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Filling the voids in the SRTM elevation model — A TIN-based delta surface approach

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Abstract

The Digital Elevation Model (DEM) derived from NASA's Shuttle Radar Topography Mission is the most accurate near-global elevation model that is publicly available. However, it contains many data voids, mostly in mountainous terrain. This problem is particularly severe in the rugged Oman Mountains. This study presents a method to fill these voids using a fill surface derived from Russian military maps. For this we developed a new method, which is based on Triangular Irregular Networks (TINs). For each void, we extracted points around the edge of the void from the SRTM DEM and the fill surface. TINs were calculated from these points and converted to a base surface for each dataset. The fill base surface was subtracted from the fill surface, and the result added to the SRTM base surface. The fill surface could then seamlessly be merged with the SRTM DEM. For validation, we compared the resulting DEM to the original SRTM surface, to the fill DEM and to a surface calculated by the International Center for Tropical Agriculture (CIAT) from the SRTM data. We calculated the differences between measured GPS positions and the respective surfaces for 187,500 points throughout the mountain range (ΔGPS). Comparison of the means and standard deviations of these values showed that for the void areas, the fill surface was most accurate, with a standard deviation of the ΔGPS from the mean ΔGPS of 69 m, and only little accuracy was lost by merging it to the SRTM surface (standard deviation of 76 m). The CIAT model was much less accurate in these areas (standard deviation of 128 m).

The results show that our method is capable of transferring the relative vertical accuracy of a fill surface to the void areas in the SRTM model, without introducing uncertainties about the absolute elevation of the fill surface. It is well suited for datasets with varying altitude biases, which is a common problem of older topographic information.

Keywords: DEM/DTM; Radar; Satellite; Accuracy; GIS; Modeling; Algorithms; Processing

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1. Introduction

The Digital Elevation Model (DEM) produced by the Shuttle Radar Topography Mission (SRTM) has set new standards for Digital Terrain Elevation Data (DTED). In the few years since this dataset has been made available

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to the public, it has found a wide array of applications. SRTM data has been used for purposes as diverse as hydrological modeling (Valeriano et al., 2006), vegetation surveys (Bourgine and Baghdadi, 2005 and Simard et al., 2006), reconstruction of prehistoric water bodies (Leblanc et al., 2006), mapping of glaciers (Berthier et al., 2006) and detection of ancient settlement sites (Menze et al., 2006).

The SRTM mission was jointly operated by NASA's Jet Propulsion Laboratory (JPL), the United States' National Imaging & Mapping Agency (NIMA; in 2003 renamed to National Geospatial-Intelligence Agency — NGA) and the German and Italian Space Agencies (DLR, ASI). Data was acquired by interferometric synthetic aperture radar (InSAR) during an 11-day flight of the Space Shuttle Endeavor in February 2000 (Kobrick, 2006). The DEM derived from C-band measurements during this mission has a spatial resolution of 1″, about 30 m, making it the best currently available near-global elevation model (van Zyl, 2001). The highest SRTM resolution is, however, only publicly available for the United States, whereas all other areas can only be obtained at a resolution of 3″, approximately 90 m.

The mission objective of SRTM was to obtain a DEM with an absolute vertical accuracy of 16 m and a relative vertical accuracy of 10 m for 90% of the data (Rodriguez et al., 2005). This means that for nine out of ten data points, the assigned elevation is within 16 m of the true elevation, and the error is within 10 m of the errors of neighboring data points. According to an internal review at JPL, the SRTM DEM meets these requirements (Rodriguez et al., 2006 and Rodriguez et al., 2005).

The accuracy of the SRTM model has been confirmed by several researchers, using GPS ground truthing points, lidar data or high-accuracy small-scale DEMs for validation (Bourgine and Baghdadi, 2005, Brown et al., 2005, Hofton et al., 2006, Jarvis et al., 2004, Kocak et al., 2005, Rodriguez et al., 2006, Smith and Sandwell, 2003 and Sun et al., 2003). Other studies found that the accuracy of the SRTM surface depended on local topography (Berthier et al., 2006, Falorni et al., 2005 and Kääb, 2005), with errors being much larger in mountainous terrain than on plane surfaces.

