of Landsat TM data by trained and experienced local people under the supervision of remote sensing experts. Fig.4 shows the Landsat ETM+ image of this agricultural area. Topographic map sheets in the scale of 1:50000 and 1:100000 have been collected for the whole coverage of this test site.

Fig.1. The location of Hetian in China map
Fig.2. SIR-C/X SAR coverage on TM image
Tab. 1  The SIR-C/X SAR dataset for Hetian of Xinjiang Autonomous Region, China

<table>
<thead>
<tr>
<th>Id number</th>
<th>Sensor imging date</th>
<th>Band</th>
<th>Asc/Desending</th>
<th>INSAR definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pr42398</td>
<td>1994.10.07</td>
<td>L</td>
<td>Ascending</td>
<td>Master $[S]_1$</td>
</tr>
<tr>
<td>Pr42400</td>
<td>1994.10.08</td>
<td>L</td>
<td>Ascending</td>
<td>Slave $[S]_2$</td>
</tr>
</tbody>
</table>

Fig. 3. Land cover map of the test site: red box shows the SIR-C/X SAR covering region (only the up part agricultural region shown here. There is not much vegetation cover in other regions of the test site.

Fig. 4. Landsat ETM+ image of 2000.10.24 for the agricultural region of the test site. R: band 5; G: band4; B: band3
3. POLARIMETRIC & INTERFEROMETRIC DATA PROCESSING

3.1 Interferometric data processing

The general INSAR data processing routes have been adopted to carry out the data pre-processing procedures: (1) decompression of SIR-C/X SAR from its compressed scattering matrix; (2) master to slave image co-registration based on intensity image multi-resolution sub-pixel accuracy auto-registration algorithm; (3) Resample slave image to the master image space; (4) baseline parameters estimation using azimuth line and range pixel offset file generated from the auto-registration procedure; (5) computation of flat earth phase image, incidence angle image and effective wave number image. These steps can be introduced with the real datasets in more detail as follows:

(1) Extracting SLC data from compressed SIR-C quad Polarization-SLC data file

The extracted images from this step are: 
- $[S]_1$: matrix for pr42398 and 
- $[S]_2$: matrix for pr42400 in 4 data files denoted as 
  $[S]_1$: hh1_slc.data, hv1_slc.data, vh1_slc.data, vv1_slc.data
  $[S]_2$: hh2_slc.data, hv2_slc.data, vh2_slc.data, vv2_slc.data

(2) Mater dataset to slave dataset co-registration. hh1_slc.data and hh2_slc.data were used for sub-pixel co-registration to get master to slave range pixel and azimuth line offsets. The polynomial function used to resample the slave dataset to the image space of master dataset were computed with range and azimuth offsets as input. The results of this processing: range pixel and azimuth line offset file and the polynomial function for re-sampling.

(3) Re-sample $[S]_2$ to $[S]_1$ image space and multi-look both $[S]_1$ and $[S]_1$ with 2 looks in range and 4 looks in azimuth. The results are as follows:
  - $[S]_1$: hh1_mlc.data, hv1_mlc.data, vh1_mlc.data, vv1_mlc.data
  - $[S]_2$: hh2_mlc_registered.data, hv2_mlc_registered.data, vh2_mlc_registered.data, vv2_mlc_registered.data

(4) Baseline estimation using offset points generated from step 2 and other geometry parameters. From this function baseline geometry parameters were estimated: Horizontal baseline -200.88 m; Vertical baseline 54.18 m; Horizontal baseline rate -3.66E-005 m/m and Vertical baseline rate 2.18E-005 m/m.

(5) Flat earth phase image, incidence angle image and effective vertical wave number image computed with baseline and other imaging geometry parameters were denoted as: kz.data, earthph.data and theta.data respectively.

