Digital Elevation Model (DEM) fusion was investigated for improving the overall accuracy of DEMs. The approach was applied to two public domain products: Shuttle Radar Topographic Mission (SRTM) DEM and Advanced Spaceborne Thermal Emission and Reflection (ASTER) DEM. The ASTER relative DEM was co-registered to the SRTM co-ordinates and converted to an absolute DEM by shifting the histogram to the average elevation of the SRTM DEM. The voids in the DEMs were filled through an erosion technique using the slope and aspect from the other DEM and the elevation of surrounding pixels. Finally, the DEMs were converted to the frequency domain and an ideal low-pass filter with a cut-off frequency of 0.024 m⁻¹ was applied to the ASTER DEM and a high-pass filter with the same cut-off frequency was applied to the SRTM DEM to filter out errors in the respective frequency ranges. The filtered DEM spectra were then summed in the frequency domain before being converted back to the spatial domain. This approach was tested in a 6000 ha test site with fairly complex topography located in the central region of Nepal. The fused DEM had a 42% improvement in Root Mean Squared Error (RMSE). The approach showed promise for improving DEM accuracy and completeness while maintaining the highest resolution of the input DEMs. This approach increased the reliability and applicability of public domain DEMs produced by Optical and Radar remote sensing technologies.
and low-cost technique for DEM generation for many years. Among the most commonly applied satellite techniques are the stereo-matching of a pair of optical images called optical stereoscopy (Ehlers and Welch, 1987) and interferometry of complex Synthetic Aperture Radar (SAR) images called InSAR (Evans and Apel, 1995). Though InSAR is a relatively new technology (started mainly with European Remote-Sensing Satellite ERS-1, launched in 1991), both optical stereoscopy and InSAR techniques are currently used in the field of geoinformatics. These two satellite techniques have been applied independently, although several synergies can be identified to overcome the limitations of each technique (Yang and Moon, 2003; Weydahl et al., 2005).

Optical stereoscopy and InSAR use entirely different sensing technologies. Optical stereoscopy is based on image parallax in which the coordinate difference between conjugate points in two partially overlapping images is found. Then, based on the imaging geometry, elevation information is extracted. The InSAR technique computes elevation from the phase difference of the point backscatter received by either the same antenna in two passes or by the two different antennas of the same mission separated by some distance (Zebker and Goldstein, 1986; Toutin and Gray, 2000).

Due to the inherent difficulties in acquiring satellite data both with the optical stereoscopic and the InSAR technologies, they are not complete in themselves (Yang and Moon, 2003). Image matching in the optical stereoscopic technique may fail if the stereo images contain cloud cover, radiometric variation and low levels of texture (Weydahl et al., 2005). Similarly the InSAR technique may fail to estimate elevations if images contain layovers, non-linear distortion of the images due to slanted geometry of the radar sensing and shadows (Secker and Vachon, 2007), or suffer from temporal decorrelation (Zebker and Villasenor, 1992) and changes in atmospheric conditions between two acquisitions (Zebker et al., 1997). Due to these problems, DEMs generated from either of these techniques may contain voids, poorly interpolated data, and erroneous values.

However, the complementary error behaviour of optical stereoscopy and InSAR provides an opportunity for DEM fusion (Kaab, 2005). Optical stereoscopy fails, as stated above, in the presence of clouds or low texture, while InSAR works fine in such cases. On the other hand, InSAR fails under high terrain steepness or rapid change in surface roughness; both issues are handled well with optical stereoscopy.

The problems associated with InSAR may affect the phase of large areas in which the interferometric height determination fails leading to a regional error in DEMs (Honikel, 1998). This phenomenon causes DEM smoothing and thus introduces low frequency artefacts in the frequency domain. On the other hand, stereo optical DEMs become much more rugged because of the spikes induced by conjugate point mismatches in the image pair (Honikel, 1998). Therefore, the errors occur locally, typically as jumps between two adjacent pixels, which lead to high frequency components in the spatial frequency domain.

