Effect of Speckle Reduction Filter and Multi-Window Image Matching on Stereo SAR

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Abstract: The author investigates the effect of the filtering for speckle noise reduction and the combined use of multiple windows with different sizes in image matching process for generating digital elevation model (DEM) by means of stereo SAR. Two RADARSAT fine-mode data with different incidence angles are used as stereo SAR data pairs. The test sites are the area around Hiroshima-city and Mt.Unzen. Two kinds of filters with different window sizes and two different methods for using multiple windows are tested. The result proves that both of speckle reduction filter and multi-window image matching enable to improve height accuracy and in addition, the latter also improves topographical patterns.
Keywords: DEM, Radarsat, Mean filter, SFP filter, Area correlation, Height anomaly

1. Introduction

Nowadays stereo SAR is one of the major tools for generating digital elevation model (DEM) using SAR data together with interferometric SAR (InSAR). Although InSAR enables to generate very smooth and continuous topographical patterns, the quality of InSAR-derived DEM tends to be significantly affected by coherence conditions and as the result, data-deficient areas tend to remain in wide plane areas [1]. Especially in tropical regions, coherence conditions are generally bad even by using L-band SAR like JERS-1/SAR and therefore, it does not seem easy to use InSAR technology for DEM generation in tropical regions. On the other hand, stereo SAR enables to be free from coherence problem and therefore, it seems more adequate and practical approach for DEM generation in the areas with bad coherence conditions like tropical regions.

In the process of DEM generation by stereo SAR, height values are computed from the results of image matching between stereo pair images. In SAR images speckle noises are always included and they might bring undesirable effect in image matching process. Therefore first, the effect of speckle reduction filter is investigated. As to the other factor than speckle noise, it has been already proved that the window size for image matching affects the height accuracy of DEM derived from image matching results and the larger window size enables to decrease height anomaly probability caused by the failure of image matching. However, the larger window size also might bring in the worse matching result due to the difference of geometric distortion between pair images. Therefore secondly, the effect of the combined use of multiple windows with different sizes is investigated.

2. Test Data and Study Area

Radarsat fine-mode data pairs with different incidence angles are used as the test stereo pair images. The study areas are the areas around Hiroshima-city and Mt.Unzen. In Hiroshima area, Radarsat-F5 and F2 data pairs with the incidence angles of 46.029° and 40.959° respectively are used. In Mt.Unzen area, F4 and F1 data pairs with the incidence angles of 44.625° and 39.17° respectively are used. The pixel size of a pair image is 6.25 meters, which is the standard size of Radarsat-SGF product. For the evaluation of height accuracy, the digital elevation data file with 50 meters grids issued by Geographical Survey Institute of Japan (GSI) is used as the reference DEM (this reference DEM is noted as *GSI-DEM* in this paper).

3. Data Processing

3.1 Filtering for Speckle Noise Reduction

Many kinds of filters for speckle noise reduction have been proposed until now. However in this paper, rather simple filters, Mean filter and SFP filter [2], an improved filter of the Mean filter, are used because it is preferable to maintain original gray level patterns for computing area correlation in the image matching process. In the Mean filter, the gray levels in a window are simply averaged, and in the SFP filter, a threshold level is set according to the theoretical variation of speckle noises and if a gray level difference from the center pixel level in a window exceeds the threshold level, then that gray level is excluded from averaging. Therefore, SFP filter enables to maintain small or isolated backscattering patterns even after reducing speckle noises by averaging. The filtering equations of the SFP filter are as follows;

$$x_c = \sum_{k=-m}^{m} \sum_{l=-n}^{n} W_{kl} \cdot Z_{kl} \Big/ \sum_{k=-m}^{m} \sum_{l=-n}^{n} W_{kl} \qquad \begin{array}{ll} W_{kl} = 1 & \mathit{if} \left| Z_c - Z_{kl} \right| < 2\sigma \overline{Z} \\ W_{kl} = 0 & \mathit{others} \end{array}$$

Where, the window size is (2m+1) x (2n+1), Z_{kl} means the original value in the window location (k,l), Z_c that in the center of the window, $\overline{Z}$ the average of all pixel values in the window. The σ in above equations means the standard deviation of speckle noises, and σ takes 0.523 in the single-look amplitude image, the SGF product of Radarsat data. Three window sizes, 3x3, 7x7 and 11x11, are selected for filtering (this window for filtering is noted as *filtering window* (FW) hereafter).