Unfortunately, the SRTM model also has large areas of data voids. According to Hall et al. (2005), these voids make up 0.3% of the total dataset analyzed in their study of the United States, but for rugged terrain, such as some regions of Nepal, they can amount to up to 30% of the area. Most data voids are less than 5 data pixels in size (Hall et al., 2005). The larger voids belong to one of two categories. Many voids occur on flat level terrain and correspond to water bodies. Water surfaces produce radar signal scattering, which makes it impossible for the interferometer to detect meaningful reflections. The second category of large data voids coincides with steep slopes in mountainous terrain. For surface inclinations above 20°, the frequency of data voids increases because of radar shadowing.

One region, where radar shadowing affects a large proportion of the area, is the range of the Oman Mountains, at the eastern tip of the Arabian Peninsula. Much of this range is made up of limestone, which forms almost vertical cliffs of often more than 1000 m around the eroded center of the range. Most settlements of the region are located near these cliffs, which are the main hydrological reservoir of the region (Buerkert et al., 2005 and Siebert et al., 2005). Many of these oases thus lie in SRTM data voids (Fig. 1), making the SRTM model unsuitable for hydrologic modeling. To improve the applicability of the SRTM surface for such purposes, several attempts have been undertaken to fill the data voids. These differ in the type of data used to fill the gap and in the methodology applied to achieve this.

1.1. Methods to fill the voids

For small data voids, which account for the majority of holes (Hall et al., 2005), simple interpolation of the values around the edges is a reasonable strategy that has been applied successfully. For water bodies, which were prone to voids in the original dataset, the elevations of the water surface have been leveled in the release of the finished version of the SRTM DEM (Slater et al., 2006). The remaining data voids are those that arise from rugged topography. These holes are mostly too large to simply be interpolated from the edges and cannot be substituted by a surface of constant elevation.

They thus need to be filled with topographic information from other sources. Global elevation models are only available at very coarse resolution, so local or regional models have to be used. Kääb (2005) used a local DEM derived from ASTER satellite images, whereas researchers at the International Center for Tropical Agriculture (CIAT) used various local DEMs or the global SRTM30 with a 30″ resolution to fill the SRTM voids (Jarvis et al., 2004). To our knowledge, all approaches to filling the voids have so far been based on digital elevation models rather than non-digital topographic maps.

The methods used to merge these auxiliary grids with the SRTM model also vary. Kääb (2005) simply replaced SRTM no data cells with values from the alternative DEM. This process cannot be recommended for most

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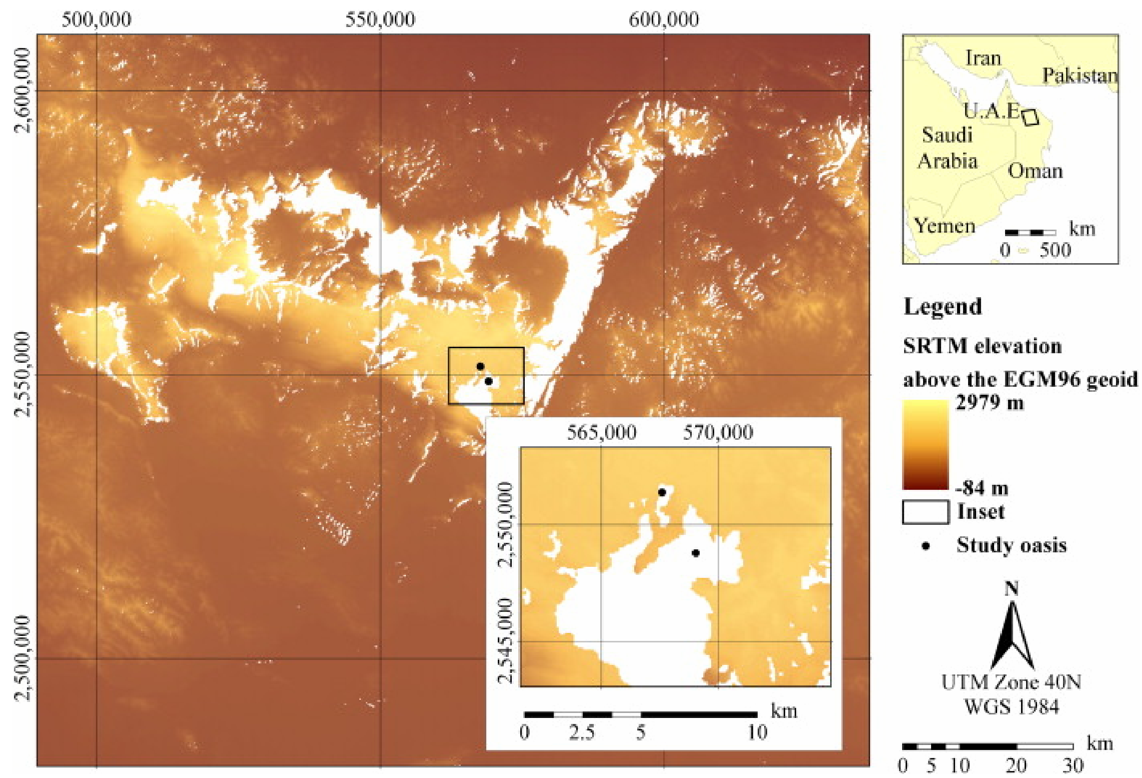