### 2. Background

As the numbers of satellite-based DEM sources are increasing, there is a strong need for careful accuracy assessment of each available DEM. Since different satellite sensors use different wavelength regions and/or viewing geometries, data collected by these sensors may provide complementary information (Liu et al., 2003; Seeker and Vachon, 2007). Availability of DEMs from multiple sources and their complementary nature open the opportunity to fuse multi-source DEM products to generate a value-added product that is more complete, accurate and reliable. Several studies have been carried out to address this need. Schultz et al. (1999) developed a methodology to fuse two stereoscopic DEMs. The methodology had two key steps: (1) detection of unreliable elevation estimates, and (2) fusion of the reliable elevations into a single optimal terrain model. Slatton et al. (2002) combined space-borne InSAR data from the ERS-1/2 platforms with multiple sets of airborne C-band InSAR data acquired by the NASA/JPL TOPSAR platform. However, both of these methodologies were developed to fuse the DEMs produced by the same technology, which may not exploit the complementary advantages of two different technologies like InSAR and optical stereoscopy.

Kaab (2005) combined SRTM and ASTER DEMs to remove the voids of SRTM DEM and used the resulting DEM to derive glacier flow in the mountains of Bhutan. Rao et al. (2003) used optical stereoscopic and InSAR techniques to process the Indian Remote Sensing (IRS-1C) PAN stereo and European Remote-Sensing Satellite (ERS-1/2) tandem data, respectively to generate DEMs. They compared the DEMs and fused them by replacing the voids of one DEM with data from the other DEM. However, this data copying strategy was likely to produce spatial irregularities as the elevation values of two DEMs developed using two different technologies may have substantially different values even over small neighbourhoods.

Tupin (2004) used optical images to improve the accuracy of SAR DEMs in an urban area. Building shapes were identified using optical image segmentation, which were then used as auxiliary data in the interferometric or radargrammetric elevation extraction process. Crosetto and Crippa (1998)
The objective of this research was to use a fusion technique to improve the overall accuracy of public domain DEM products with complementary sensing technologies and compare the accuracy of fused DEM with original DEMs. A void-filling approach was developed and used prior to fusing the two publicly available DEM products to improve the accuracy and completeness. The methodology addressed problems resulting from technological limitations of the optical stereoscopy and InSAR and exploited the good aspects of one product to minimize the shortcomings of another product.

3. Methodology

The DEM fusion method used in this research consisted primarily of three steps: co-registration of DEMs, void-filling and frequency domain fusion (Fig. 1). First, DEMs were co-registered and DEM voids were filled. Then, the Fast Fourier Transform (FFT) was applied to convert the DEMs into the frequency domain. Ideal low-pass and high-pass filters were then applied to remove the erroneous frequency components from both of the DEMs before they were combined into a single DEM. In this work, a DEM produced from a contour map was used as the reference data to compare the accuracy of the input DEMs with that of the DEM produced through fusion.

3.1. Test site and data

The test site was located in central region of Nepal (85°32′E, 27°36′N, 1530 m above sea level, asl) about 25 km east of Kathmandu. It covered about 6000 ha (60 km²) of terrain consisting of varying topography including plains, valleys, very rugged hilly regions with slopes up to 60 degrees, and an elevation range of 655 m (Maximum: 1840 m and Minimum: 1185 m asl). Seasonal cultivation was the main land use type in the low land area whereas forest (mainly pine trees) was the main cover of upland region. The DEMs acquired for the research were a 3′ (≈90 m) spatial resolution SRTM DEM with absolute elevations and a 30 m spatial resolution ASTER DEM with relative elevations. To generate equal spatial resolution datasets, the SRTM DEM was over-sampled to 30 m by dividing a pixel into nine pixels with the same elevation. The reference elevation data was acquired from a 1:25 000 contour map (Fig. 2) developed by the Survey Department of Nepal in cooperation with the Finnish International Development Agency (FINNIDA). This contour map was interpolated using spatial analyst extension of ArcView GIS software (Version 3.1 ESRI, Redlands, CA) to generate a reference DEM with a 30 m spatial resolution. The UTM projection system was used with the Indian datum. The test site was in zone 45N.

