ANALYSIS OF DEM COMBINATION METHODS USING HIGH RESOLUTION OPTICAL STEREO IMAGERY AND INTERFEROMETRIC SAR DATA

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ABSTRACT:

Digital elevation models (DEM) from satellite data are generated mainly from two types of datasets using completely different methods: photogrammetry for optical stereo images (e.g. SPOT5, CARTOSAT) and interferometry for Synthetic Aperture Radar data (InSAR, e.g. ERS-Tandem, SRTM). Both generation methods show advantages and disadvantages but have similar accuracy values in comparison to a reference DEM. The paper aims at showing the potential for combined usage of several DEM (derived with different sensors and methods) to provide a "gap-less" DEM and improve the overall accuracy. Some results are given for three combination methods: DEM fusion utilizing height error maps for each DEM; DEM integration, where single point information from another DEM is inserted during the triangulation process; and the delta surface fill method. The quality of the DEM derived from one source and of the combined DEM depends on the steepness of the terrain and on the land cover type. For flat terrain or moderate hilly landscapes, a height accuracy in the order of 5 meters (RMSE) or better can be achieved for the mentioned sensors. Two test areas are chosen, where many different data sets are available and much knowledge exists from previous studies. The first test area is a region in the south-eastern part of Bavaria comprising a mostly hilly, post-glacial landscape. The second test area is located in Catalonia, Spain including also a mostly hilly terrain with some steep slopes. The received DEM are compared qualitatively and quantitatively to the reference DEM with superior quality by looking at profiles and statistics. The results show an improvement of the combined DEM that can be quantitatively measured. Although overall statistics for larger regions show only a slight improvement, local errors and blunders are reduced significantly and the overall accuracy of the combined DEM is higher.

1. INTRODUCTION

Information about the shape of the Earth's surface are required for several tasks like the creation of orthoimages or flood modelling. Digital elevation models (DEM) are generated by airborne laser scanning, by traditional photogrammetry with aerial stereo photos, with stereo images from space, or with interferometric synthetic aperture radar (InSAR) (Jacobsen, 2004). In this study, two techniques are used: DEM derivation with optical stereo satellite data and interferometric DEM.

Data sets of the French SPOT-5 HRS sensor with high resolution and of the Indian IRS-P5 CARTOSAT sensor with very high resolution are available for optical DEM generation in this study. Stereo image pairs of both sensors are matched to get a large number of automatically located conjugate points. The algorithm uses area-based matching in image pyramids and subsequent local least squares matching (Lehner & Gill, 1992). These conjugate points are then converted with photogrammetric adjustment software based on collinearity equations into 3D object points in the final projection. A DEM is retrieved from these points by triangulation and interpolation.

Interferometric SAR uses phase information from two SAR images of the same area. For the world's landmass between ±60°, a complete DEM was generated with data from the Shuttle Radar Topography Mission (SRTM) in 2000. The C-band DEM is of high quality due to its viewing geometry and high coherence, but only a ground sampling distance of about 90 m is available to the public. DLR also processed data of the German/Italian X-band system with a spacing of about 30 m. However, the SRTM X-band DEM covers only swathes of 45 km and is therefore not available area-wide (Adam et al., 1999).

With both remote sensing methods, actually a mixture of a digital surface model (DSM) and a digital elevation model is retrieved since the reflection/back scatter results from a mixture of different ground objects (often with different heights) in each resolution cell. Both optical and InSAR DEM generation methods show advantages and disadvantages but have similar accuracy values in comparison to a reference DEM. However, both methods also produce DEM, which, besides height information, exhibits small and large gaps, or voids, resulting in incomplete datasets. The matching of optical images sometimes leads to areas with no or only few points, e.g. due to low contrast (for example in forest areas). Simple interpolation does not fill these gaps adequately. Also in InSAR DEM, gaps occur due to radar shadow and layover, especially in steep terrains. In general, the quality of the derived DEM depends on the steepness of the terrain and on the land cover type.

