BASELINE ESTIMATION ALGORITHM WITH BLOCK ADJUSTMENT FOR MULTI-PASS DUAL-ANTENNA INSAR

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ABSTRACT:

Baseline parameters and interferometric phase offset need to be estimated accurately, for they are key parameters in processing of InSAR (Interferometric Synthetic Aperture Radar). If adopting baseline estimation algorithm with single pass, it needs large quantities of ground control points to estimate interferometric parameters for mosaicking multiple passes dual-antenna airborne InSAR data that covers large areas. What’s more, there will be great difference between heights derived from different passes due to the errors of estimated parameters. So, an estimation algorithm of interferometric parameters with block adjustment for multi-pass dual-antenna InSAR is presented to reduce the needed ground control points and height’s difference between different passes. The baseline estimation experiments were done with multi-pass InSAR data obtained by Chinese dual-antenna airborne InSAR system. Although there were less ground control points, the satisfied results were obtained, as validated the proposed baseline estimation algorithm.

1. INTRODUCTION

Interferometric Synthetic Aperture Radar (InSAR) is one of the potential techniques for earth observing and mapping. It develops rapidly. It can be used in topographic mapping, earth surface deformation monitoring, ice sheet motion monitoring, etc. And there are some prominent advantages in InSAR, such as fast, accurate, day and night data acquisition ability, all climates, large areas, etc. A main research work of InSAR is to derive accurate DEM (Digital Elevation Model) rapidly. Another active research work is to monitor surface deformation by Differential InSAR (DInSAR). Some InSAR software systems have come forth. For example, EarthView INSAR coded by Earth View company, InSAR coded by ASF, and Doris InSAR, GAMMA, Sentinel Tool Box etc. There are many organizations in China that research InSAR techniques too.


Most of the above achievements are aimed at single pair of interferometric data. If the relations between different data are not considered in baseline estimation or calibration of interferometric parameters for multiple passes dual-antenna airborne InSAR data that covers large areas, there will be the following two problems. Firstly, it needs enough Ground Control Points (GCPs) in each pass, so, large quantities of GCPs are needed for multi-pass InSAR data that covers large areas. Secondly, there will be notable height differences in overlapping areas due to errors of baseline estimation.

The idea of block adjustment is often used for obtaining plenty of GCPs that needed in mapping from less known GCPs in both optical photogrammetry and radargrammetry. In order to reduce the number of needed GCPs, the baseline estimation algorithm with block adjustment for multi-pass dual-antenna InSAR is presented in this paper. The baseline estimation experiments with block adjustment were done with multi-pass InSAR data obtained by Chinese dual-antenna airborne InSAR system. Although there were less ground control points, the satisfied...
results were obtained, as validated the proposed baseline estimation algorithm.

2. BASELINE ESTIMATION WITH BLOCK ADJUSTMENT

The airborne dual-antenna InSAR geometry was shown in Fig.1. Where, \( A_1 \) is the phase center position of master antenna, which both transmits and receives radar signals. \( A_2 \) is the phase center position of slave antenna, which only receives signals. \( H \) is the height of master antenna’s phase center \( A_1 \). \( R \) is the slant range between \( A_1 \) and the ground point \( P \). \( R' \) is the slant range between \( A_2 \) and \( P \). \( \Delta R \) is the difference between these two slant ranges (\( \Delta R = R - R' \)). \( h \) is the height of the ground point \( P \). Baseline parameters can be described as length \( B \) which is the distance between \( A_1 \) and \( A_2 \), and angle \( \alpha \) which is the angle between baseline and horizontal line. And they can also be described as Parallel baseline \( B_1 \) and vertical baseline \( B_2 \).

In Fig.1, \( \angle PA_2 A_1 = \beta \), \( \theta = \frac{\pi}{2} + \alpha - \beta \).

For dual-antenna airborne InSAR systems, the relationship between \( \Delta R \) and unwrapped interferometric phase \( \Delta \phi \) can be described as:

\[
\Delta R = \frac{\phi_0 + \Delta \phi}{2\pi}\lambda
\]

(1)

Where, \( \phi_0 \) is the offset of unwrapped interferometric phase \( \Delta \phi \), as should be calibrated. \( \lambda \) is the wavelength of InSAR.

According to the geometry and theorem of driving DEM from InSAR, height \( h \) of ground point \( P \) can be calculated by formula(2) [3]:

\[
h = H - R\cos \theta
\]

\[
h = H - R\cos(90^\circ + \alpha - \arccos(\frac{\Delta R}{B} + \frac{B}{2R} - \frac{\Delta R^2}{2RB}))
\]

(2)

For obtaining better interferometric SAR images and deriving accurate DEMs, motion compensation in imaging should be carried out to reduce track errors and interferometric phase errors. During the motion compensation, both of the baseline parameters including length \( B \) and angle \( \alpha \) are forced to be referenced values. Actually, the baseline parameters change slightly due to inaccurate motion compensation. Considering the accumulation of errors and the processing abilities of computers, the data were processed in blocks when imaging. In each block, the reference track is different. And the baseline parameters in a block are seemed as invariable. The interferometric processing in each block is independent, and the interferometric phases between different blocks are discontinuous, the interferometric phase offsets \( \phi_0 \) are different. In order to mosaic the phases and the derived DEMs easily, the blocks overlap in some degree, as is shown in Fig.2.