ASTER DEMs have a vertical RMSE of 10–50 m (Lang and Welch, 1999). In the case of SRTM DEMs, the mission expected a vertical RMSE of 10 m (Rabus et al., 2003). However, studies in mountainous regions revealed relatively higher RMSEs, which were in the range of 20–36 m (Strozzi et al., 2003; Kaab, 2004). The reference contour map had an RMSE of 6 m (Survey, 2004). Assuming that the ArcView contour interpolation algorithm had minimal inaccuracy, the reference DEM was accurate enough to provide a reasonable accuracy assessment of the satellite DEMs and the resulting DEM from the fusion process.

3.2. Co-registration

The ASTER DEM provided a relative representation of the terrain. Therefore, co-registration of two DEMs was essential to remove the potential horizontal and vertical shifts between input DEMs before applying the void-filling and fusion.
techniques. The ASTER relative DEM was co-registered to the coordinate system of the SRTM absolute DEM based on GCPs collected from the two DEMs. It was very difficult to select GCPs on DEMs because no distinct features like road intersections, building corners, or river courses were available. To solve this problem, hydrological features like stream networks and watershed boundaries were derived from the DEMs using ArcView 3.1. The co-registration process geometrically transformed and re-sampled the ASTER relative DEM according to a non-linear mapping function established for the process. The mapping function was developed using the GCPs collected based on the features being matched between the two DEMs. The co-registration process was also performed using ArcView. The co-registered ASTER relative DEM was then converted into an absolute DEM by shifting the histogram to the average elevation of the SRTM absolute DEM.

3.3. Void filling

The DEM void-filling algorithm scanned the DEMs row by row starting from top-left corner to find the void pixels. When a void pixel was found, pixels in the eight-connectivity neighbourhood of the void pixel (Fig. 3a) were checked to find out how many of those were not void. The elevation of the void pixel was calculated only when four or more of the eight neighbouring pixels were not void. For each non-void neighbour, the elevation at the void pixel was estimated based on its slope and aspect values along with the elevation of the neighbouring pixels (refer to Section 3.3.1). Since there were four or more non-void neighbours, this resulted in four or more estimates of the elevation of the void pixel. A weighted-averaging method (refer to Section 3.3.2) was used to calculate the final elevation value from those multiple estimates. If

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Fig. 1 – Flowchart of the algorithm consisting of processes and data units. The two DEMs were pre-processed and fused to develop a value-added DEM. The new product was compared to the reference DEM for accuracy assessment.
more than four of the eight neighbouring pixels were also void, the pixel was left unfilled and scanning continued until the bottom-right pixel of the DEM was reached. When the end pixel was reached, the DEM was updated by filling the void pixels with newly estimated elevations. This process of scanning the DEM and filling the void pixels was repeated until all the void pixels were filled. The successive repetition or passes of the scanning and filling process eroded the voids starting from the void-data borders and moving towards the centre of each void. The technique minimized the carry-over of estimation error from one pixel to the other since it offered the best use of the available non-void pixels in the void-data boundary.

To assess the accuracy of the filling algorithm, 1700 pixel void regions were manually created in each DEM. The voids were created in areas with fairly large variation of elevation, slope and aspect to test the robustness of the algorithm. This void-filling algorithm consisted of two parts, which were void-pixel elevation estimation from each neighbouring non-void pixel and weighted averaging of all elevation estimates to determine the final estimate. These two techniques are described in detail in the following paragraphs.

3.3.1. Elevation estimation

Void-pixel elevations were estimated using the elevation of the neighbouring non-void pixels and the slope and aspect values of the void pixel derived from the complementary DEM. ArcView was used to derive slope and aspect maps from each DEM. Because it was important to maintain the terrain continuity while filling the DEM void, slope and aspect values were copied instead of directly copying elevation values from one DEM to the other.