Therefore the paper aims at showing the potential for combined usage of several DEM (derived with different sensors and methods) to provide a "gap-less" DEM and improve the overall accuracy. The combination methods can be divided into ones applied during DEM generation (DEM integration) and ones used with complete DEM (DEM fusion, delta surface fill method). DEM integration inserts single point information from another DEM during the triangulation process in optical DEM generation (Hoja et al., 2006). DEM fusion utilizes height error maps for the weighted combination of the DEM (Reinartz et al., 2005; Honikel, 1999). The generation of such height error maps as a prerequisite is critical and can still be improved. Therefore

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the delta surface fill method (Grohmann et al., 2006) is proposed, which shows improvment over traditional fusion approaches without using a height error map.

The delta surface fill method adjusts the values of both DEM taking into account the edges of the gap where both DEM are available. Normally, merely removing a bias or a void-specific difference will be insufficient if there are variable deltas and/or slope differences between the two surfaces. For the void filling we propose a triangulation and interpolation of points extracted from the delta surface along the edges of the voids. For very large gaps, only the transition area is treated, the center is filled completely with the information of the second DEM.

Two test areas are chosen, where many different data sets are available and much knowledge exists from previous studies. The first test area is a region of about 40 km × 50 km in the south-eastern part of Bavaria. Elevations range from 400 to 2000 m in a mostly hilly, post-glacial landscape including lakes and also mountains of the German Alps. The second test area is located in Catalonia, Spain, and includes the city of Barcelona. The size of the test area is about 60 km × 60 km and it includes also a mostly hilly terrain with some steep slopes and additionally the Mediterranean coast. Both test areas allow the comparison with a reference DEM for different land surface shapes, including forest and steep terrain.

Figure 1 shows a detail of the Catalonia testsite together with the reference digital terrain model (DTM) provided by the Institut Cartographic de Catalunya (ICC). In the following figures, all generated DEM show the same clip and are compared to this reference DTM by difference images.

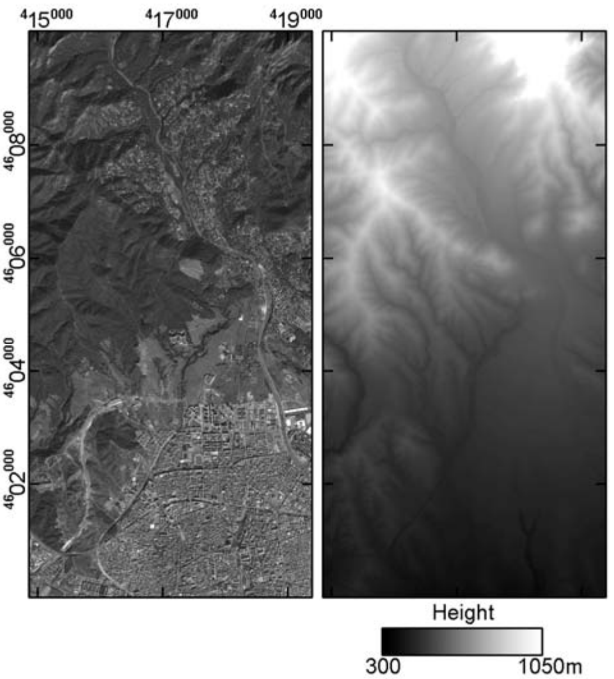

Figure 1. Clip of Catalonia test site. (Left) Ortho image generated from IRS-P5 CARTOSAT data with a GSD of 2.5 m. (Right) Reference DTM with a GSD of 15 m provided by ICC.

In both areas optical image pairs of the SPOT-5 HRS or of the CARTOSAT sensor as well as InSAR DEM of the SRTM mission (X-band and C-band) are used. From the optical stereo data a DEM is generated and the inherent voids are analysed. Furthermore the InSAR DEM is used as reference in the combination methods. Comparisons are shown and discussed for the independently derived and for the combined DEM.