Fig. 1. SRTM surface of the central part of the Oman Mountains, showing the data voids (white areas) and the locations of two mountain oases in these voids (magnified in the inset). The map in the upper right corner shows the location of the study area on the Arabian Peninsula.

datasets, since most elevation surfaces differ from the SRTM surface by a vertical bias. A more sophisticated approach is the fill and feather technique, in which the void-specific bias of the alternative surface is removed by adding a constant, and the surfaces are then feathered at the edges to provide a seamless transition. This method provides smooth DEMs, but has the disadvantage that it corrupts the presumably correct SRTM surface at the void edges and cannot account for varying vertical biases within the void. Such variable biases, however, are likely to occur in older elevation models or when a surface is derived by optical interpretation of stereo images. A more promising approach is the delta surface fill method, proposed by Grohman et al. (2006). The delta surface in this method is used to remove the vertical bias of the auxiliary DEM. For the central area of a void, the delta surface is assigned a mean value representing the mean vertical difference between the SRTM and the fill surface. The outer 20 to 30 pixels of the void are then interpolated from the fill surface and the edge of the SRTM outside the void. This method preserves the original values of the SRTM model, while providing a smooth transition.

In this study, we use a DEM derived from topographic maps, from which only the void areas were digitized to fill the SRTM voids in the Oman Mountains. To merge the SRTM surface with this auxiliary DEM, we use a method that resembles the delta surface fill method, but is based on a Triangular Irregular Network (TIN) surface to quantify the pixel-specific difference between the surfaces.

To illustrate our method description, we include two figures (Fig. 3 and Fig. 4) to clarify the sequence of processes and the functions of the various elements of the method. We use a dataset of GPS ground control points to compare the resulting DEM with the original topographic maps and the interpolated SRTM surface published by CIAT (Jarvis et al., 2006).

2. Materials

2.1. Study area

The Oman Mountains are a rugged desert mountain range forming a 600-km long arch spanning the northern part of the Sultanate of Oman and the United Arab

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Emirates, on the Eastern tip of the Arabian Peninsula (Fig. 1). The main arc of the mountain range consists of formerly plane limestone formations and underlying sediments, which were warped upwards by the opening of the Red Sea in the Eocene around 35 million years ago. Since then, erosion of the central area of the range has formed an extensive basin, around which the full thickness of the limestone formations has been exposed. The resulting rock faces, steep slopes and deep valleys present a major challenge for the SRTM approach and are the target of this study. The study area covered the entire mountain range, including the Musandam Peninsula, the Batinah Coastal Plain and part of the interior desert, ranging from 26°30′N to 21°20′N in north–south direction and from 59°50′E to 55°10′E from east to west.

2.2. SRTM data

Finished grade C-band SRTM data for the region with a resolution of 3″ were obtained from the United States Geological Survey (USGS, 2002). Terrain elevations specified by the SRTM surface were between − 84 and 2979 m above the EGM96 geoid. Of our area of interest, 2.6% of the total dataset of 206,823 km^2 was void, mostly concentrated in the interior of the mountain range, with the size of the two largest voids amounting to 255 and 225 km^2 (Fig. 1).

2.3. Russian topographic maps

Between the 1950s and 1980s, the Russian military conducted extensive mapping operations all over the world leading to a wealth of topographic information covering most of the globe at varying scales. The results of these surveys became available to the public after the demise of the Soviet Union. For the region of the Oman Mountains, we obtained 16 map sheets at a scale of 1:200,000 with elevations given as 40-m contour lines from a German distributor of these maps (Därr Expeditionsservice GmbH, Munich, Germany). All maps use the Krassowsky ellipsoid and the Pulkovo 1942 datum.

