AUTOMATIC GENERATION OF BALD EARTH DIGITAL ELEVATION MODELS FROM DIGITAL SURFACE MODELS CREATED USING AIRBORNE IFSAR

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ABSTRACT

This paper presents a novel approach for the automatic generation of 'bald-earth' digital elevation models (DEMs) from digital surface models (DSMs) created using STAR-3i - the Intermap Interferometric Synthetic Aperture Radar (IFSAR) system. The method uses a hierarchical surface fitting technique to yield bald earth DEMs. It first generates a hierarchy of images from the original DSMs, and bald earth DEMs are created hierarchically through the image pyramid. At the same time, a self-diagnostic process is incorporated into the method, which automatically locates and corrects 'problem areas' based on the difference map between the original DSM and the derived bald earth DEM. The method has been tested on several DSM data sets and the results show that it can remove objects on the ground such as trees and buildings effectively while retaining most of the detail and accuracy of the original data. The program at this stage has been developed to work in urban and rural areas with varying terrain expression from flat to mountainous but excluding heavily forested areas. It is implemented in a software program referred to as TerrainFit©.

INTRODUCTION

Digital Elevation Models (DEMs) are increasingly available for a range of applications at a variety of spatial scales and accuracies. DEMs created by Interferometric SAR (IFSAR) have created a new wide-area availability demonstrated by SRTM's quasi-global data set on the one hand and by the STAR-3*i* airborne IFSAR on the other. The STAR-3i DEM is normally produced at 5 meter postings with an accuracy at the 1-2 meter (RMS) level and as such provides a level of detail that approaches that of LIDAR while retaining wide area coverage and lower cost (Sties et. al., 2000). The day/night cloud penetration advantages of radar are well known, and this, together with its high altitude and fast flying platform, contributes to the rapidity with which it is able to acquire data. However among its limitations is the fact that the DEM thus created is a 'first-surface' model – more correctly called a Digital Surface Model (DSM). Like other technologies, it responds to the surface of the scattering object whether it is a 'hard' object such as a building, or a 'soft' object such as an individual tree or a wooded area. For many applications a so-called 'bald-earth' or 'bare-surface' DEM is required. This is one for which objects situated on the terrain surface such as buildings, towers, trees, etc. have been removed. Irrespective of the technology, photogrammetric, LIDAR or IFSAR, editing is usually invoked to create bald-earth DEMs. Often the editing is manually performed, with sophisticated support tools. Nonetheless manual editing represents a major component of the cost of a bald-earth DEM and it is time-consuming and subjective. This paper deals with attempts to automate the process for DSMs originating with the STAR-3i IFSAR system. Although developed in the context of IFSAR, at this stage the approach is generic, relying only on the DSM input.

In recent years, some efforts have been made on this subject and a number of methods have been developed. Various methods for the automatic detection of buildings and trees from high-resolution digital surface models have been developed (Haala and Brenner, 1999; Soergel et al, 2000; Wang and Schenk, 2000). Some methods use image processing techniques such as classification method and image understanding method to remove buildings and trees (Lu et al, 1998). Due to the complexity of remotely sensed imagery, objects can not be classified accurately with the existing classification methods. As well, image understanding techniques are not mature enough to recognize objects from images reliably. Zhang and Tao (1999) proposed a method for automatic generation of bald earth DEMs based on observations that local minima usually correspond to true terrain points. In their method, local minima are extracted and false terrain points are removed by comparing them with a trend surface which is determined by surrounding terrain points. This method generally works well in residential areas, but needs further improvements to deal with mountainous areas (Tao, et al, 2001).

In this paper, a novel method for the automatic generation of bald-earth DEMs from digital surface models (DSMs) produced from Intermap's STAR-3*i* IFSAR system is presented. The method uses an image pyramid of input DSM data, and generates bald earth DEMs hierarchically through this image pyramid (Wang and Tao, 2000). It is assumed that true terrain points usually correspond to local minima when the terrain is relatively flat, and therefore objects on the terrain surface such as buildings and sparse trees can be removed through the generation of an image pyramid. An approximate bald-earth DEM can be derived from the image at the top of the pyramid by interpolation. In order to obtain an accurate bald earth surface, images at lower levels in the pyramid are used. The generated bald earth surface at each level is used as a reference for the image at the next level to eliminate false terrain surface points and the remaining terrain points are used to interpolate a new bald earth surface. This process is repeated through the image pyramid until the bottom level is performed.

Due to the effects of rapidly changing terrain slope, the generated bald-earth DEMs can be incorrect in some areas. To mitigate these problems, a self-diagnostic process is incorporated in the method which can locate problem areas and correct them automatically based on the difference map, i.e. the difference between the original DSM and the generated bald earth surface.

In this paper we describe the various steps of the process and summarize the results both qualitatively and quantitatively. The DSM and bald earth DEM of a tile near Denver, CO. called the Morrison quad are presented for visual inspection. Statistics of differences with respect to 'truth' are also presented. In this instance, truth is represented by a pre-edited LIDAR DEM made available for test purposes by a third party.