2. DEM GENERATION

2.1 Photogrammetric evaluation of optical stereo imagery

The DEM generation from optical stereo image pairs is carried out using DLR software. Details are described in Lehner et al. (1992). During image matching a large number of conjugate points is extracted from the stereoscopic imagery using the Förstner operator (Förstner & Gülch, 1987) and the homologous points are searched for in the other image. The intensity matching in image resolution pyramids with pixel accuracy is refined in a subsequent local least squares matching (LLSQM) to sub-pixel accuracy. An Otto-Chau region growing procedure is applied for dense matching (Heipke et al., 1996). For cross checking a backward match is performed for all points found. These conjugate points together with the orientation parameters of the camera system (SPOT) or the rational polynomial coefficients (RPC, CARTOSAT) are then converted using forward intersection into 3D points in the final projection.

The irregular distribution of these points in object space is transferred into an equidistant grid to ease further applications. This regularization is carried out in two steps. First, the points are connected by Delauney triangulation into a triangulated irregular network (TIN). Finally, the triangles are superimposed on the regularly spaced grid of the resulting DEM. For each pixel inside a triangle the height value is interpolated on the plane defined by the three vertices of the triangle. A more detailed description is given in Hoja et al. (2005).

The automatic image matching depends on distinguishable and corresponding, but not necessary identical grey patterns in the conjugate image areas (Jacobsen, 2004). In images with high and very high resolutions, large homogeneous areas like fields, meadows, and water bodies appear where good patterns for image correlation cannot be extracted. Areas with steep slopes, shadows, forests, snow and ice fields are likely to pose problems in the correlation process. Therefore, large areas can occur with no conjugate points resulting in a DEM with gaps (also called voids). Simple interpolation does not fill these gaps adequately resulting in a low accuracy at such places. DEM combination methods described in section 3 are a solution to overcome this problem.

Figure 2 shows the DEM generated using a CARTOSAT stereo image pair by fully automatic processing as described in d'Angelo et al. (2009). Large areas with low point density are shown as gaps (in white). The remaining areas have a high conformance to the reference DTM (light and dark green areas). Similar results are shown in Figure 3 for the DEM generated by using SPOT data. Here, large voids are removed by simple interpolation. The smooth overall result confirms the application of this technique. However, a closer look reveals some visible triangles, so gaps should be filled by other methods (see section 3). Also higher differences in comparison to the reference DTM occur (yellow areas in right image part) due to the smaller resolution of the original image data (CARTOSAT 2,5 m, SPOT 10 m).

2.2 Interferometry with synthetic aperture radar data

The coherent analysis of two synthetic aperture radar (SAR) images of the same area acquired under slightly different incidence angles is called interferometric SAR (InSAR). Points with the same distance to a single antenna cannot be distinguished in a single SAR image. The usage of a second antenna position dissolves this ambiguity and can therefore be used for DEM generation. InSAR uses the phase information contained in complex SAR data and the direct proportionality of the phase

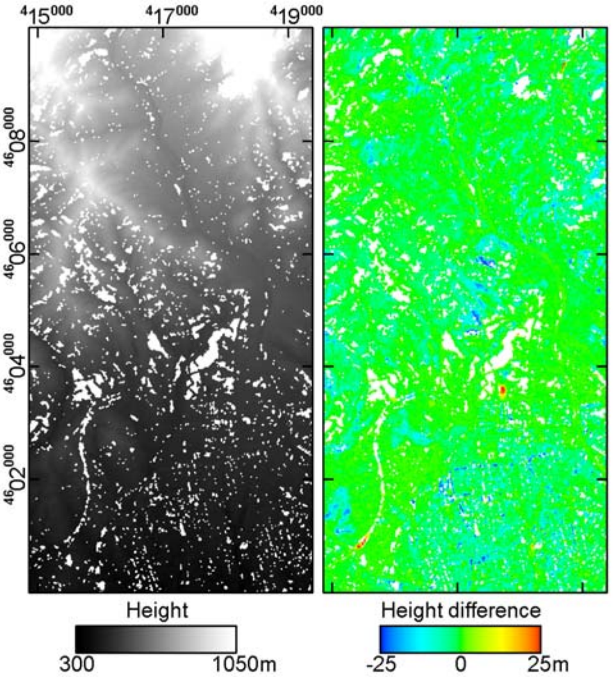

Figure 2. DEM generation result using a CARTOSAT stereo image pair and the difference to the reference DTM. Colour coding is also valid for the following figures, gaps are shown in white (only this figure).