3.2 Polarimetric interferometric coherence and tree height inversion method

The hh1_mlc.data, hv1_mlc.data, vh1_mlc.data and vv1_mlc.data of $[S]_1$ and hh2_mlc_registered.data, hv2_mlc_registered.data, vh2_mlc_registered.data and vv2_mlc_registered.data from $[S]_2$, as well as the kz.data, earthph.data and theta.data were taken as inputs to the three-stage tree height inversion tool developed in [4]. Based on coherence images of HH-HH, HV-HV and VV-VV, the following three kinds of tree-height inversion routes have been investigated:
1) Maximum difference inversion (MDD);
2) Vegetation bias removal inversion (VBR);
3) Full model inversion (FMI).

4. RESULTS AND ANALYSIS

4.1 Polarimetric and interferometric data processing results
Fig. 5 shows HV-HV coherence’s phase images before (plate a.) and after (plate b.) earth phase flattening for the whole image. Please note that there is one red box on both images. Currently we only use the image shown in the box for tree height inversion. This small region is relatively flat, however, the low part of this image is in mountainous region and the interferometry fringes are not so clear, which was probably caused by topography decorrelation.

For all the images shown in this paper, the range direction is from left to right; and azimuth direction is from top to down. Fig. 6 shows some coherence phase images. The complex coherence images have been flatten using flat earth phase computed from co-registration offset points and imaging geometry. So Fig. 6 shows the phase pattern caused by the real topography. These phase fringes were compared with the elevation contours of the 1:50 000 topographical map, their changing patterns are consistent with each other. So the baselines parameters estimated should not be so much deviated from their true values, which can never be found out for space-borne system without precise ground control points.

Fig. 7 shows absolute value of coherence images (coherence amplitude). Coherence smooth window size is 7*7 pixels for all the polarizations. Fig. 8 shows the histogram of HH-HH, VV-VV and VH-VH coherence. From Fig. 7 and Fig. 8, we know that most of the pixels’ coherence is bigger than 0.5. The coherence distribution of HH-HH is almost the same as that of VV-VV. But the mean coherence of cross-polarization (VH-VH) is much lower than co-polarization coherence,
specially in the Gobi area in the middle of the low part of Fig.7.

Fig. 9 is the incidence angle image corresponding to the master dataset [S]. According to the CEOS meta information records of the master SIR-C/X SAR dataset (pr2398), the near range incidence angle is 21.95 degree, the far range incidence angle is 26.43 and the middle incidence angle is 24.37. From Fig.9, the estimated incidence angle changes from 20.60 to 24.75 degree. The mean difference between the estimated and product provided incidence angle range is around 1.5 degree. So we think the accuracy of the estimated incidence angle image is good enough for inversion methodology validation. Fig. 10 is the effective wave number image, the range of the image value is also meaningful.

4.2 Comparison of tree height inversion results of three methods

Tree height inversion result by MDD method is shown in Fig.11- (a) for a selected window (see the red box shown in Fig.7-c ) and that by VBR method is shown in Fig.11-(b). Fig.11-(c) is the inversion result using FMI method.

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![Fig.6 coherence phase image after earth phase flattening](image)
According to the Landsat ETM+ image shown in Fig.4 and the land use map shown in Fig.3, there existed forest stand and agriculture filed in the right and left region of this small area as shown in Fig.11, where the coherence is much lower than the inner part. But most of the inner part of them is Gobi area. Although it is difficult to know the ground true of this region in 1994, it is evident that there should not be many forest stand on the Gobi area. We also know that the tree height around this region was about 15 meters since that most of the forest stands in this region is fruit orchards.

Compared with MDD (Fig. 11-(a)) and VBR (Fig. 11-(b)), the tree height image generated with FMI (Fig. 11-(c)) appears much noisy and erroneous, especially in the bottom of this image, where the estimated tree high is large than 15 meters, but the terrain type of this area should be Gobi, where the tree height should be near zero. So, from Fig. 11 we can conclude that the tree height estimation results of MDD method and VBR method are relatively better than FMI.

Fig. 12 is the histogram of tree height images generated from MDD and VBR methods. The mean tree height of MDD is 1.4m and that of VBR is 2.9m. Further more, Fig. 13 shows one horizontal tree height profile line comparing results from VBR and MDD. According to the ground true information, around the two end part of the horizontal profile line, there should be relative large forest stands, while the inner part of this line should be Gobi region without forest stands. Plate d. shows that the maximum tree height of MDD is below five meters, while the tree height of VBR varies from 5
to 12 meters. So it can be concluded that (1) MDD can underestimate tree height; (2) VBR can produce better tree height inversion result than MDD and FMI.