In the eight-connectivity neighbourhood, the distance between non-diagonal pixels was given by

\[ \Delta d_1 = x \]  

(1)

whereas the distance between diagonal pixels was given by,

\[ \Delta d_2 = x \sqrt{2} \]  

(2)

where \( \Delta d_1 \) and \( \Delta d_2 \) are the distances between two pixels in two different cases (Fig. 3b), and \( x \) is the pixel size or resolution of the DEM.

Now, having calculated the distance between a void and a neighbouring non-void pixel, the elevation difference between the two pixels was calculated using the slope at the void pixel location in the other DEM and the elevation of the neighbouring non-void pixel (Fig. 3c). The actual elevation difference also depended on the aspect or the direction of the slope and direction of the neighbourhood between the two pixels. The estimated elevation difference was then given by

\[ \Delta h_i = \cos(\alpha - \hat{\alpha}_i) \cdot \tan(\theta) \cdot \Delta d_i \]  

(3)
where \( i \) is the range from one to eight, depending on the number of non-void neighbours, \( \Delta h_i \) is the elevation difference between \( i \)th neighbour and the void pixel, \( \theta \) is the slope angle, \( \alpha \) is the aspect angle measured clockwise from north (Fig. 3d), \( \beta_i \) is the angle made by the centre of the \( i \)th neighbouring non-void pixel about the centre of the void pixel measured clockwise from the north (Fig. 3a and d), and \( \Delta d_i \) is the distance between \( i \)th neighbour and the void pixel (Eq. (1) or (2)).

Fig. 3 – Concept of void filling: (a) representation of eight-connectivity neighbourhood, (b) representation of pixel distance, (c) calculating elevation difference from slope, and (d) representation of aspect or direction of the slope and angle between centre pixel and a neighbour.

Fig. 4 – Profiles of SRTM and ASTER relative DEMs against the reference profile: (a) before co-registration (circled area shows the vertical and horizontal shift of the profiles) and (b) after co-registration and histogram shifting. The reference profile was created using the contour map developed by the Survey Department of Nepal.
The sign and magnitude of $\Delta h_i$ depended on the difference between aspect of the slope and the location of the respective neighbour pixel relative to the void pixel. The elevation of the void pixel was calculated using,

$$ h_i = h_i' + \Delta h_i \quad (4) $$

where $h_i$ is the elevation of the void pixel estimated from the elevation of its neighbour and $h_i'$ is the elevation of the neighbour pixel.

### 3.3.2. Weighted averaging

Because there will be multiple elevation estimations of a void pixel, a weighted-average method was applied to calculate the final elevation. A filled void pixel (and thus now non-void) from previous passes may also appear in the eight-neighbourhood of the void pixel. Smaller weights were given to elevation estimates from previously filled pixels. To keep track of the history of the filling and take estimation uncertainty into account, weights were maintained in a weight matrix during the void pixel filling process. At the start of the algorithm, the weight matrix was filled with ones, and each time a pixel was filled, a weight associated with the pixel was evaluated and inserted into the corresponding location in the weight matrix. The weights were calculated with the following equation:

$$ w = \frac{1}{\sum_{i=1}^{n} \left( \frac{1}{w_i} + 1 \right)} \quad (6) $$

where $w_i$ is the weight of $i$th non-void neighbour, $n$ is the number of non-void neighbour pixels.

For example, if a pixel was filled from five neighbouring pixels of which none were previously filled pixels, the weight would be reciprocal of $(1 + 1 + 1 + 1 + 1)/5 + 1$, which is equal to 0.5. And, if a pixel was filled with three non-void pixels and two pre-filled pixels having weighing factor of 0.5 each, the filled pixel would have the weight of the reciprocal of $(1 + 1 + 1 + 2 + 2)/5 + 1$, which is equal to 0.41.