GENERATION OF BALD EARTH DEM BY HIERARCHICAL SURFACE FITTING

Generation of an image pyramid is actually a process of image filtering in which high-frequency components are filtered out. For digital surface data, objects on the ground such as buildings and trees are removed during the creation of the image pyramid. Therefore, a bald earth DEM can be generated from the image data at the top of the pyramid. However, the generated bald-earth DEM is inaccurate due to the low spatial resolution of the top image. To obtain an accurate bald earth DEM, high-resolution image data, i.e. images at lower levels of the pyramid should be used. In images at lower levels of the pyramid, some points are not true terrain points when they are on top of buildings or trees. Points on top of buildings and trees must be removed before a bald earth DEM is interpolated. In order to eliminate these points, the generated bald earth DEM at a higher level is used as a reference surface and points with a distance to the reference surface larger than the given threshold are removed. In this way, non-terrain surface points are removed and a bald earth DEM can be interpolated hierarchically. The main advantage of the hierarchical surface fitting method is that objects on the ground with widely varying spatial extents, such as buildings and trees, can be removed more reliably and thus, a more accurate bald earth DEM can be produced. The process consists of the generation of an image pyramid from the original DSM data, the derivation of an initial bald earth DEM, the extraction of terrain surface points and the interpolation of the bald-earth surface.

Generation of Image Pyramid

An image pyramid is a series of images with different resolutions which are usually generated from the original image by resampling. There are two common ways for resampling an image. One is to take the average of pixels in a defined window, e.g. 2x2, and the other is to convolute the original image with a kernel function, for example, a Gaussian function. The image pyramid used in this study is different from the traditional one in image processing in two aspects. First, the value of a pixel in an IFSAR DSM image represents the elevation of a terrain point instead of the gray value expressing the reflectance of terrain or an object in a small area. Secondly, the image at a higher-level in the pyramid is generated by taking the minimum in a defined window in a lower-level image rather than the average. In this way, the points on buildings, trees and noisy data can be removed gradually. The total number of levels of the image pyramid depends on the spatial resolution of the input DSM data and the maximum size of buildings to be removed from the DSM data.

Derivation of Initial Bald Earth DEM

It is assumed that non-terrain surface points are removed during the generation of the image pyramid and the remaining pixels at the top-level image of the pyramid are true terrain surface points. Thus, a true bald earth DEM can be generated by interpolation. To obtain a smooth surface, a moving averaging method is used to interpolate all points in this study.

Hierarchical Interpolation of Bald Earth DEM

Due to the low-spatial resolution of the top image in the pyramid, the derived bald earth DEM is inaccurate and can not be used as the final product. To yield an accurate bald earth surface, the images at lower levels of the pyramid are used and a bald earth surface is generated hierarchically through the image pyramid. At each level, various types of terrain points are extracted and evaluated using the derived bald earth surface as a reference surface. A more accurate surface is then interpolated using the verified terrain surface points. This process is repeated until the image at bottom level is reached.

Extraction of Terrain Points. To interpolate a bald earth surface at each level, terrain surface points should be extracted. The accuracy of the interpolated surface depends on the reliability of the extracted points and their distribution. To create an accurate bald earth surface, sufficient terrain points should be used. It is assumed that local minima in DSM images usually correspond to true terrain surface in residential areas. Considering the complexity of the terrain surface, other types of terrain surface points such as slope points and points in flat areas are also detected in addition to local minima. A total of five classes or types of points are recognized. These types of terrain surface point are defined in a local area and are extracted efficiently using a defined strategy in order to detect a well-distributed point set which is sufficiently dense to retain the detail of the terrain.

Since not all the extracted points are true terrain surface points, false terrain points should be removed before a bald earth DEM interpolated. As one point has very limited information, it is difficult to differentiate between a true terrain surface point and a false point by using information associated with it alone. To eliminate spurious terrain surface points effectively, the extracted points are compared with the derived bald earth DEM. When the distance from a point to the reference surface is larger than the given threshold, it is considered as a spurious surface point. The criterion for eliminating spurious surface points can be described as:

$$\text{if } |h_i - h_i^0| < T_\text{h}, \text{ point i is accepted, otherwise it is a spurious surface point.} \tag{1}$$