All of the baseline parameters (\( B \) and \( \alpha \)) and interferometric phase offset \( \phi_0 \) in blocks need to be estimated to derive accurate DEMs and mosaic the DEMs.

Formula (3) can be deduced from formula (2):

\[
\theta = 90^\circ + \alpha - \arccos\frac{\Delta R}{B} - \frac{B}{2R} - \frac{\Delta R^2}{2RB} = \arccos\frac{H - h}{R}
\]

(3)

\[
\sin(\theta - \alpha) = -\frac{\Delta R}{B} + \frac{B}{2R} - \frac{\Delta R^2}{2RB}
\]

(4)

\[
F = B\sin(\theta - \alpha) + \Delta \phi \frac{B^2}{2R} + \frac{\Delta R^2}{2R}
\]

\[
= B\sin\left(\arccos\frac{H - h}{R} - \alpha\right) + \frac{\phi_0 + \Delta \phi}{2\pi}\lambda - \frac{B^2}{2R} + \frac{\phi_0 + \Delta \phi}{2\pi}\lambda^2 = 0
\]

(5)

In formula (5), the parameters needed to be estimated are respectively \( B \), \( \alpha \) and \( \phi_0 \). The values of slant range \( R \), \( H \), \( h \), wavelength \( \lambda \) and unwrapped phase \( \Delta \phi \) can get from systemic SAR parameters, orbit parameters, GCPs and unwrapped phases.

Formula (5) describes the relationship between all of the above parameters, and it can be used to estimate the interferometric parameters \( B \), \( \alpha \) and \( \phi_0 \) when other parameters are known. It needs at least 3GCPs to get enough equations to solve the values of the three parameters (\( B \), \( \alpha \) and \( \phi_0 \)) for each block.

Because formula (5) is a nonlinear equation about \( B \), \( \alpha \) and \( \phi_0 \), it should be linearized. In order to deduce the linearization clearly, formula (5) is described briefly as:

\[
F(B, \alpha, \phi_0, h) = 0
\]

(6)

The linearized formula is list as below:
\[ F(B, \alpha, \phi_0, h) = F^0(B, \alpha, \phi_0, h) + b_0 \Delta B + b_1 \Delta \alpha + b_2 \Delta \phi_0 + b_3 \Delta h = 0 \]  

(7)

When considering existence of errors, it can be described as formula (8).

\[ v = F^0(B^0, \alpha^0, \phi_0^0, h^0) + b_0 \Delta B + b_1 \Delta \alpha + b_2 \Delta \phi_0 + b_3 \Delta h \]  

(8)

Where, the initialization of \( F^0(B, \alpha, \phi_0, h) \) is:

\[ F^0(B, \alpha, \phi_0, h) = B^0 \sin(\arccos \frac{H - h^0}{R}) \]

\[ - \alpha^0 + \phi_0^0 + \Delta \phi + \frac{(B^0)^2}{2} + \frac{2R}{2} \]  

(9)

To estimate interferometric parameters, for it needs at least 3 GCPs in each block. In order to illuminate the issue, Fig.5 is used, which includes two passes of interferometric SAR data. If the baselines parameters and phase offsets of the two passes are estimated by single pass baseline estimation method, which only uses the GCPs covered in corresponding image, more than 3 GCPs are needed because each pass needs at least 3 GCPs. The more passes, the more GCPs are needed.

Formula (9) can be described by matrix equation (11):

\[ V = [A \ B] [\Delta]_1 - L \]  

(11)

Where,

\[ V = [v_1 \ v_2 \ v_3] \]

\[ A = [b_{00} \ b_{11} \ b_{21} \ b_{31}] \]

\[ B = [b_{01}] \]

\[ \Delta_1 = [\Delta B \ \Delta \alpha \ \Delta \phi_0] \]

\[ \Delta_2 = [\Delta h] \]

\[ L = [-F^0(B^0, \alpha^0, \phi_0^0, h^0)] \]

(12)

It needs \( N (N \geq 3) \) GCPs to estimate interferometric parameters in each block. Assuming that there are no errors on heights of GCPs, Formula (11) and (12) can be converted to:

\[ V = \Delta_1 - L \]  

(13)