3.2 DEM Generation by Image Matching

After filtering of input pair SAR images, the pair images are registered each other by selecting GCPs only in coastal lines or river-side areas in a low-plain where elevations are almost zero. Next, the parallaxes of all pixels in the master image are computed from the results of pixel-wise image matching process between registered pair images, and then the height values in all pixels are computed based on the parallaxes and incidence angles. Total five window sizes, 32x32, 48x48, 64x64, 80x80, and 96x96, are selected for computing area correlation coefficient values in all possible pixel locations in a search area (this window for area correlation computation is noted as *matching window* (MW) hereafter).

After computing pixel-wise height values, it is necessary to detect abnormal height values (this abnormal height values are noted as *height anomaly* (HA)) and interpolate them because the parallax values are not always correct due to the failure of image matching. The height anomaly is detected based on the height differences from neighboring pixels and also on the maximum correlation coefficient value obtained by image matching. The detected height anomaly data are then interpolated by the average of the normal height values in neighboring pixels. The remained height anomaly data are finally replaced by the average of height values in left-side and upper-side pixels to generate a complete DEM product. The window size for interpolation is 11x11, and the pixel resolution of a final DEM product is reduced to 12.5 meters from 6.25 meters of original SAR images.

3.3 DEM Generation by Multi-Window Image Matching

In the DEM generation process described above, two kinds of methods are tested to evaluate the effect of the use of multiple matching windows with different sizes. The descriptions for each method are as follows;

(Method-1): Several DEM products are generated individually by using single matching windows with different sizes and after that, the height values in all individual DEM products are averaged pixel by pixel to generate a single DEM product.

(Method-2): During the image matching process, two matching windows with different sizes are applied step by step (first the larger window and next the smaller window) to compute pixel-wise parallax values.

3.4 Accuracy Assessment of the DEMs by Stereo SAR

First, the DEM products generated by above procedures are ortho-corrected together with the master SAR image by using pixel-wise height values. Next, the shading images are simulated from the reference DEM (GSI-DEM) in the study areas and then the GSI-DEMs are registered onto the DEM products by stereo SAR through the registration of ortho-corrected SAR images and shading images. After registration, pixel-wise regression analyses are conducted between SAR-derived DEMs and GSI-DEMs. The standard deviation of the residuals obtained by regression analyses (this value is noted as *relative height error* (RHE)) is used as the index of height accuracy. In addition, the probability of height anomaly data occurrence (noted as *height anomaly rate* (HAR)) and the average value of the maximum correlation coefficient values obtained by pixel-wise image matching in the study areas (noted as *maximum correlation* (MCOR)) are used as the indices for the evaluation of image matching process.

4. Results and Discussion

4.1 Effect of Speckle Reduction Filter

In the preliminary study, the effect of speckle reduction filter was evaluated with two kinds of filters (Mean and SFP filter as described in 3.1) and three kinds of filter window (FW) sizes in Hiroshima study area. As the result, SFP filter was slightly better than Mean filter, and the best FW size was 3x3. Therefore, the effect of speckle reduction filter was evaluated again using SFP filer with FW 3x3 in both of Hiroshima and Mt.Unzen study areas.

Table 1 shows the results of the average of maximum correlation coefficient in the image matching process (MCOR), the height anomaly rate (HAR), and the relative height error (RHE) in Hiroshima and Mt.Unzen respectively. In Table 1, it is definitely clear that the results of three indices (MCOR, HAR, and RHE) are always better for filtering than for non-filtering in all cases of five different matching window (MW) sizes. As the effect of filtering, MCOR clearly increases almost twice in both study areas. HRA decreases significantly with MW sizes more than 64x64, and especially in Hiroshima, HRA decreases over hundreds times with 64x64 MW size. As to RHE, error values are always smaller for filtering than for non-filtering, although the differences are rather small. These error differences might be brought by the decrease of HAR and this is the reason why error differences are small because height anomaly occurs only in a pixel-wise manner.