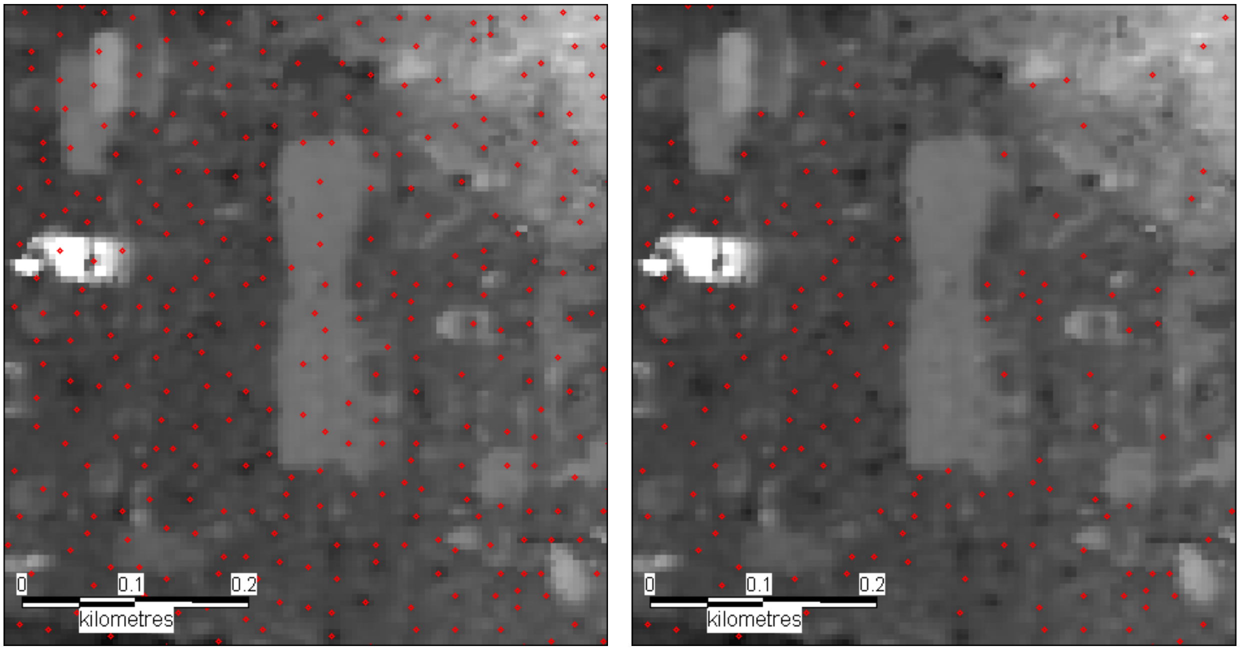
Where h_i and h_i^0 are the elevations of point i on the original DSM and reference surface respectively.

Figure 1 shows the partial results of terrain point extraction from a test data set in which there is a large building approximately 200m x 50m and some smaller buildings. Figure 1(a) represents all extracted terrain points while Figure 1(b) demonstrates the results after the elimination of spurious surface points. It is shown that spurious points are successfully removed during the hierarchical surface fitting and the remaining points correspond to the true terrain surface.

Interpolation of Bald Earth Surface. After false terrain surface points are removed, the remaining points are used to interpolate a new bald earth surface. There are a number of methods available for DEM interpolation (Greve, 1996). A moving facet algorithm is used in this study. The algorithm fits a facet to the surface where the point to be interpolated is located and works in two steps: selection of surface points around the point to be interpolated within a defined area and fitting a surface to the selected points. To keep the fitting accuracy, the selected points should meet the following criteria:

a. they should be distributed in three or four different quandrants with the point to be interpolated as the origin
b. they should form a good configuration (internal angles between two neighbouring sides of a triangle or rectangle should be larger than 30°).

Once all points are interpolated, a moving averaging process is applied to the interpolated data to create a smooth bald earth DEM.



(a) (b)

Figure 1. Extracted surface points (a) extracted surface points (b) extracted surface points after elimination of spurious surface points

AUTOMATIC LOCATION AND CORRECTION OF PROBLEM AREAS

Due to the effects of terrain slope, some areas in the generated bald-earth surface, especially in mountainous areas, may be represented incorrectly. Therefore, it is necessary to develop a self-diagnostic process which can locate problem areas and correct them automatically. In this study, a method called 'zero' surface is developed using a ' difference map', which shows the difference between the original IFSAR DSM and the derived bald-earth DEM. As the difference map only gives the difference of elevations between the original IFSAR DSM and the derived bald-earth DEM, problem areas can not be located from it directly. To define the problem areas correctly, a bald surface is generated from the difference map. It is assumed that the bald surface from the difference map should have a value of zero if the derived bald-earth DEM from the original IFSAR DSM is correct. In problem areas, the derived bald surface from the difference map has a non-zero value. Thus, it is very easy to locate problem areas in the bald surface generated from the difference map. The whole process of defining problem areas includes:

a. creating a difference map from the original IFSAR DSM and the generated bald-earth DEM
b. deriving a supplementary bald surface from the difference map using hierarchical surface fitting method
c. locating non-zero areas in the supplementary bald surface.

Figure 2 shows the results of problem area location using the above method to the data from Morrison quad. Figure 2(a) is the difference map in which white shows positive differences in elevation, black represents negative differences, and grey gives differences around zero. It can be seen that the bald-earth surface in residential areas is generated correctly and the eliminated buildings and highways above the ground are clearly shown in the difference map. However, most mountainous areas are not represented correctly as shown in the difference map and some small hills in residential areas are removed incorrectly.

The supplementary bald surface yielded from the difference map is shown in Figure 2(b). It can be seen that the supplementary bald surface has values around zero in residential areas while in mountainous areas it has non-zero values. Most problem areas are shown in the generated supplementary bald surface properly. Figure 2(c) shows problem areas located from the supplementary bald surface generated from the difference map. It can be seen that most problem areas correspond to mountainous areas. Some small hills are also located since they are treated as large buildings and removed incorrectly in the previous process.