Where,

\[ V = [v_1 \ v_2 \ v_3 \ \vdots \ v_N] \]

\[ A = [b_{00} \ b_{11} \ b_{21} \ \vdots \ b_{3N}] \]

\[ \Delta_1 = [\Delta B \ \Delta \alpha \ \Delta \phi_0] \]

\[ \Delta_2 = [\Delta h] \]

\[ L = [-F^0(B^0, \alpha^0, \phi_0^0)] \]

(14)

The results can be got with:

\[ \Delta_1 = (A^T A)^{-1} A^T L \]  

(15)
In order to validate the proposed baseline estimation method, the multi-pass InSAR data that covered some areas in Shandong, China, were applied to do experiments. These data were obtained by a dual-antenna airborne InSAR system researched independently by the Institute of Electronics, Chinese Academy of Sciences. The data covered some plain areas and some mountains. The systemic parameters related to experiments were listed in Tab.1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (m)</td>
<td>0.0312</td>
</tr>
<tr>
<td>Wave Band</td>
<td>X</td>
</tr>
<tr>
<td>Resolution in Azimuth (m)</td>
<td>1.1</td>
</tr>
<tr>
<td>Resolution in Range (m)</td>
<td>1.25</td>
</tr>
<tr>
<td>Absolute Flight Height (m)</td>
<td>6190.0</td>
</tr>
<tr>
<td>Doppler Frequency (Hz)</td>
<td>0</td>
</tr>
<tr>
<td>Polarization</td>
<td>HH</td>
</tr>
</tbody>
</table>

Tab. 1 Parameters of InSAR

In this paper, two passes of InSAR data were employed. And in each pass, two adjacent blocks were selected. The relationship between the selected blocks is shown in Fig.7.

The intensity images of selected blocks are shown in Fig.8. In order to calibration, the GCPs were selected according to the features in images, and their coordinates were measured by differential GPS. The GCPs’ distributions for two blocks in pass 0001 were Data 0001_04 and Data 0001_03. The GCPs’ distributions for blocks in pass 1001 were Data 1001_04 and Data 1001_03. The heights of GCPs are list in Tab.2.
The vertical baseline determines sensitivity of phase to height. \( B_z \) is more fit for evaluating the precision of calibration, so, the vertical baselines are calculated and list in Tab.3 and Tab.4. The height’s differences on TPs derived from estimated interferometric parameters with different algorithms were shown in Tab.5. The distribution of heights’ differences on TPs with estimated parameters by the two methods was shown in Fig.10. The average of heights’ difference derived with single pass method is 6.298m. While the average of heights’ difference derived with block adjustment method is 0.161 m, which is close to zero. The results show that the differences of derived heights in overlapping areas by baseline estimation algorithm with single pass are larger than that with block adjustment. By a way, the statistical average of heights’ difference is none zero because there is only a part of TPs that are list and in Tab.5. The heights’ differences of other TPs in overlapping areas of passes are not calculated for their heights can not be derived with single pass algorithm. These TPs include 1, 2, 3, etc. All of the above TPs are in data 1001_03.

From the results, we can see that it can effectively reduce the heights’ differences in overlapping areas by adopting baseline estimation algorithm with block adjustment. The facts that may induce errors in both baseline estimation algorithms include height errors and phase errors of GCPs/TPs, inaccurate motion compensation in imaging, errors in navigation data, earth curvature, etc. Especially, the height errors of GCPs affect the results greatly in baseline estimation algorithm with single pass, which can be seen from the standard deviation of heights’ difference on TPs.

The distributions of selected TPs were shown in Fig.9. The parameters calibrated with single pass (or Block) calibration method were list in Tab.3. In Scene 1001_03, there are just two GCPs, so it’s unable to calibrate 3 interferometric parameters by single pass (block) calibration algorithm because the number of GCPs is not enough (it needs at least 3 GCPs).

While adopting calibration method with joint adjustment, the interferometric parameters for 1001_03 can be successfully calibrated due to applying TPs. All of the calibrated parameters were shown in Tab.4.