Table 1 also shows the remarkable effect by matching window (MW) sizes. That is, HAR clearly decreases with larger MW sizes, and MCOR slightly increases with larger MW sizes. On the other hand, RHE becomes minimum with 48x48 MW size in Hiroshima and with 64x64 MW size in Mt.Unzen. The result for RHE is quite interesting because this suggests the existence of optimal MW size, although the optimal size also changes according to study areas. The reason for this change might be the difference of land cover conditions of the study areas as discussed later in 4.4.

4.2 Effect of Multi-Window Image Matching

Table 2 shows the results of RHE for the image matching using single-size matching window (single-window) and for multi-window image matching in both study areas. All results in Table 2 are those using SAR images after filtering by SFP-filter with FW 3x3. For Method-1 of multi-window case, the upper rows means that three individual DEM products generated by three MW sizes (32x32, 48x48, and 64x64 in Hiroshima, and 64x64, 80x80, and 96x96 in Mt.Unzen) are finally averaged into single DEM product. The lower rows means that first three DEM products are generated through Method-2 with different MW combinations and then they are averaged into single DEM product.

Table 1. Effect of speckle reduction filter in two study areas.

<Hiroshima>

Indices	Size of MW	Non-Filter	SFP-Filter (3x3)
Average Max. Corr. Coef. (MCOR)	32 x 32	0.278	0.472
	48 x 48	0.283	0.487
	64 x 64	0.287	0.496
	80 x 80	0.290	0.502
	96 x 96	0.292	0.506
Height Anomaly Rate (HAR) (%)	32 x 32	6.272	3.094
	48 x 48	2.194	0.792
	64 x 64	2.086	0.005
	80 x 80	0.011	0.0
	96 x 96	0.018	0.0
Relative Height Error (RHE) (m)	32 x 32	26.0	23.0
	48 x 48	22.6	21.6
	64 x 64	23.3	22.3
	80 x 80	24.2	23.1
	96 x 96	25.4	24.1

<Mt.Unzen>

Indices	Size of MW	Non-Filter	SFP-Filter (3x3)
Average Max. Corr. Coef. (MCOR)	32 x 32	0.220	0.400
	48 x 48	0.222	0.420
	64 x 64	0.225	0.432
	80 x 80	0.227	0.440
	96 x 96	0.228	0.444
Height Anomaly Rate (HAR) (%)	32 x 32	36.757	28.616
	48 x 48	4.455	(*)
	64 x 64	2.498	0.788
	80 x 80	1.461	0.520
	96 x 96	1.295	0.494
Relative Height Error (RHE) (m)	32 x 32	184.2	158.8
	48 x 48	47.9	(*)
	64 x 64	42.9	38.1
	80 x 80	44.4	39.9
	96 x 96	47.6	43.1

*For MW48x48 and SFP-Filter, it was impossible to detect and correct height anomaly.

Table 2. Effect of multi-window image matching compared with single-window image matching.

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<table>
<tr><td rowspan="2">Index</td><td rowspan="2" colspan="2">Single-Window</td><td colspan="4">Multi-Window</td></tr>
<tr><td colspan="2">Method-1</td><td colspan="2">Method-2</td></tr>
<tr><td rowspan="5">Relative Height Error (RHE) (m)</td><td>32 x 32</td><td>23.0</td><td rowspan="5">32+48+64
(64+32)+(80+40)+(96+48)</td><td rowspan="5">20.4
21.0</td><td rowspan="5">64+32
80+40
96+48</td><td rowspan="5">23.6
22.0
21.8</td></tr>
<tr><td>48 x 48</td><td>21.6</td></tr>
<tr><td>64 x 64</td><td>22.3</td></tr>
<tr><td>80 x 80</td><td>23.1</td></tr>
<tr><td>96 x 96</td><td>24.1</td></tr>
</table>

<Mt.Unzen>

<table>
<tr><td rowspan="2">Index</td><td rowspan="2" colspan="2">Single-Window</td><td colspan="4">Multi-Window</td></tr>
<tr><td colspan="2">Method-1</td><td colspan="2">Method-2</td></tr>
<tr><td rowspan="5">Relative Height Error (RHE) (m)</td><td>32 x 32</td><td>158.8</td><td rowspan="5">64+80+96
(64+32)+(80+40)+(96+48)</td><td rowspan="5">38.6
32.0</td><td rowspan="5">64+32
80+40
96+48</td><td rowspan="5">34.5
33.8
34.1</td></tr>
<tr><td>48 x 48</td><td>(*)</td></tr>
<tr><td>64 x 64</td><td>38.1</td></tr>
<tr><td>80 x 80</td><td>39.9</td></tr>
<tr><td>96 x 96</td><td>43.1</td></tr>
</table>

* For MW48x48, it was impossible to generate DEM due to the failure of height anomaly detection (see Table 1).