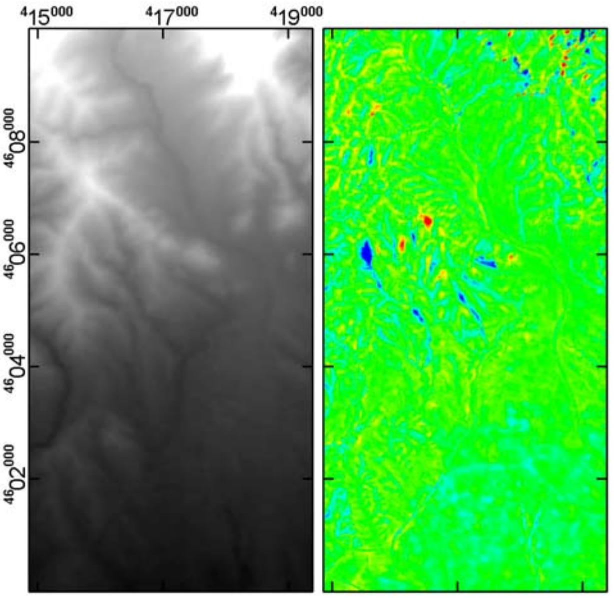

Figure 3. DEM generation result using a SPOT stereo image pair and the difference to the reference DTM.

difference to object height variations. A detailed description is given, e.g. in (Henderson & Lewis; Bamler & Hartl, both 1998). The side-looking illumination and signal reception causes specific geometric characteristics in SAR images. In mountainous areas, radar shadow and layover affect the resulting DEM (Eineder & Holzner, 2000, Henderson & Lewis, 1998). The SRTM incidence angle of 54° avoids layover in mountainous areas, restricting these problems to extremely steep areas. The resulting SRTM DEM is of high quality due to its viewing geometry and high coherence preserved due to the single-pass observation (Eineder & Holzner, 2000).

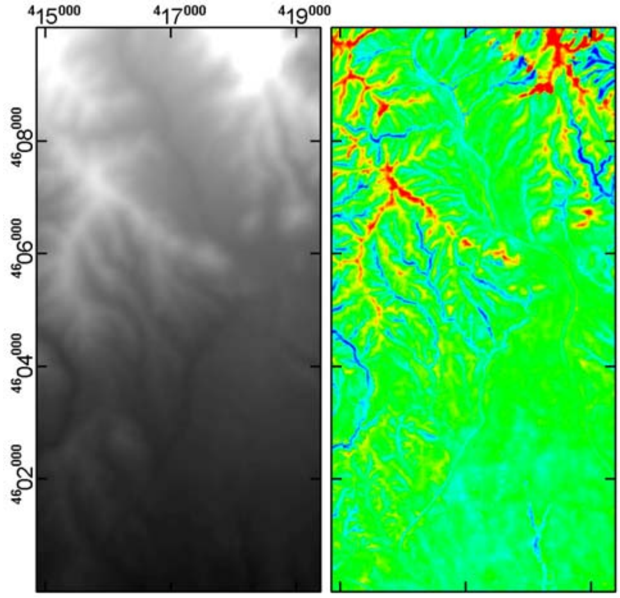

Figure 4. DEM generation result using SRTM C-band InSAR data and the difference to the reference DTM.

Figure 4 shows the InSAR processing result for SRTM C-band data. The difference image to the reference DTM shows high deviations mainly in the mountainous areas. Due to the steep slopes a small lateral deviation can result in a large height deviation. Also the ground resolution difference (SRTM C-band 90 m, reference DTM 15 m) has to be taken into account.The DEM generated from SRTM X-band data has a higher conformance to the reference DTM.