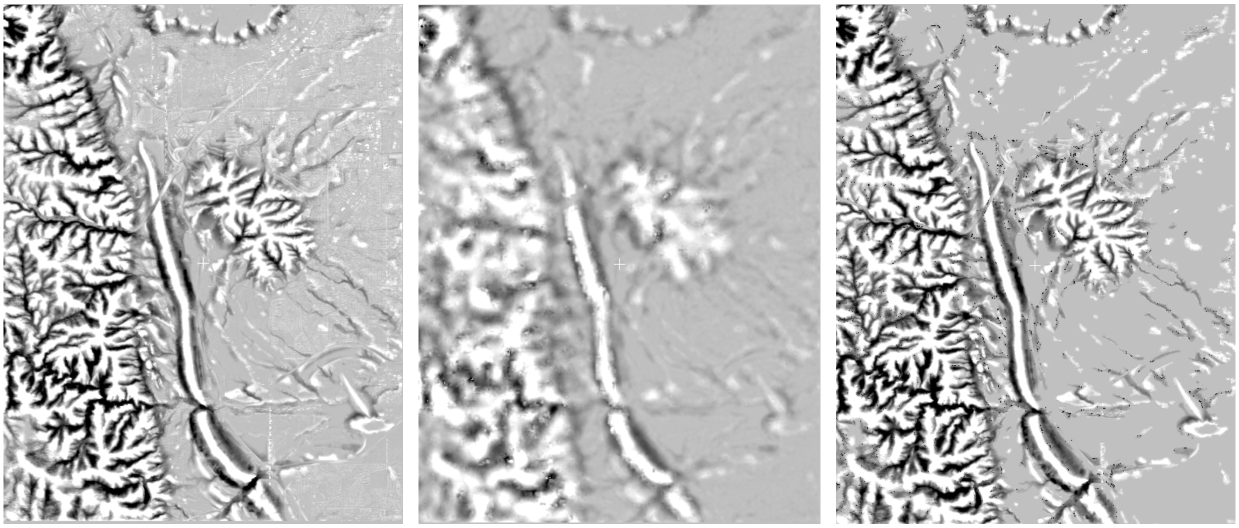

(a) (b) (c)

Figure 2. Location of problem areas using difference map (a) the difference map created from the original IFSAR DSM of Morrison and the derived bald earth DEM (b) supplementary bald surface (c) located problem areas

Once problem areas are located, they are corrected automatically using a new bald earth DEM. As there are trees and some small buildings sometimes in mountainous areas, the terrain points in the original DSM data can not be used as true terrain points. To remove sparse trees and small buildings, the hierarchical surface fitting is applied again to the original DSM data with some modification to generate a new bald earth DEM. The new bald earth DEM is then used to replace the old one in problem areas.

RESULTS

To verify the developed method, a number of tests have been done on data with different types of terrain. Some of the test results are shown in Figures 5, 6 and 7. Figure 5 shows a test data set of the Morrison quad, near Denver, CO. The original DSM shown in Figure 5 has spatial sampling of 5 m and covers an area of about 14 km x 11 km. The area covered by the data contains different types of terrain, including mountains, residential areas, highways with overpasses, hydro towers, dams, etc. The mountains on the western part and the central part are generally bald, with some dense forest patches covering about 30% of the total area and some sparse tree coverage elsewhere. There is elevation variability of more than 700 m in the quad and it is quite steep in some parts. The residential areas are mostly located in the eastern half of the quad and the sizes of buildings vary from a few meters to more than 200 meters. The elevations of buildings range from 3 m to more than 30 m. As the residential areas are close to the mountains, most houses are located on smooth slopes. Figures 6 and 7 display the derived bald earth DEM and the difference map (grey scale) between the original DSM and the derived bald-earth DEM which shows the objects removed from the original DSM data. It can be seen in the difference map that most buildings in residential areas, trees, and power lines are removed successfully while the shape of terrain is accurately preserved. There is a small area at the lower part of the data (white blob) removed incorrectly. The terrain in this portion has a very steep slope and some parts are chopped off when they are interpolated using neighbouring points.

To evaluate the quality of the generated bald earth DEM, a LIDAR bald earth DEM (provided by Eaglescan) was used as 'truth', and the derived bald earth DEM was differentiated with respect to this truth surface. A number of areas were selected for evaluation of the difference statistics, as represented in Figure 8 by the polygons. The areas within the polygons were classified as bald, flat, urban and mountainous areas. To show the impact of the forests which were not removed by the TerrainFit© from the IFSAR DEM, and may not be completely removed from the LIDAR DEM, an additional set of statistics was created. An ortho-rectified, pan-sharpened multi-spectral IKONOS image was used to identify large stands of trees, and a polygon mask was created of these forested sub-regions. Statistics were then created of the area excluded from the forest mask. While this method did not eliminate all the wooded areas, it is believed to account for more than 90% of the heavily wooded areas.