For Method-2, the first row, for an example, means that single DEM product is generated by two-step image matching process with MW 64x64 and then 32x32. In Method-2, the size of search area for the second-step matching is reduced compared with that for the first-step matching. In Table 2 the minimum RHE appears in the results by multi-window image matching (Method-1) in both study areas. Method-2 does not result in any numerical improvement in Hiroshima, however in Mt.Unzen, both of Method-1 and Method-2 result in smaller RHEs compared with those by single-window image matching. Therefore, the multi-window image matching is considered to be effective to improve the height accuracy of DEM by stereo SAR.

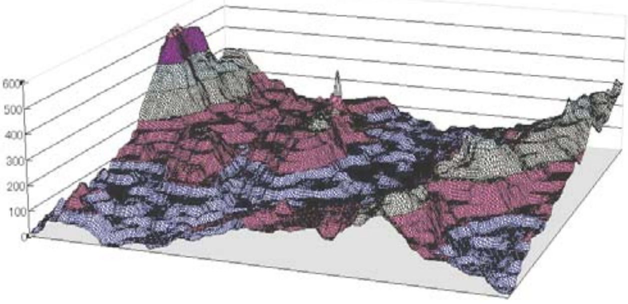
4.3 Evaluation of Topographical Patterns

Figure 1 and 2 show the topographical patterns by the DEMs which give relatively smaller RHEs in single-window and multi-window cases of Table 2 in both of Hiroshima and Mt.Unzen study areas respectively. The patterns by GSI-DEM of the study areas are also shown in the figures. In both figures, it is clearly shown that the topographical patterns by multi-window image matching are more smooth and natural compared with those by single-window matching, although the DEMs by multi-window tend to be less contrastive in height differences. Therefore, the results in Figure 1 and 2 clearly support that multi-window image matching is one of the effective approaches to improve the DEMs by stereo SAR in the aspect of topographical patterns as well as in the numerical aspect.

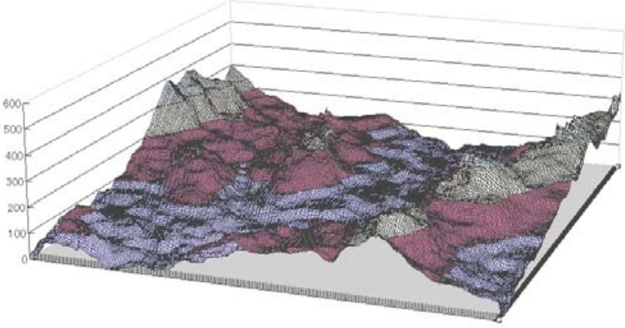
4.4 Comparison of the Results between Two Study Areas

From Table 1 and 2, there are significant differences between Hiroshima and Mt.Unzen study areas. In Table 1, MCORs are larger for Hiroshima than for Mt.Unzen, and both of HRAs and RHEs are smaller for Hiroshima than for Mt.Unzen. These differences clearly indicate that the land cover conditions of Hiroshima are better for image matching than those of Mt.Unzen. Actually, Mt.Unzen study area is almost covered with forest and lava, and therefore, the land cover patterns are less clear in SAR images than those of Hiroshima study area, which is covered with urban and agricultural areas as well as forested areas.

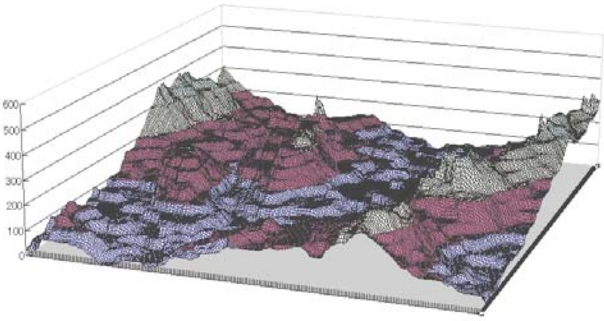
The differences by land cover conditions also appear in the suitable MW sizes in Table 1 and 2, that is, larger MW sizes are required for Mt.Unzen than for Hiroshima to generate the DEMs with smaller RHEs. This difference also might be due to the difference of land cover conditions. More important difference is recognized in Table 2, that is, the effect of multi-window image matching is greater for Mt.Unzen than for Hiroshima. This result suggests that the multi-window image matching becomes more effective in the target areas with worse land cover conditions for image matching process, like Mt.Unzen study area.