3. COMBINED USAGE OF SEVERAL DEM

State of the art is DEM generation from scratch, i.e. a completely new DEM is generated from a new satellite data set. On the other hand, worldwide DEM coverage is already available. Since 1996 GTOPO30 is accessible, a global DEM with a horizontal grid spacing of 30 arc seconds (approximately 1 km). Data of the SRTM mission refined the globally available DEM (80% of Earth's land mass) to a resolution of 3 arc seconds and much better height accuracy.

The observed scene is unique, so it seems natural to obtain only a single DEM instead of having several individual DEM. Thereby, the density of reliable information increases resulting in more precise DEM than with individual DEM. Here three different methods are presented to produce combined DEM.

3.1 DEM fusion

When different DEM exist of the same area, they can be combined by DEM fusion. The availability of several measures of the elevation for a given point also increases the accuracy of the fused DEM with respect to the individual DEM (Reinartz et al., 2005; Papasika et al., 2009).

For a correct fusion a possible offset is taken into account by calculating the mean height values of the given independently derived DEM in the overlapping areas. One DEM is taken as reference height. The fusion is accomplished with the support of height error maps.

The fused DEM covers the area available in all given DEM. Each pixel is then

- Set to background value if pixel is in no DEM;
- Set to given height if pixel is only in a single DEM;

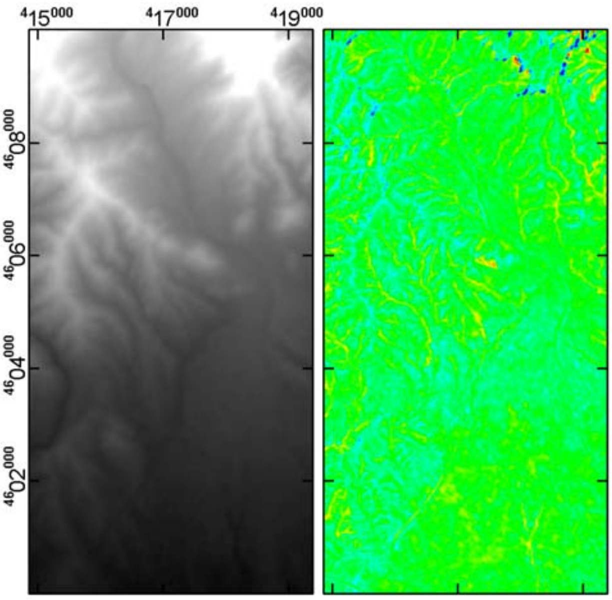

Figure 5. Result from fusing SPOT DEM, SRTM C- and X-band DEM and the difference to the reference DTM.

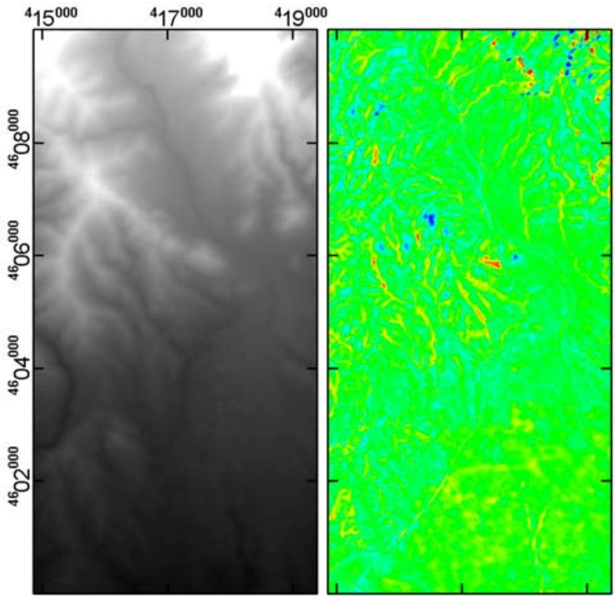

Figure 6. Result from integrating points of SRTM-C DEM into the 3D point data set of SPOT and following regularization and difference to the reference DTM.