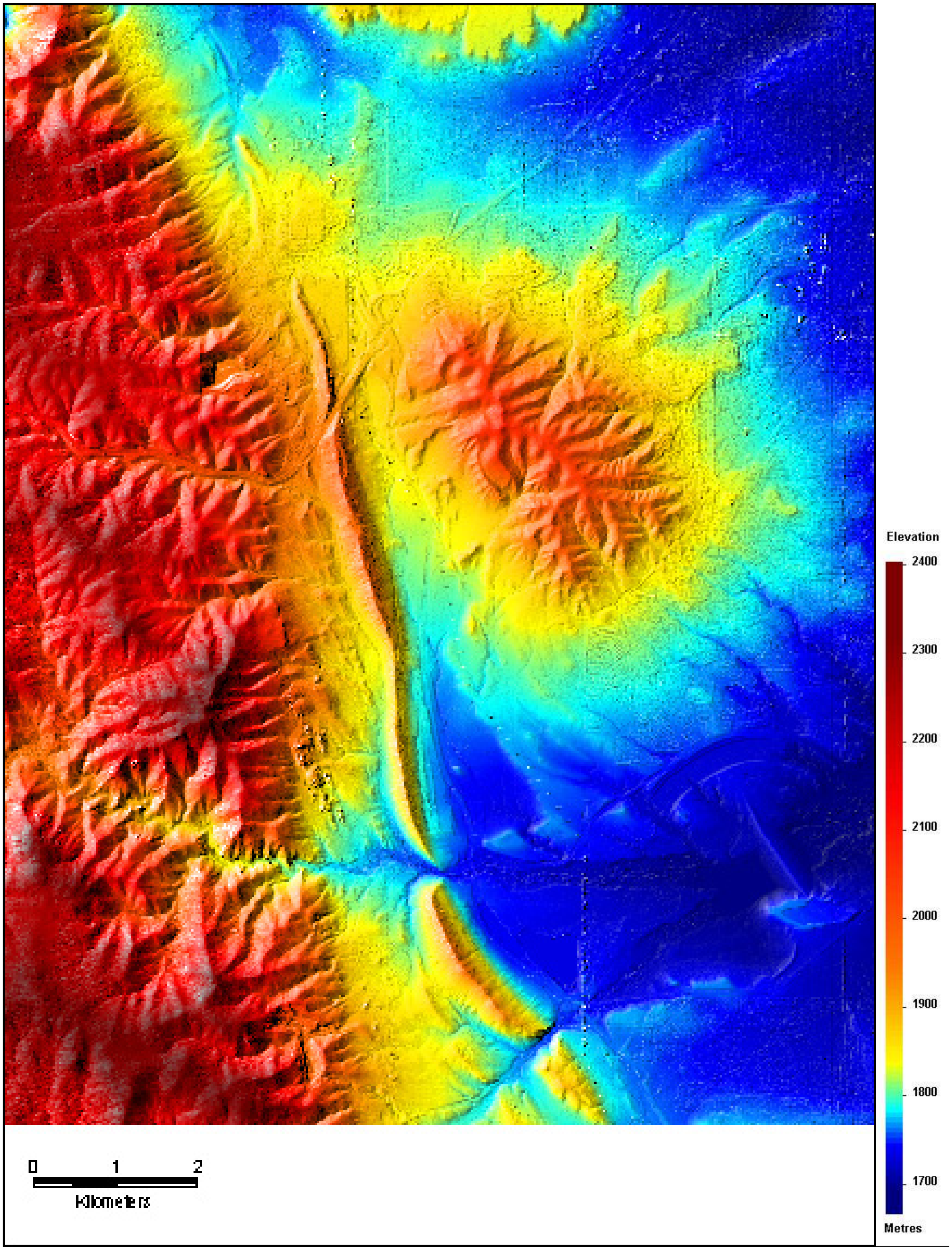


Figure 5 Original IFSAR DSM of Morrison Data

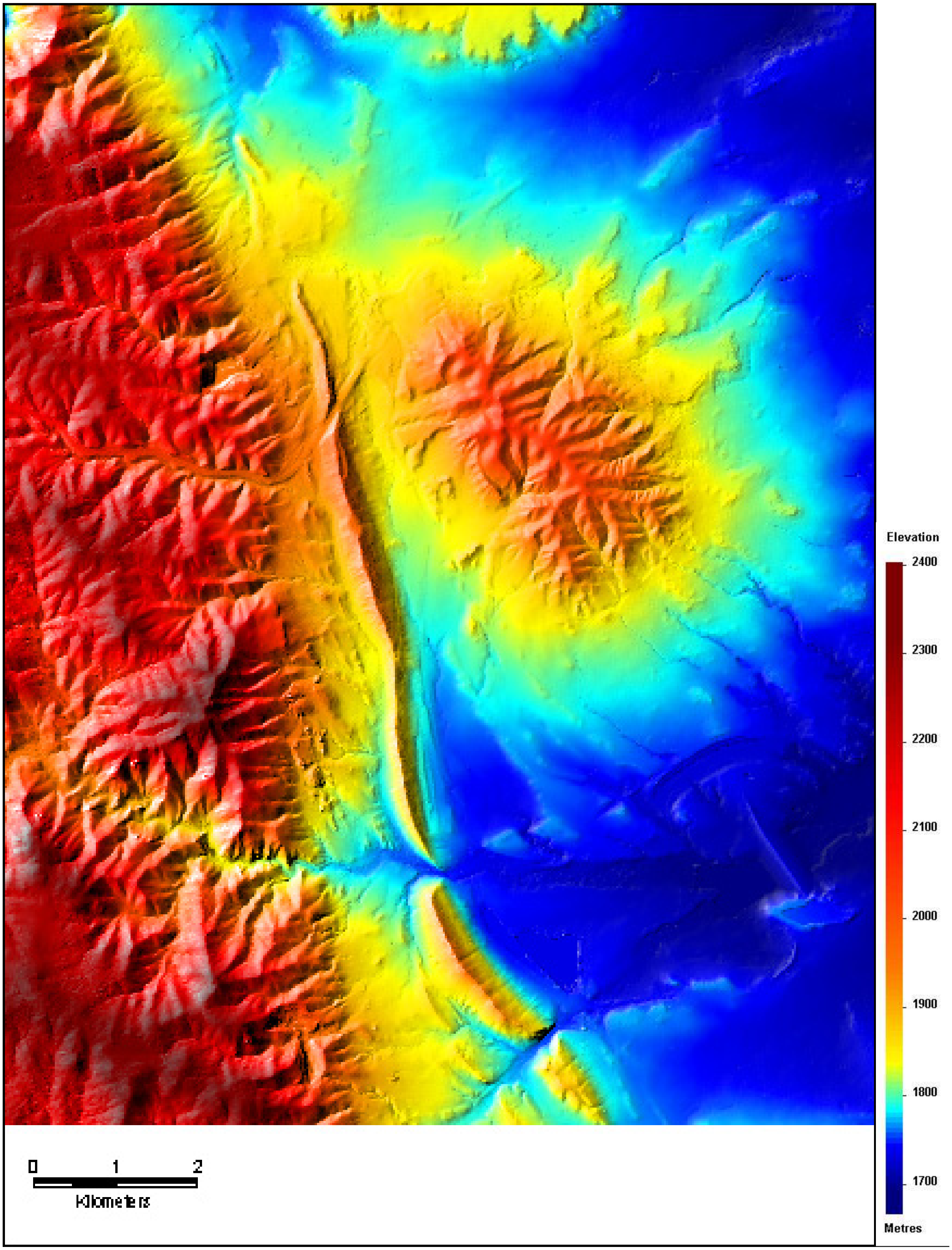