2.4. Hole-filled SRTM data from CIAT

The International Center for Tropical Agriculture (CIAT), a member of the Consultative Group for

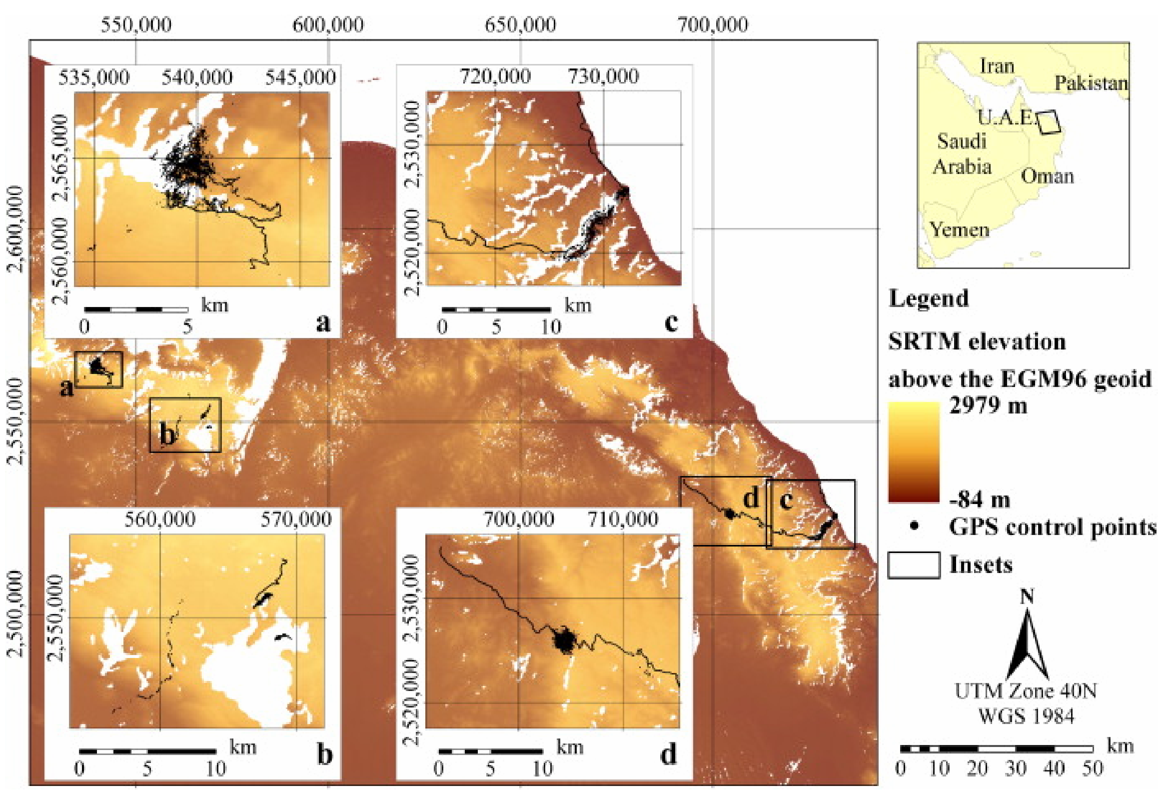

Fig. 2. Location of the GPS control points in the Oman Mountains. The insets a–d show the surroundings of the oases, where most of the positions were recorded. The small map in the upper right corner shows the location of the large map window on the Arabian Peninsula.

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International Agricultural Research (CGIAR), has published a modified version of the SRTM data, in which all holes have been filled (CIAT, 2004 and Jarvis et al., 2006). For filling the voids, several local elevation models were used where available, whereas for most of the land surface, the global SRTM30 model formed the basis for filling the holes. To our knowledge, this DEM is the only SRTM product covering the full extent of the SRTM dataset, in which all holes have been filled. At this point, the CIAT model is therefore the standard, with which other void-filling efforts have to be compared.

2.5. GPS control points

To evaluate the accuracy of the three existing elevation models and compare them to the model derived from our new method, we used 187,500 GPS survey points collected over seven years at several sites in the Oman Mountains (Fig. 2). Most of these points were recorded using Differential GPS (Trimble Pro XRS and Trimble GeoExplorer II, Trimble Navigation Limited, Sunnyvale, CA, USA), while some points were measured remotely from known GPS positions, using a Leica Vector range finder (Vectronix AG, Heerbrugg, Switzerland). These points are centered around several mountain oases, the agricultural systems of which we investigated (Buerkert et al., 2005, Luedeling et al., 2005 and Nagieb et al., 2004), but span large parts of the mountain range both inside (13.9% of all measured points) and outside (86.1%) of SRTM data voids. The GPS points covered an elevation range from 1 to 2375 m above EGM96 sea level.