4.3 Tree height inversion error sources analysis

Although mean coherence amplitude of this area is high, temporal baseline de-correlation should be existed for this kind of repeat pass interferometric configuration. The problem is that we have no indication from the data itself how much temporal decorrelation has occurred [3]. As a comparison, using the same kind of SIR-C/X SAR polarimetric interferometry data acquired around Tianshan area, successful tree height inversion result has been produced [1]. It seems there should be other sources of error to lead to the bad performance of tree height inversion observed in the test site.

As shown in equation (1), interferometric coherence can be written as the product of volume coherence and non-volumetric decorrelation caused by range, temporal, SNR, system and data processing.
\[ Y_{\text{total}} = Y_{\text{Volume}} \cdot Y_{\text{range}} \cdot Y_{\text{temporal}} \cdot Y_{\text{SNR}} \cdot Y_{\text{system/processing}} \] (1)

From the VH-VH and HV-HV coherence images shown in Fig. 7, we can see that the non-vegetation region (Gobi) has very low coherence leading to overestimated tree height in this smooth surface area. These areas may be seriously affected by SNR decorrelation, because smooth surfaces are susceptible of SNR decorrelation. Inversion processing cannot distinguish these SNR decorrelation caused low coherence from volumetric coherence, so these non-volumetric coherence region should be masked out before model inversion. With inspection of the |HV| and |VH| images, it has been found that most of the smooth surface scatters can be masked out if the corresponding |HV|+|VH|<180. Fig. 14 shows the masked tree height image that was produced with FMI. The maximum tree height shown in Fig.14 is 21 meters. Fig.15 is the three dimension viewing of the FMI tree height image with non-volumetric decorrelation pixels being masked.

The boxcar filtering process for generating coherence images may be one possible error sources. With simulated SAR dataset, reference4 [3] has observed the effect of boxcar filter to tree height inversion: poor estimates happen at the edges of forest stands, because the boxcar filter can mix surface and volume scattering. In the flat crop filed area of this study site, there are pixels with low coherence. These pixels maybe small cluster of forest scattered in the crop filed. The boxcar filter applied can lead to noisy tree height estimate around these pixels [5]. Furthermore, the vertical tree structure is another possible cause for the poor estimates of FMI. From the ground true, we know that this area is not forestry region but agricultural region. The test site is one oasis with spatial extended large area of Gobi surrounding it. There exists forest stands on the left and right part of Fig.11 as shown by Fig.3 and Fig.4, but most of the forest stand here is fruit stand in orchards or around farm houses. So the forest stand has special vertical canopy structure which may not be modeled by the two-layer backscattering model [3]. This can also explain why VBR can achieve better tree height estimates than MDD and FMI. When temporal de-correlation and vertical structure exists, VBR is suggested as the best method for tree height inversion [3].

5. CONCLUSIONS

The INSAR data pre-processing frame were adopted for SIR-C/X SAR POLinSAR tree height inversion application. With baseline parameters and co-registered scatter matrix [S] from INSAR data pre-processing as inputs, three-stage tree height inversion algorithm established by S. Cloude were evaluated taking some limited ground true information as reference. The results confirmed the issues concluded from theory analysis and simulated POLinSAR data study by S. Cloude, etal: (1) Longer temporal baseline and other factors makes the full model inversion method problematic; (2)
Better inversion result was observed using vegetation bias removal method; (3) The maximum DEM difference method can underestimate forest height. All these problems maybe existed for repeat pass POLinSAR have been observed in this case study.

Non-volumetric decorrelation in the smooth surface scatter region of the test site is observed and maybe caused by SNR decorrelation. These region should be masked out before applying full model inversion. In additional, temporal decorrelation, boxcar filtering and vertical canopy structure are some possible error sources.

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