Figure 6 Generated bald earth DEM of Morrison

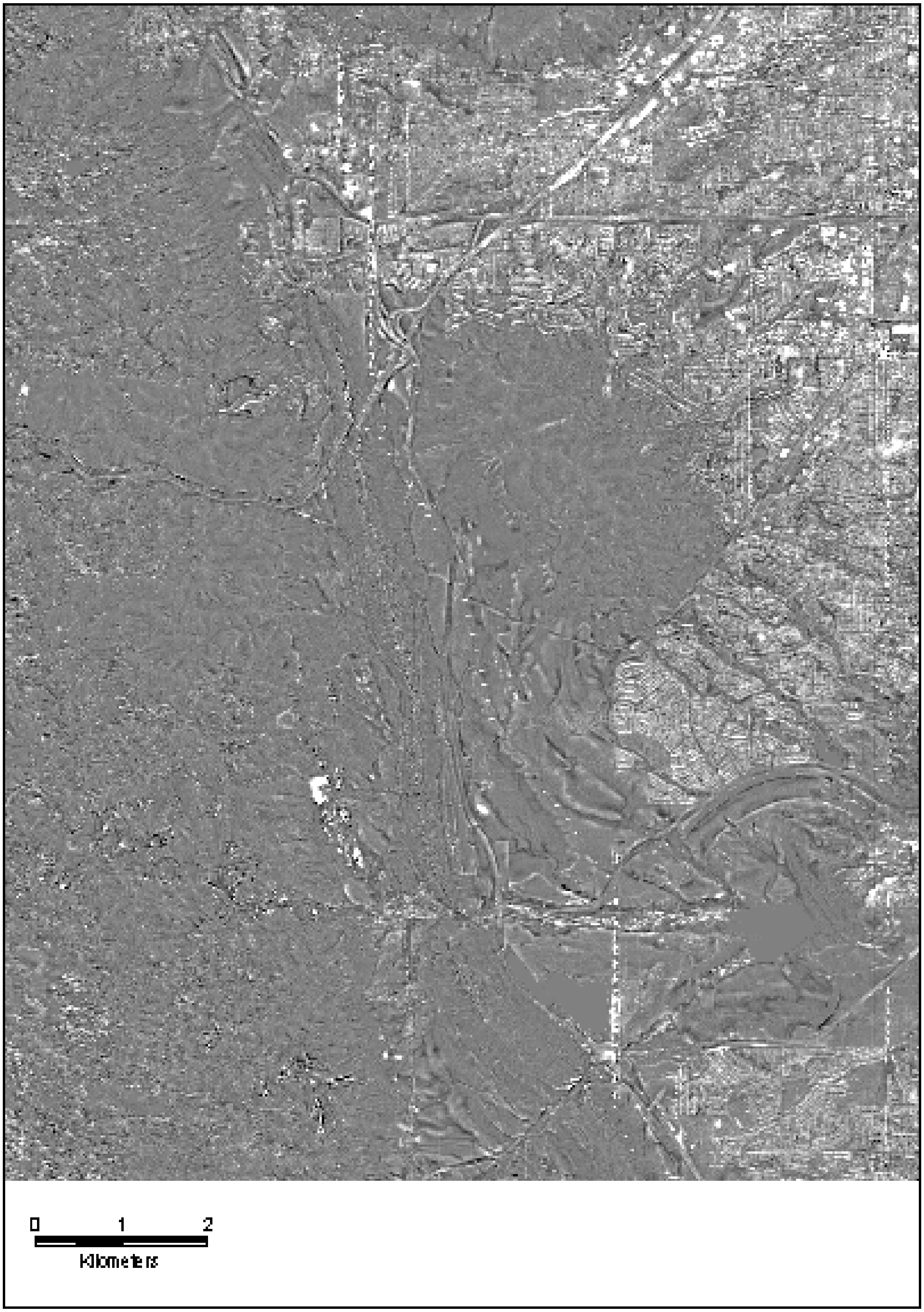
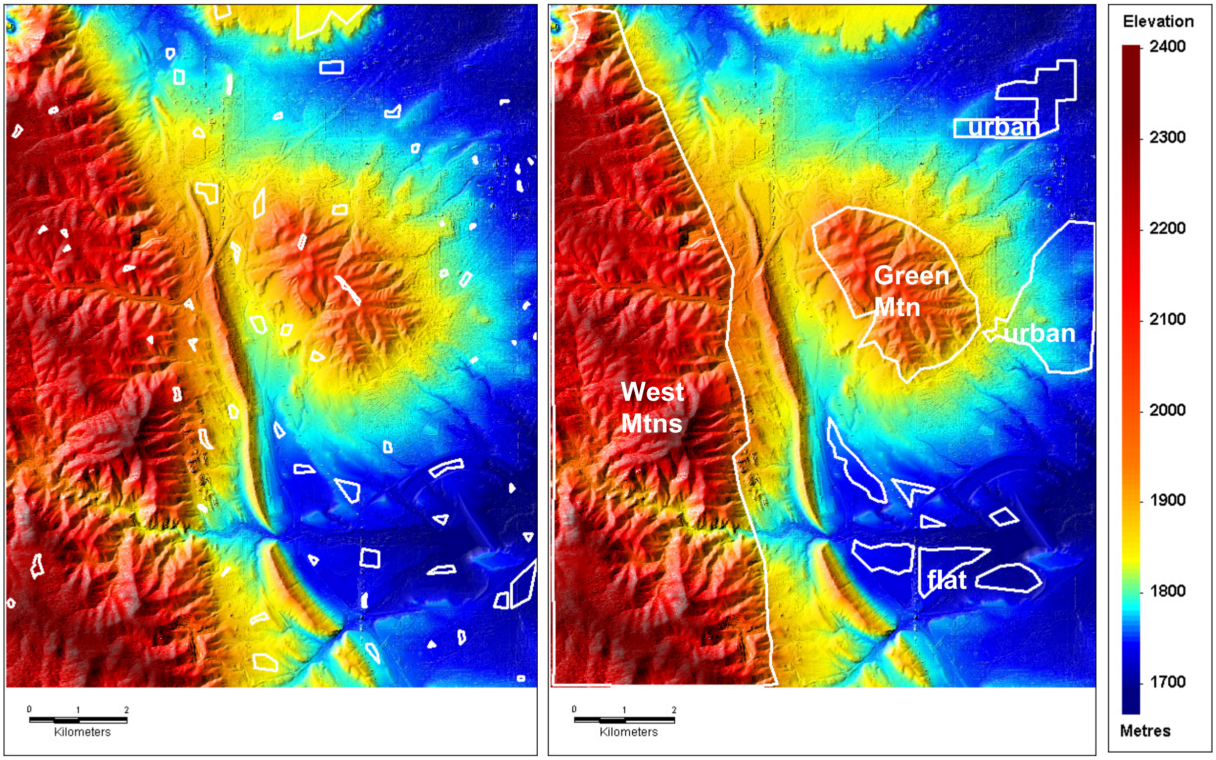