Complete coverage of such a large area with GPS positions is impossible, and finding sample locations that are representative of the entire area is very difficult. Besides, our GPS measurements were not taken primarily for the purpose of validating elevation models, but for the study of mountain oases. Consequently, the sample locations are particularly concentrated around a few settlements. Nevertheless, since the sample size is fairly large, the full range of elevations, bearings and slopes that occur in the mountains is covered by an adequate number of positions (Table 1), allowing a validation of the different DEMs.

3. Methods

3.1. The TIN delta surface fill method

Elevation datasets for the Oman Mountains are scarce. The region has only been mapped in the context of global mapping endeavors, such as those by the Russian military. The Russian maps, however, have two major disadvantages. They only exist as paper maps and, as can easily be seen by visual comparison, they do not correspond very well to absolute elevations specified in other sources. The reason for this is probably the kind of equipment used for mapping as well as the large extent of the survey, which might have offset accuracy at times. For the Oman Mountains, it seems that the maps accurately specify the sea surface, an obvious reference, but decrease in absolute accuracy towards the country's interior. This varying bias makes it impossible to directly replace SRTM data voids with values derived from the Russian dataset, as done by Kääb (2005), who merged SRTM and ASTER data. Unlike the absolute elevations above a fixed reference level, the elevations of topographic features relative to the surrounding area are nevertheless likely to be good approximations of the true elevations. We therefore attempted to develop a method to extract these relative elevations from the Russian maps and combine them with the more accurate absolute elevations of the SRTM model. Thereby we generated a fill surface for the SRTM data voids, which combines the absolute

Table 1.
Frequencies of different levels of elevation, slope and slope bearing (aspect) among the GPS control points and on the OmanTopo surface

n	GPS points (%) 187,500	OmanTopo (%) 22,576,394
Elevation		
< 500 m	4.3	83.1
500–1000 m	30.9	13.0
1000–1500 m	48.2	2.6
1500–2000 m	9.5	0.9
> 2000 m	7.1	0.3
Slope		
Low (0–10°)	34.2	84.5
Moderate (10–20°)	44.0	8.4
Steep (20–30°)	12.8	4.8
Very steep (30–60°)	9.0	2.3
Slope bearing		
N	8.6	10.9
NE	13.3	12.1
E	19.5	12.1
SE	9.9	12.9
S	6.1	13.1
SW	8.5	12.8
W	22.1	13.9
NW	12.0	12.1

n represents the number of GPS points and the number of OmanTopo raster cells, respectively.

accuracy of the SRTM DEM with the relative accuracy of the Russian topographic maps.

This is achieved by extracting the points bordering the holes from both the Russian and the SRTM DEMs, and calculating Triangular Irregular Networks (TIN) from these points for both datasets. In the creation of a TIN, the original elevation points remain unaltered, and the spaces between them are filled by triangular planes connecting these points. By converting these TINs to rasters with the SRTM cell size, we obtain base elevations for both surfaces, the pixel-specific difference of which represents the local vertical bias of the Russian model. Subtracting the Russian base surface from the Russian elevation model then yields the relative elevation of the Russian model above the base surface spanning the void. Adding this difference surface to the SRTM base surface results in an elevation model that accounts for the varying vertical bias within the void and can seamlessly be merged with the SRTM model (Fig. 3).

3.2. Detailed method description

To create the DEM for filling the voids (referred to as 'fill' hereafter), the Russian topographic maps were scanned and georeferenced to the Russian ellipsoid and datum specified above using ArcGIS 9.1 (ESRI, Redlands, CA, USA). We extracted the voids from the SRTM surface into a feature layer using the ArcGIS Spatial Analyst's 'Is Null' tool, reprojected this layer to fit the Russian datum, and manually digitized the contour lines for the area covering the data voids plus a buffer of about 500 m around each void from the Russian maps. These contours were reprojected to UTM Zone 40N, the Universal Transverse Mercator projection suitable for this longitude, and interpolated using the 'Topo to Raster' tool of the ArcGIS 3D Analyst. To avoid interference patterns in the final DEM, care was taken that from the beginning all raster surfaces were created with cell sizes and cell locations corresponding exactly to those of the SRTM dataset. This was mainly achieved by adjusting the settings in ArcGIS' Analysis Environment, except for the 'Topo to Grid' command, which required a manual approach. For this step, a rectangle corresponding to the extent of the area of interest was extracted from the SRTM surface, converted to a polygon layer and buffered by half an SRTM cell size. This extent was then fed into the Analysis Environment.