The estimated elevation is given by,

$$ h = \frac{\sum_{i=1}^{n} w_i + h_i}{\sum w_i} \quad (5) $$

where $h$ is the final estimation, $h_i$ is the estimated elevation from $i$th neighbour and $w_i$ is the weight given to $i$th neighbour.

This weighted-averaging algorithm took into account the void-filling history. If higher numbers of pre-filled pixels were used in estimating the elevation of a void pixel, the weight would be relatively low. Similarly, the weight for a pixel would be lower if the input pixels had a higher number of pre-filled ancestors throughout the history of filling.

Though the case of overlapping voids in the two original DEMS was rare, there had to be a strategy to deal with this case. The slope and aspect in this case were estimated by extrapolating the slope and aspect values from the neighbouring non-void pixels of the same DEM. It should be noted...
that the uncertainty associated with terrain estimation for this case will be higher.

3.4. Frequency domain fusion

The FFT was next applied to each input DEM to convert them into the spatial frequency domain as described in Honikel (1998). A low-pass filter then removed the high frequency artefacts from the ASTER relative DEM. The filtering operation was represented by the following equation.

\[ F_{lp}(p, q) = F(p, q)H_{lp}(p, q) \]  

(8)

where \( p, q \) are the frequency domain indices, \( F(p, q) \) is the resulting filtered DEM 2D spectrum, \( F(p, q) \) is the original stereo optical DEM 2D spectrum, and \( H_{lp}(p, q) \) is a low-pass filter.

Because of its simplicity, an ideal low-pass filter given by (Honikel, 1998)

\[ H_{lp}(p, q) = \begin{cases} 1 & \text{for } \sqrt{p^2 + q^2} < \sigma_0 \\ 0 & \text{Otherwise} \end{cases} \]  

(9)

where \( \sigma_0 \) was the cut-off frequency used to perform this operation. This type of filter may cause ringing in the filtered image since it completely removes the frequency components beyond the cut-off frequency. For this algorithm, however, the fusion of two spectrums in the following step replaced the removed frequency components, and the inversion to spatial domain did not suffer from ringing.

An ideal high-pass filter with the same cut-off frequency \( \sigma_0 \) was used to remove the low frequency artefacts from the SRTM DEM. Finally, the two spectra were summed and the inverse FFT was applied to convert the fused DEM back into spatial domain.

The selection of the cut-off frequency \( \sigma_0 \) of the ideal low-pass filter was crucial in the filtering process. A number of trial and error experiments were necessary to determine the cut-off frequency that was suitable for a particular topography based on the accuracy of the fused DEM. In this study, a cut-off frequency \( \sigma_0 \) of 0.024 m\(^{-1}\) or 71% of the highest frequency of the spectrum was used.

4. Results and discussion

4.1. Co-registration

Even though the ASTER relative DEM profile followed the reference and SRTM profiles quite well, significant horizontal as well as vertical shifts between the terrains were observed. Also the deep valleys were smoothed in the ASTER DEM. These issues appeared in the vertical and horizontal shifts of the terrain profiles (Fig. 4a), as well as horizontal shifts of the valley lines (stream network, Fig. 5) and the ridge lines (watershed boundaries, Fig. 6). Since the ASTER DEM was relative, the vertical shift was obviously expected. The horizontal shift of the ASTER DEM was probably because of the less accurate GCPs used by USGS in producing a relative DEM.

To improve the accuracy of the void-filling and fusion algorithms, it was essential to improve the registration accuracy of the ASTER relative DEM.
Co-registration of two DEMs was performed using 12 GCPs collected over the DEMs. The river network crossing points and watershed boundary crossing points were selected as the control points since they could be easily and accurately located in the derived maps (Figs. 5 and 6).