- Set to the weighted mean height

$$h_{out} = \frac{\sum h_i \cdot p_i}{\sum p_i} \text{ with } p_i = \frac{1}{a_i} \text{ (}a_i\text{ is given accuracy)}$$

  if the pixel has a value in several DEM.

Quality values of pixels on the border of a DEM are attenuated.
Figure 5 shows the fusion of the SPOT with the SRTM C- and X-band DEM. Changes to the DEM generated by single datasets can be seen first of all in the corresponding difference maps to the reference DTM. The homogeneous green color shows the high conformance. Only in the mountainous areas slightly larger deviations occur (yellow and cyan lines) at ridges and in valleys. This good result is due to the different local distributions of errors for the single processing techniques.

3.2 DEM integration

Another approach is the integration of additional information during DEM generation (Hoja et al., 2005). It covers also the described advantages of data fusion. This method and also the following method are suggested when a single data set is prior to the other ones, e.g. gaps in a new data acquisition are filled by integrating an already available DEM. Especially in cases with existing DEM having lower resolutions as the new data set, the integration of single points in 'voids' instead of a complete fusion seems more suitable.
The most promising approach for a DEM combination already during the generation process is to integrate single points from the existing DEM (e.g. SRTM DEM) into areas with a too low point density in the new data set (e.g. areas of low contrast in stereo image pairs). Such areas can be found after the triangulation. When the size of a triangle is above a threshold, additional points are integrated that are located inside this triangle. The selection of the threshold has to be determined in dependence on the resolution of the existing DEM, the resolution of the DEM to be generated, as well as on the density of the given point cloud (Hoja et al. 2005).
Various methods for point integration into triangles are analysed. Different to rectangles no division exists for triangles into similar smaller triangles with equal area. Therefore all pixels belonging to triangles above the threshold are tested for points in their surrounding area defined as circle with radius equal to the square root of the limiting area size. If no point is found, a new one is integrated at this position using the given DEM. Result is a regular point distribution. As in the DEM fusion process, mean values of the given independently derived DEM in the overlapping areas are calculated and a possible offset is included to the point height before integration.
An exemplary result is presented in Figure 6. Here, 171 points from the SRTM C-band DEM are integrated into the SPOT 3D points. Then the new DEM is generated. The difference map looks smoother than the independent one in Figure 3, right part, with fewer and lower maxima. Some former minima (blue in Figure 3, SPOT DEM lower than reference DTM) are reverted to maxima (red in Figure 6, integrated DEM higher than reference DTM). In these areas points have been integrated from SRTM but probably both methods have problems. The DEM fusion result (Figure 5) shows lower differences to the reference DEM in this area but nevertheless the information of a single DEM may be prefered with only adding few information instead of the fusion of several complete DEM.

3.3 Delta surface fill method

This new technique is presented here since it shows improvements over traditional approaches. The delta surface fill process replaces the void with fill source posts that are adjusted to the DEM values found at the void interface (Grohmann et al., 2006). Input to the process are two DEM, one of them containing voids. In contrast to DEM fusion, no height error map is needed. Also, not the complete DEM are combined, only gaps in DEM are filled by the other DEM thus providing the same advantages as DEM integration.
Different DEM would merge seamlessly when they differ only by a vertical bias after removing this bias. However, removing a (void-specific) bias is insufficient if there are variable deltas and/or slope differences between the two DEM. Such deviations occur due to different means of the DEM generation technologies, e.g. horizontal accuracy (both internal vairance and general bias), post spacing (possibly missing certain smaller features), and smoothing (often causing slopes to vary).