Figure 7 Final difference map of Morrison



(a) (b)

Figure 8: Areas selected for accuracy evaluation (a) bald areas, (b) flat, urban, and mountainous areas

The statistical difference results (mean, standard deviation and RMSE) are given in Table 1 for each of the classes. In order to demonstrate the impact of errors associated with the underlying DSM, comparative statistics with respect to the LIDAR are provided for both the DSM and the bald earth DEM. Two points should be noted:

1. The differences are computed with respect to each of the LIDAR points within each of the polygons. The LIDAR point spacings were about 5 meters on average, very close to the STAR-3*i* sample spacing. A bi-linear resampling was done to obtain the STAR-3*i* elevation value within each cell that corresponded to the exact (x, y) location of the particular LIDAR point.
2. The STAR-3*i* DSM was adjusted to minimize the overall mean difference in bald, relatively flat sub-areas distributed around the tile. These vertical adjustments to the DSM swaths that comprise the merged tile DSM ranged from 0.5 to 1.5 meters and are consistent with the expected offsets for the particular data set.

In the bare and 'flat' areas, we note that the noise level (standard deviation) of the Bald Earth DEM is similar to that of the original DSM and only small offsets are introduced.

Table 1 Vertical Accuracy of the Bald Earth DEM (all values in meters)

		Bald Areas	**Flat Areas**	**Urban Areas**	**Green Mtn**	**West Mtns (forests removed)**	**West Mtns (all data)**
(STAR-3*i* DSM – Lidar)	**Mean**	0.00	0.08	0.89	0.22	0.26	1.00
	Std Devn	0.76	0.42	1.40	1.26	2.18	3.04
	RMSE	0.76	0.42	1.66	1.28	2.19	3.20
(STAR3*i* Bald Earth DEM - Lidar)	**Mean**	-0.17	-0.03	0.11	0.19	0.23	0.97
	Std Devn	0.66	0.60	1.18	1.32	2.18	3.00
	RMSE	0.68	0.60	1.19	1.33	2.19	3.16

In urban areas, the RMSE of the bald-earth DEM is about 1.2 meters which is smaller than that of the DSM. It might be expected that the difference would be greater until it is recognized that the LIDAR points are, by definition, ground points (except where LIDAR editing errors might have occurred) and therefore the DSM points in the sample will also be on the ground. The fact that the IFSAR DSM is somewhat worse is probably due to points that were sampled in vegetated areas. Although they would show up in the DSM statistics, they would have been excluded in the bald DEM.