The co-registration RMSE achieved in this process was 0.99 m with 12 GCPs. After co-registration, the histogram of the ASTER relative DEM was shifted to the mean elevation of the SRTM DEM. A 30 m downward shift was necessary to bring the histogram of the ASTER DEM (mean elevation 1561 m) to the mean elevation (1531 m) of the SRTM DEM. The shifting was necessary to make the frequency spectra of the two DEMs similar (both in terms of amplitude and phase) before applying the spatial frequency domain filtering.

4.2. Void filling

For the test site and the surrounding area, SRTM DEM was found to be more problematic in terms of voids. It was probably due to the complex topography of the site, which might have caused several failures in the InSAR process. The ASTER relative DEM, however, contained relatively few voids in the study area. Cloud cover was not a major problem in the development of ASTER relative DEM used in this study, because it was produced from imagery acquired in February, 2001 which was the dry season in the study area.

The void in the central hill slope of the SRTM DEM may have been due to the geometry related constraints like shadows. The ASTER relative DEM had a void in the north-western hilltop, which may have been due to cloud cover in the stereo images. These voids covered approximately 0.5% of each input DEM test area. Voids were completely non-overlapping. Additional manually-generated voids increased the void area to almost 3% of the study area in each DEM. The void-filling algorithm was applied to fill those voids before proceeding to the fusion process. Qualitatively, the areas filled by the algorithm matched the natural topography reasonably well (Fig. 7b). No irregularities were found in the edges and no unnatural slopes were created. The valley lines and ridge lines were maintained (Fig. 8). The filled topography in the manually voided portion was compared with the actual topography of each DEM. In the case of ASTER relative DEM, mean estimation
error was 2.82 m and RMSE was 9.7 m. Similarly, the mean estimation error for the SRTM DEM was 0.41 m and RMSE was 8.3 m. The relationship between the predicted and the original elevation of the void areas was good with $R^2$ value of 0.91 for SRTM DEM and 0.81 for ASTER DEM (Fig. 9).

Because the SRTM DEM was over-sampled to 30 m from 90 m, the actual profile of the DEM shows a staircase effect. In this case, the filled profile was smoother than the original profile because the slope and aspect values used in the filling process were smoother (Fig. 8a). The primary source of error in this case was due to the difference between staircase-type original profile and smoothed estimated profile. Another source of error in the case of filling voids of the SRTM DEM was the relatively poor representation of topography by the ASTER relative DEM. As seen in the profiles (Fig. 4), deep valleys and high peaks were smoothed in the ASTER relative DEM, which also caused error in the calculation of slope and aspect maps and finally may introduce error in the void filling.

To some extent, the error in void filling can also be attributed to the spatial shift between two terrains. A small shift between them still remained even after the co-registration. In the critical location like a valley line, a minor shift between two terrains may cause a large error in slope and aspect prediction, which may lead to a substantial error in the estimated elevation. Also, as the void area becomes larger, the innermost pixels may carry the estimation error from the outer pixels, which might have caused some of the larger estimation errors.

### 4.3. DEM fusion

Qualitatively, the terrain accuracy was much improved from the DEM fusion process as can be seen from the closer resemblance of the fused terrain profile to the reference profile (Fig. 10). The elevation difference between the fused DEM and reference DEM was almost always smaller than that of the individual DEMs. Because the ASTER DEM did not have many local irregularities, the filtering threshold frequency for the best fusion result was found to be 0.71, meaning that 71% of the frequency range of the ASTER DEM was preserved. Due to this reason, there was no apparent reduction in the local irregularities in the profile (Fig. 10b). Error maps were computed by subtracting individual DEMs from the reference DEM. The SRTM DEM had 8.7 m higher average elevation than that of the reference DEM (Table 1). The DEM had a negligible number of pixels with absolute error greater than 100 m and 2.4% pixels with absolute error between 50 m and 100 m. The ASTER relative DEM was co-registered and shifted to the mean elevation of the SRTM DEM. So the error mean of this DEM was the same as the error mean of the SRTM DEM. The RMSE was 28.3 m for the ASTER relative DEM whereas that for the SRTM DEM was 18.3 m (Fig. 11).