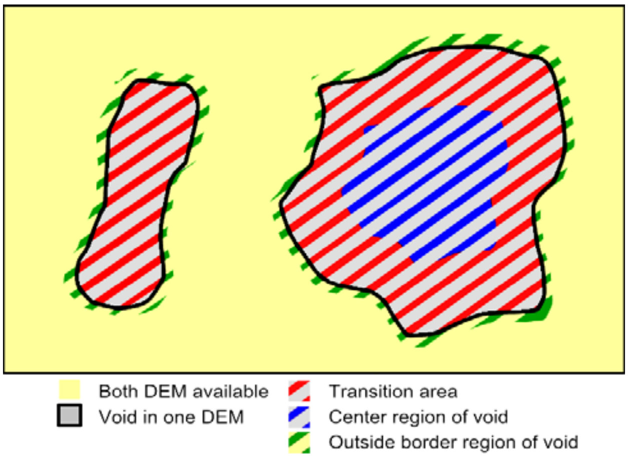

Figure 7. Draft defining the different areas (small and large voids, transition area, center region, border region).

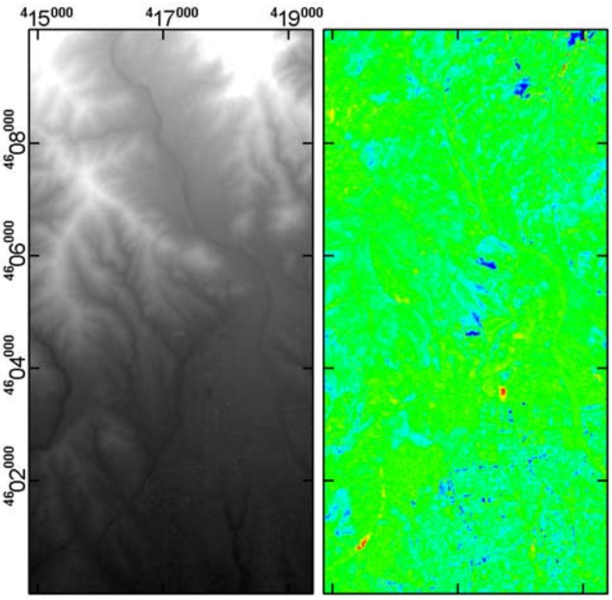

Figure 8. DEM result from filling the gaps in the CARTOSAT DEM with the delta surface fill method using SRTM DEM and the difference to the reference DTM.

The filling is done using a so-called delta surface: the difference between the DEM with gaps and the DEM used for filling is computed. A threshold is defined describing the transition area between the two DEM inside the voids (for example 20 pixel width in the Catalonia data set). Small voids consist only of such a transition area (Figure 7). In large voids, the border region will be the transition area, whereas the center region is processed separately. The center areas in the delta surface are filled with a constant value. In the original paper (Grohmann et al., 2006) this value is equal to the mean value of the overall difference between both DEM. In our implementation a mean value per void is calculated in the outside border region of the void (2 pixel width).

The tranisition areas have finally to be filled by some interpolation. Grohmann et al. (2006) apply an inverse distance weighted interpolation algorithm. Since triangulation and regularization procedures are already included in our software for the overall DEM generation (compare section 2.1), it is used here too. The borders of the transition area are digitized into points. Z value is the delta surface value for the outer border and the mean value per gap for the inner border (small transition areas have only an outer border). These points are triangulated and the result is filled into the delta surface and subsequently into the DEM to be filled after regularization.

Figure 8 shows the application of the delta surface fill method to the CARTOSAT DEM (presented in Figure 2). Gaps are filled by the SRTM C-band DEM with inverse distance weighted interpolation. The result is very smooth, also in comparison to the reference DTM. Remaining deviations (blue and red areas) are already in the pure CARTOSAT DEM (not in gaps), and the transfer of the SRTM DEM values with the delta surface fill method provides no further deviations. This result is much smoother than the previous results of the different combination methods. It does not show the mountainous structures (ridges and valleys) in the difference images that can be seen in Figures 5 and 6 (right part respectively).

4. ANALYSIS OF RESULTS

A qualitative analysis of the results is already given together with the figure descriptions for the single methods. Here some quantitative analysis should make the results more comparable. Some more results, especially for the test area in Bavaria, can be found in (Hoja et al., 2006).