We extracted the grid cells contained in a 170-m buffer around the data voids from both the SRTM and the fill surface and converted them to points. From these points, we created TIN layers, which were transformed into grids of SRTM extent and cell size. These raster layers constitute base surfaces, which can be compared to obtain a linear approximation of the vertical bias between each pixel of the SRTM and the corresponding pixel of the fill surface.

We subtracted the fill base surface from the fill surface, obtaining a raster that describes the relative difference between the fill surface and the fill base level inside the specific data void. This relative surface was added on top of the SRTM base surface to generate an elevation surface that can seamlessly be mosaicked into the holes of the SRTM model. Subsequently, we replaced the no data cells of the SRTM surface with the values from this new surface. Finally, we replaced all data cells containing negative elevations with interpolated values to obtain the final product, which will be referred to as OmanTopo in the following. An overview of all geoprocessing operations is given in Fig. 4.

3.3. Validation and analysis of the DEMs

A first quality assessment of the OmanTopo DEM was done visually, based on a shaded relief calculated

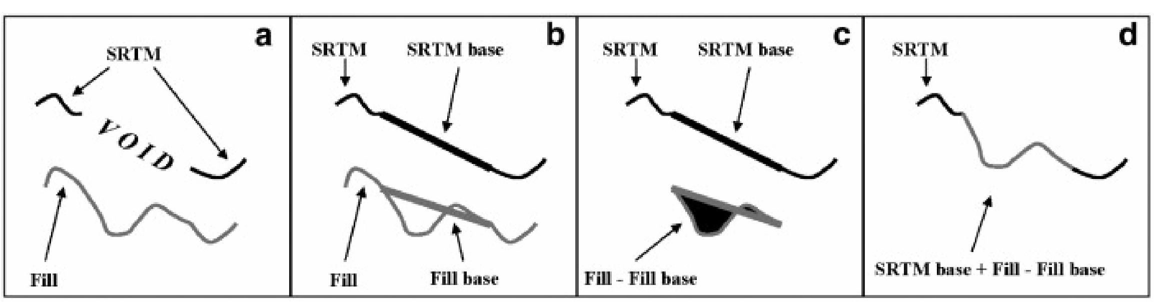

Fig. 3. Illustration of the process used to merge the two elevation surfaces. For the void area in the SRTM model and for the corresponding region in the fill surface (a), TINs are calculated from points at the edges to create base surfaces (b). The fill base surface is then substracted from the fill surface (c) and added on top of the SRTM base surface (d) to obtain a seamless DEM.

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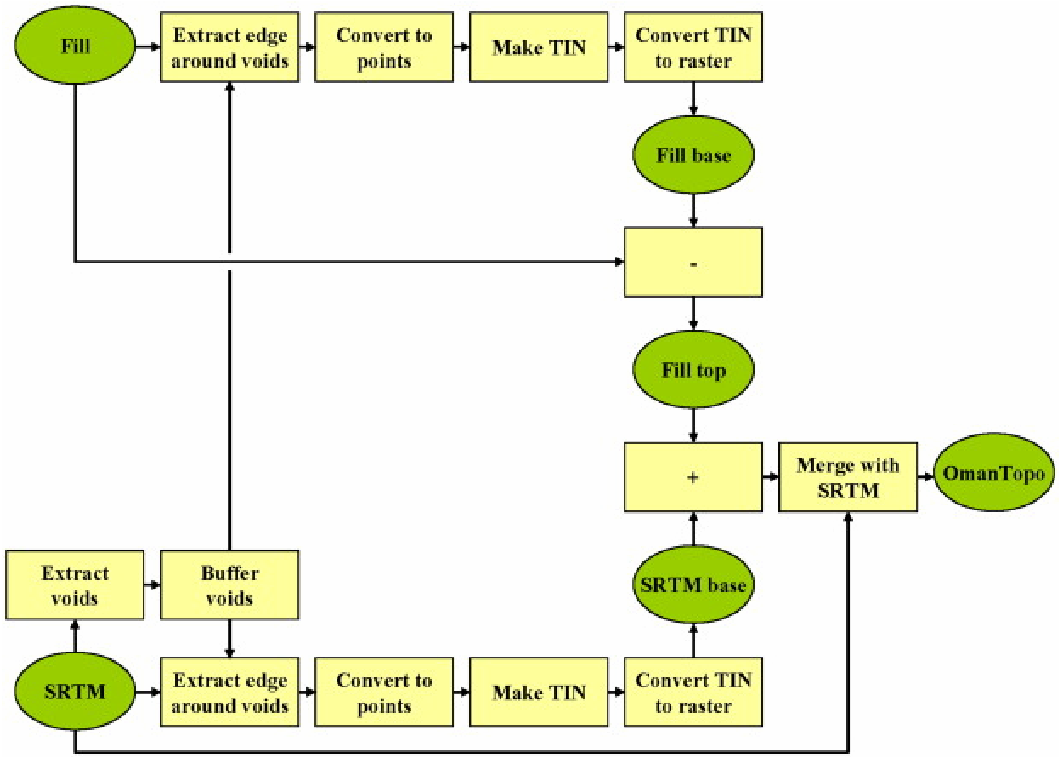