### Tab. 2 Heights of GCPs

<table>
<thead>
<tr>
<th>Data</th>
<th>GCPs’ No.</th>
<th>Heights (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0001_04</td>
<td>95</td>
<td>61.810</td>
</tr>
<tr>
<td></td>
<td>96</td>
<td>62.734</td>
</tr>
<tr>
<td></td>
<td>97</td>
<td>61.969</td>
</tr>
<tr>
<td></td>
<td>98</td>
<td>64.577</td>
</tr>
<tr>
<td></td>
<td>99</td>
<td>64.033</td>
</tr>
<tr>
<td></td>
<td>105</td>
<td>57.607</td>
</tr>
<tr>
<td></td>
<td>44</td>
<td>54.516</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>54.028</td>
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<tr>
<td></td>
<td>59</td>
<td>52.599</td>
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<tr>
<td></td>
<td>60</td>
<td>55.188</td>
</tr>
<tr>
<td>0001_03</td>
<td>61</td>
<td>52.854</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>52.299</td>
</tr>
<tr>
<td></td>
<td>68</td>
<td>54.005</td>
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<tr>
<td></td>
<td>75</td>
<td>53.249</td>
</tr>
<tr>
<td></td>
<td>103</td>
<td>56.297</td>
</tr>
<tr>
<td></td>
<td>104</td>
<td>55.088</td>
</tr>
<tr>
<td>1001_04</td>
<td>105</td>
<td>57.607</td>
</tr>
<tr>
<td></td>
<td>102</td>
<td>58.227</td>
</tr>
<tr>
<td></td>
<td>103</td>
<td>56.297</td>
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<tr>
<td></td>
<td>104</td>
<td>55.088</td>
</tr>
<tr>
<td>0001_03</td>
<td>91</td>
<td>51.902</td>
</tr>
<tr>
<td></td>
<td>68</td>
<td>54.005</td>
</tr>
</tbody>
</table>

### Tab. 4 Estimated Parameters with Block Adjustment

<table>
<thead>
<tr>
<th>Data</th>
<th>Length of Baseline(m)</th>
<th>Angle of Baseline(rad)</th>
<th>Phase Offset(rad)</th>
<th>Vertical Baseline(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0001_0</td>
<td>4</td>
<td>0.5654</td>
<td>0.3447</td>
<td>48.550</td>
</tr>
<tr>
<td></td>
<td>0001_0</td>
<td>0.5457</td>
<td>0.4355</td>
<td>18.958</td>
</tr>
<tr>
<td></td>
<td>1001_0</td>
<td>0.5834</td>
<td>0.2828</td>
<td>68.977</td>
</tr>
<tr>
<td></td>
<td>0001_0</td>
<td>0.5628</td>
<td>0.3442</td>
<td>54.575</td>
</tr>
</tbody>
</table>

### Fig. 9 Tie Points’ Distribution for Data 0001_04, Data 0001_03, Data 1001_04 and Data 1001_03

<table>
<thead>
<tr>
<th>Data</th>
<th>Length of Baseline(m)</th>
<th>Angle of Baseline(rad)</th>
<th>Phase Offset(rad)</th>
<th>Vertical Baseline(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0001_0</td>
<td>4</td>
<td>0.5761</td>
<td>0.3093</td>
<td>53.1417</td>
</tr>
<tr>
<td></td>
<td>0001_0</td>
<td>0.5368</td>
<td>0.4771</td>
<td>14.1151</td>
</tr>
<tr>
<td></td>
<td>1001_0</td>
<td>0.6099</td>
<td>0.2141</td>
<td>78.6679</td>
</tr>
<tr>
<td></td>
<td>0001_0</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

### Tab. 3 Estimated Parameters by Each Pass (or Block)

<table>
<thead>
<tr>
<th>Name of TPs</th>
<th>Calibration by single pass (block)</th>
<th>Calibration with joint adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Height’s difference</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>14</td>
<td>13.654</td>
<td>3.641</td>
</tr>
<tr>
<td>15</td>
<td>26.009</td>
<td>14.786</td>
</tr>
<tr>
<td>23</td>
<td>9.403</td>
<td>1.128</td>
</tr>
<tr>
<td>24</td>
<td>13.198</td>
<td>4.368</td>
</tr>
<tr>
<td>25</td>
<td>8.164</td>
<td>-0.799</td>
</tr>
<tr>
<td>33</td>
<td>-7.284</td>
<td>10.190</td>
</tr>
<tr>
<td>34</td>
<td>-2.494</td>
<td>-2.410</td>
</tr>
<tr>
<td>35</td>
<td>-3.108</td>
<td>3.121</td>
</tr>
<tr>
<td>36</td>
<td>-5.849</td>
<td>-9.904</td>
</tr>
<tr>
<td>37</td>
<td>5.279</td>
<td>3.626</td>
</tr>
<tr>
<td>38</td>
<td>12.311</td>
<td>-10.100</td>
</tr>
</tbody>
</table>
4. CONCLUSIONS

It’s significant to estimate interferometric parameters for the applied surveying and mapping with airborne dual-antenna InSAR systems. Baseline parameters and interferometric phase offset are key parameters to be estimated. Their errors will reduce the heights’ accuracy. In order to apply the airborne dual-antenna InSAR systems in large areas’ topographic surveying and mapping, the baseline estimation algorithm with block adjustment for multi-pass InSAR data was presented to reduce the needed ground control points and the heights’ difference between different passes.

The baseline estimation experiments with block adjustment were done with multi-pass InSAR data obtained by Chinese dual-antenna airborne InSAR system. Although there were less ground control points, the satisfied results were obtained. It can reduce the heights’ difference obviously by adopting the proposed baseline estimation algorithm.

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