The independently derived DEM (SPOT, CARTOSAT, SRTM C-band, and X-band) are fused pairwise (SPOT + C-band = FUS_SC, SPOT + X-band = FUS_SX) and altogether (SPOT + C-band + X-band = FUS_All). The InSAR DEM are also used for the DEM integration into the SPOT 3D point cloud resulting in the following DEM: INT_SC, INT_SX, and INT_SF (integrating the fusion result of C-band and X-band DEM =FUS_CX) as well as for the delta surface fill method (CARTOSAT + C-band = DSF_CC).

Some statistics are analysed for the difference images of the test site in and around Barcelona shown before. It shows several effects generated by the DEM combination processes. The mean values, which are a kind of bias between the differently generated DEM are generally low for the independently derived DEM as well as for the DEM combinations (1 to 2 m). During the combination process one of the DEM (here: SPOT and CARTOSAT) is introduced as correct in the sense of the mean height for the whole area, therefore mean values in comparison to the reference DEM may vary only little. More variation and in particular improvements can be seen from the standard deviations with values around 5 m due to the mountainous area. The large values of SRTM (standard deviation and minimum/maximum) do not decline the results of the different combination methods. For all fusion processes standard deviation and minima/maxima are similar to each other and lower or similar to the DEM generated from single datasets. This implies that the combined DEM are more reliable even if the standard deviation does not change a lot. The differentiation into terrain classes (almost no slopes to steep slopes) allows a more detailed analysis (compare Hoja et al., 2006).

Similar results are received for all DEM combination methods with slightly better mean values for DEM integration, slightly better standard deviations for DEM fusion and best qualitative result for delta surface fill method (cf. Figure 8). However, during DEM fusion all values (in the overlapping part) are averaged to new heights, which is not always the optimal solution. As described above, there are cases when only data holes should be filled but in the surrounding areas only the information of a single DEM is preferred. Then DEM fusion is left out of consideration and the delta surface fill method is preferred to DEM integration due to the detailed analysis of the single voids.

Effects of the delta surface fill method are illustrated in Figure 9. Here, a cut through the CARTOSAT DEM is given (dark-green line) showing some gaps to be filled by SRTM DEM data (light-green line). The SRTM data is mainly lower than the CARTOSAT DEM, but the values inside the gap are not just taken over but they are adjusted per void. This results in the DSF-CC DEM (violett line, overlaid outside gaps by dark-green line of CARTOSAT DEM). Not all effects can be explained by this cut, e.g. the uprise in the gap on the right side, however the method works in two dimensions and not only in the one shown. For comparison purposes, the same cut through the reference DTM is given and shows the good quality of the delta surface fill method result.

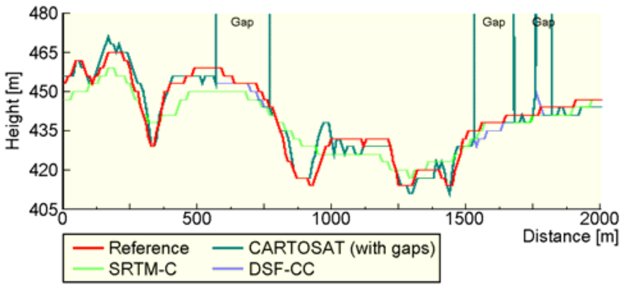

Figure 9. Cut through the hilly area north of Barcelona by the different DEM in comparison to the reference DTM.

5. CONCLUSIONS AND OUTLOOK

From different data sets of optical stereo image pairs and InSAR data, different DEM and DEM combinations are generated and compared to a reference DTM. Three combination methods are used: DEM fusion with the support of height error maps, DEM integration supplementing a given 3D point data set with only few additional information, and the delta surface fill method filling voids in compliance with a void-specific bias.

The received absolute accuracy of terrain heights is in the order of 1 to 2 m shown for a hilly test area Catalonia. Further investigations analysing the dependence on slope angles will be done. For DEM of similar quality, DEM fusion results in the most evenly distributed results. But when one dataset has preferences to an existing DEM, e.g. more recent data acquisition or much better resolution, the DEM integration or the delta surface fill method delivers results depending more on this preferred data set and only filling data gaps.

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