Fig. 4. Overview of the geoprocessing operations carried out to derive the OmanTopo surface from the SRTM DEM and the fill surface derived from Russian military maps. Rectangles indicate processes, whereas ovals are used to depict important raster surfaces.

from the OmanTopo surface for better visualization (Fig. 5). For more quantitative validation of the DEM, we used our reference dataset of 187,500 differential GPS positions. For each position, we extracted the corresponding values of the SRTM DEM, the CIAT DEM, the Russian fill surface and the new OmanTopo DEM from the respective surfaces. In addition to these, slope and slope bearing (aspect) were calculated from the OmanTopo DEM and also assigned to each GPS point. We calculated the differences between each surface and the GPS elevations. These differences will be referred to as the ΔGPS of the DEMs. We choose this term, because the GPS positions have a much higher resolution than the raster cells, and the differences thus cannot be referred to as the error of the DEM. The ΔGPS values were then analyzed using the SPSS 12.0 statistics package (SPSS Inc., Chicago, IL, USA).

We calculated the means and standard deviations of the ΔGPS for each surface. The mean is a good measure of the average absolute deviation from the true elevation, whereas the standard deviation describes the relative accuracy of a DEM. For CIAT and OmanTopo, we differentiated between GPS locations inside and outside the holes, whereas SRTM elevations only existed outside and fill elevations only inside the holes. Since several authors reported a bearing-specific bias of the SRTM model, we also calculated the respective means and standard deviations for each of eight bearings (N, NW, W, SW, S, SE, E, and NE).

4. Results

Visual assessment of the OmanTopo surface did not reveal major flaws (Fig. 5). Overlay with a hillshade often highlights topographic steps arising from incorrect merging of DEMs. The only visual disturbance was a slight striping pattern in the shaded relief, which seems to originate from the merging of SRTM tiles from different longitudes. The SRTM tiles downloaded from USGS have slightly different cell sizes, and the resampling necessary for merging the tiles may have caused interference, which produced the striping.

Comparison of the mean values and standard deviations of the ΔGPS values inside and outside of the SRTM data voids showed that the OmanTopo surface underestimated the GPS elevations by 7.8 m on average, whereas the fill DEM lay considerably above the GPS heights (+ 84.3 m) and the CIAT surface almost matched the GPS elevations (+ 2.8 m) (Table 2). Standard deviations of the ΔGPS values were comparable for the OmanTopo and CIAT