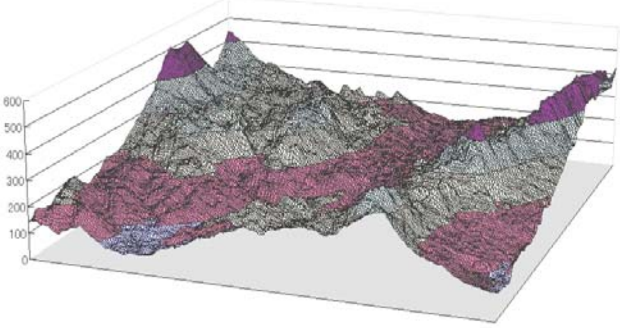
(1) Single-Window, MW : 48x48



(2) Multi-Window, Method-1, MW : 32+48+64

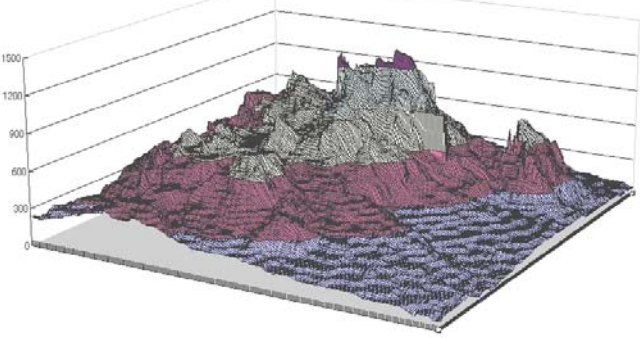


(3) Multi-Window, Method-2, MW : 96+48

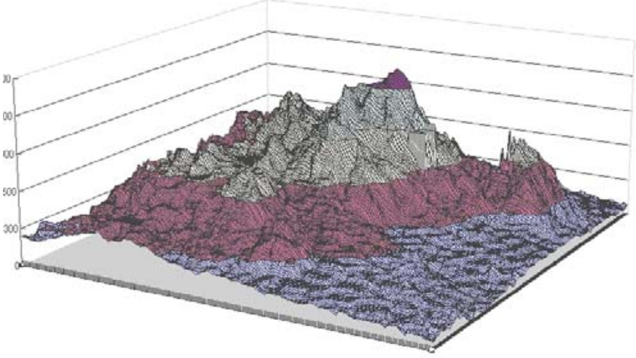


(4) GSI-DEM

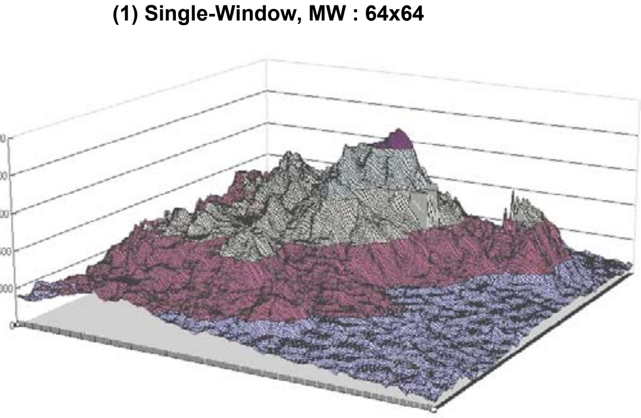
Fig.1. Topographical patterns of the DEMs by stereo SAR and GSI in Hiroshima study area.