The fused DEM showed improvement in accuracy, completeness, and reliability. There was a 42% reduction in error with respect to the ASTER relative DEM. There was 10%
improvement in the RMSE of the SRTM DEM. The number of pixels with absolute error greater than 50 m was reduced to 2.3% from 6.4% of the ASTER relative and 2.4% of the SRTM DEM. The error range of the resulting DEM was reduced to 201 m (Min: 119 m, Max: 82 m) from 308 (Min: 169 m, Max: 139 m) of the ASTER relative DEM and from 239 m (Min: 121 m, Max: 118 m) of the SRTM DEM. Since the fusion was applied to the 30 m resolution input DEMs, the fused DEM had the same resolution. These improvements in accuracy and completeness are vital to improve the reliability and thus the applicability of the public DEMs.

Slightly higher error was observed in the area with higher elevation of the fused DEM. This effect was probably because of the poor stereo-matching in the higher elevation area of ASTER DEM due to partial cloud cover. Similarly, higher magnitude errors were observed in the areas with higher slope. This effect was possibly due to the low accuracy SRTM data in higher slopes. A fairly good relationship was found between the error and the aspect of the slope (Fig. 12). The relationship showed a cyclic effect of the slope aspect on the DEM error. This relationship may be attributed to the low surface texture in the slope that is oriented parallel to the

Fig. 10 – Profiles of fused DEM, and reference DEM along with that of (a) SRTM DEM and (b) ASTER DEM. Fused DEM profile fits better to the reference profile than the SRTM and ASTER profiles.

<table>
<thead>
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<th>DEMs</th>
<th>Minimum error, m</th>
<th>Maximum error, m</th>
<th>Mean error, m</th>
<th>RMSE, m</th>
<th>% Number of pixel with Absolute error &gt; 100 m</th>
<th>Absoloute error &gt; 50 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRTM</td>
<td>–121</td>
<td>118</td>
<td>–8.7</td>
<td>18.3</td>
<td>0.0%</td>
<td>2.4%</td>
</tr>
<tr>
<td>ASTER</td>
<td>–169</td>
<td>139</td>
<td>–8.7</td>
<td>28.3</td>
<td>0.6%</td>
<td>6.4%</td>
</tr>
<tr>
<td>Fused</td>
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<td>82</td>
<td>–8.7</td>
<td>16.4</td>
<td>0.0%</td>
<td>2.3%</td>
</tr>
</tbody>
</table>
5. Conclusion

The proposed methodology of void filling and data fusion benefited from the complementary error phenomena of the two different satellite sensor technologies and resulted to a substantial improvement in the completeness and accuracy of the fused DEM. The following conclusions can be drawn from this research:

- The void-filling process is a practical means for increasing the completeness of the satellite DEMs. The technique successfully filled the voids of ASTER relative DEM with mean error of 2.82 m and RMSE of 9.7 m and likewise the voids of SRTM DEM with a mean error of 0.41 m and an RMSE of 8.3 m. The estimated elevations and the actual elevation showed a good relationship ($R^2 = 0.91$ for SRTM DEM and 0.81 for ASTER relative DEM).

Fig. 11 – Result of the fusion process (elevation in metre). (a) SRTM DEM, (b) ASTER relative DEM co-registered with SRTM coordinates and histogram shifted to the mean elevation of SRTM, (c) fused DEM, and (d) error map. The darker regions in (d) represent the higher negative errors and vice versa. The gray region was the area with lower absolute error.

Fig. 12 – Relationship between fused DEM error and aspect of the slope. The line represents the third order polynomial fit to the data.
• The frequency domain fusion of the DEMs was an effective technique to improve the accuracy and consequently the reliability of satellite DEMs. As compared to the ASTER relative DEM, the technique achieved up to 44% improvement in RMSE and range of the error while maintaining the resolution of 30 m. Similarly, as compared to the SRTM DEM, the technique improved the resolution to 30 m from 90 m while improving the RMSE by 12%.

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