The 'Green Mountain' results are interesting as they show the performance in terms of retaining detail in relatively moderate mountain conditions. The RMSE of the (bald-earth DEM – LIDAR) is almost identical to that of the (DSM – LIDAR).

The errors of both the DSM and the assumed LIDAR truth are expected to increase in the steep western mountains. This is reflected by the 2.2 meter RMSE observed in the data set from which the forest component has been removed. It should be noted that horizontal location errors become very important in such steep areas, for example, a 2 meter horizontal error, when coupled with a 45 degree terrain slope, would create a 2 meter vertical error in either the LIDAR or IFSAR data. The main point to be noted here is that the bald earth DEM reflects the underlying DSM and quantitatively as well as visually retains the mountain terrain detail.

The final statistic shows the impact of the wooded areas on the statistics. As would be expected, it is mainly manifested as an apparent increase of the mean elevation of the IFSAR data and is observed in both the DSM and the bald earth DEM. Because of the degree of radar penetration of these pine forests, the effective height recorded is typically about 5 meters which would be consistent with the overall impact on the statistics, given that the masked area was about 20% of the total for the western mountains.

CONCLUSIONS

A method has been successfully developed for the automatic generation of a bald-earth DEM from a digital surface model (DSM) created using Intermap's interferometric SAR system, STAR-3*i*. The method was designed to address the situation of open urban areas and rural areas of varying terrain type from flat to mountainous. It does not at this stage address heavily forested areas.

This novel method extracts terrain surface points from an image pyramid and interpolates a bald-earth surface hierarchically. Since the derived bald-earth surface at each level is used as a reference for the next level during surface fitting, spurious terrain surface points can be eliminated effectively, and a bald-earth DEM can be generated. As the method works in a hierarchical way, it is suitable for different resolutions of input data and for different scale sizes of above-terrain object.

The method incorporates a self-diagnostic process for automatically locating problem areas using a difference map created from the intermediate bald-earth DEM and the original DSM, and for correcting them. This is very important because the method does not need human intervention before a final bald-earth DEM is generated. Since the detection of problem areas is based on the bald surface derived form the difference map, problem areas can be located reliably and an accurate bald earth DEM can be derived. A small number of residual errors may remain in the derived surface and depending on the required specification will require manual QA and final editing.

A software package, based on the method, and referred to as TerrainFit©, has been developed. Tests on various DSMs with different resolutions and different types of terrain have shown that the software can generate a bald-earth DEM that retains detail and vertical accuracy. Visual examples have been presented to demonstrate the quality of derived DEM. Tests against a LIDAR-derived bald-earth DEM have demonstrated vertical accuracies better than 1.5 meters RMSE in urban and moderate mountainous regions, increasing to 2.2 meters RMSE in the steep mountains. The underlying DSM had a similar accuracy, and it may be supposed that a higher level of bald-earth DEM accuracy could be achieved with a correspondingly more accurate DSM as input.

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REFERENCES

Digital Photogrammetry: an Addendum to the Manual of Photogrammetry (Ed.: C. Greve). American Society of Photogrammetry and Remote Sensing, 1996.

Haala, N. and Brenner, C. (1999). Extraction of Buildings and Trees in Urban Environments. ISPRS Journal of Photogrammetry and Remote Sensing, 54, pp. 130-137.

Lu, Y., Kubik, K. and Bennamoun, M. (1998). An Accurate Approach to Localize House Areas for 3D Terrain Reconstruction. Proceedings of the 9th Australasian Remote Sensing and Photogrammetry Conference, Sydney, Australia.

Soergel, U., Thoennessen, U., Gross, H. and Stilla, U. (2000). Segmentation of Interferometric SAR Data for Building Extraction. International Archives of Photogrammetry and Remote Sensing, CD-ROM.

Sties, M., Krüger, S., Mercer, J.B. and Schnick, S. (2000). Comparison of Digital Elevation Data from Airborn Laser and Interferometric SAR Systems. International Archives of Photogrammetry and Remote Sensing, Vol. 33(3), pp. 866-873.

Tao, C.V., Wang, Y., Mercer, B., and Zhang, Y. (2001). Automatic Reconstruction of Bald Digital Terrain Models from Digital Surface Models Generated from an Airborne SAR System, Proceedings of the 3rd International Symposium on Mobile Mapping Technology, Cairo, Egypt, January 3-5, 2001.

Wang, Y. and Tao, C.V. (2000). Automatic Generation Bald Earth DEM from STAR-3i Digital Surface Model Data. Internal project report, Department of Geomatics Engineering, the University of Calgary.

Wang, Z. and Schenk, T. (2000). Building Extraction and Reconstruction from LIDAR Data. International Archives of Photogrammetry and Remote Sensing, CD-ROM.

Zhang, Y. and Tao., V.C. (1999). Automatic Reconstruction of ground DEMs from Airborn SAR DSMs. Internal project report, Department of Geomatics Engineering, the University of Calgary.