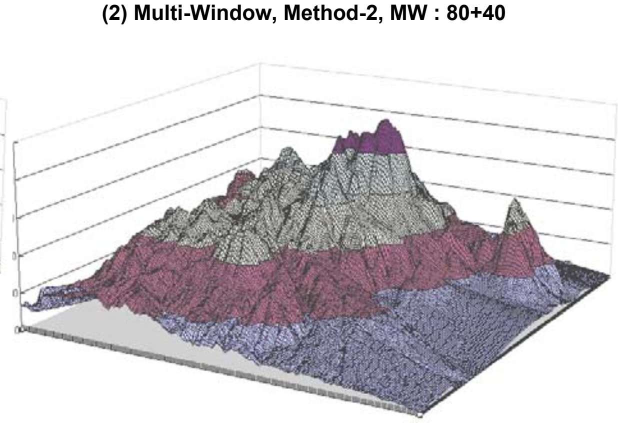
(1) Single-Window, MW : 64x64



(2) Multi-Window, Method-2, MW : 80+40



(3) Multi-Window, Method-1, MW : (64+32)+(80+40)+(96+48)



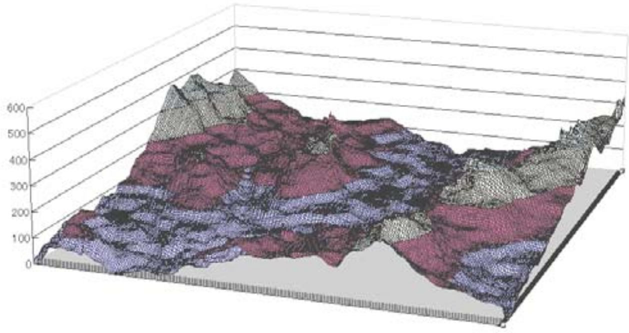
(4) GSI-DEM

Fig.2. Topographical patterns of the DEMs by stereo SAR and GSI in Mt.Unzen study area.

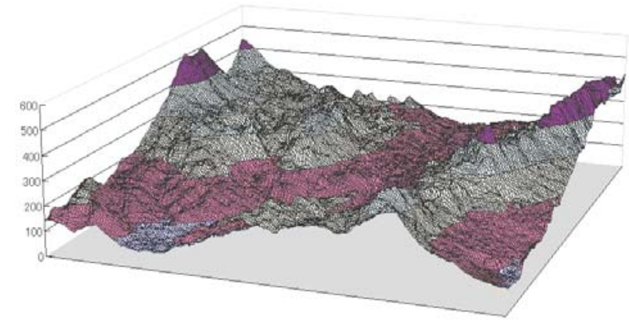
4.5 Comparison with the DEM by InSAR

Another approach for DEM generation by SAR is interferometric SAR (InSAR) as described in introduction. Figure 3 shows the DEMs by stereo SAR and InSAR for comparing the topographical patterns in Hiroshima study area. The L-band repeat-pass data pairs acquired by JERS-1 are used for InSAR. The observation interval of InSAR data pairs is 88 days, and the baseline length is 782 m. In Figure 3, the topographical patterns of the DEM by InSAR are still more smooth and more similar to GSI-DEM than those of the DEM by stereo SAR. As to the height accuracy, RHE is 21.2 m for InSAR-DEM and this is almost comparable to that by stereo SAR (the minimum RHE is 20.4 m for stereo SAR).

On the other hand, the existence of data-deficient areas is a serious problem for InSAR-derived DEM [1]. The data-deficient rate is only 0.353 % in the DEM of Figure 3, and therefore it is almost negligible. However, the land cover conditions in Hiroshima are relatively suitable for InSAR as well as for stereo SAR, because urban and agricultural areas are still better for InSAR than forested areas. This is not always the case for the areas covered with more dense vegetation.



(1) stereo SAR (same as Fig.1 (2))



(2) InSAR with JERS-1/SAR

Fig.3 Comparison of the DEMs by stereo SAR and InSAR.

5. Conclusion

Foregoing experimental results clearly verify that both of speckle reduction filter and multi-window image matching are effective approaches for generating more accurate DEM by using stereo SAR technology. Especially, multi-window image matching is considered to work effectively for the target areas with less land cover patterns like Mt.Unzen study area in this study. As an alternative approach for DEM generation by SAR data, InSAR is an effective approach. It is experimentally verified that the quality of DEM derived by InSAR can be improved by combining multiple interferometric data pairs with different baseline lengths [1]. It is very interesting that the combination of multiple parameters works effectively in both of two different approaches for DEM generation. For verification of this effect by using multiple parameters further investigation should be done for DEM generation by optical stereo data pairs.

Acknowledgement

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