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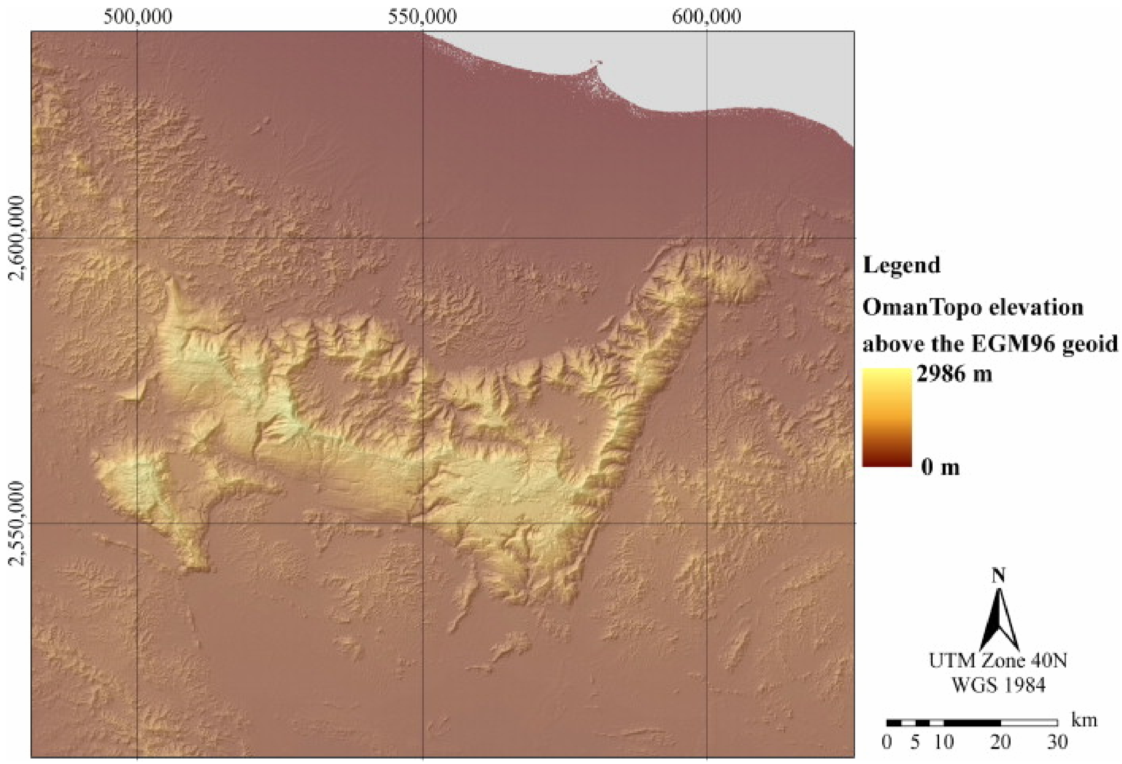

Fig. 5. Shaded relief of OmanTopo for visual inspection.

surfaces outside the void areas (27.7 and 24.1 m), but much lower for the fill surface (69.2 m) and OmanTopo (76.3 m) than for the CIAT DEM (128.0 m) in the areas, where the SRTM surface had no data (Table 2).

Analysis of the bearing-specific bias of the surfaces showed that ΔGPS standard deviations outside the voids were between 14 and 33 m for CIAT, OmanTopo and SRTM, and tended to be highest on north and northeast facing slopes (Fig. 6). Inside the void areas, differences between the surfaces were much greater. The lowest ΔGPS standard deviations occurred in the fill surface, followed closely by OmanTopo. The CIAT DEM had much larger ΔGPS standard deviations. The bias due to bearing was strongest in north and west facing directions for CIAT and OmanTopo, and in northwest direction for the fill surface (Fig. 6).

The ΔGPS values also varied according to slope, with steeper slopes leading to higher deviations from the mean values (Table 3).

5. Discussion

The comparison of the SRTM dataset to the measured GPS elevations revealed that the absolute elevation of the SRTM DEM is 6.4 m below the surface indicated by the GPS readings (Table 2). This corresponds well to the absolute height error estimated for Africa (including the Arabian Peninsula) by Rodriguez et al. (2005), who determined the continental error to be 5.6 m. The absolute error of the CIAT model was + 2.8 m, suggesting that CIAT (Jarvis et al., 2006) added a correction to the original SRTM surface. Our

Table 2.
Means and standard deviations of ΔGPS values for the DEMs derived from the method applied in this study (OmanTopo), the Shuttle Radar Topography Mission (SRTM), the SRTM-based interpolated surface released by CIAT (CIAT) and the Russian topographic map (Fill)

		OmanTopo (m)	SRTM (m)	CIAT (m)	Fill (m)
Inside void	Mean	− 16.3	–	+ 10.6	+ 84.3
	Std. dev.	76.3		128.0	69.2
Outside void	Mean	− 6.4	− 6.4	+ 1.6	–
	Std. dev.	27.7	27.7	24.1	
Total	Mean	− 7.8	− 6.4	+ 2.8	+ 84.3
	Std. dev.	38.4	27.7	52.8	69.2

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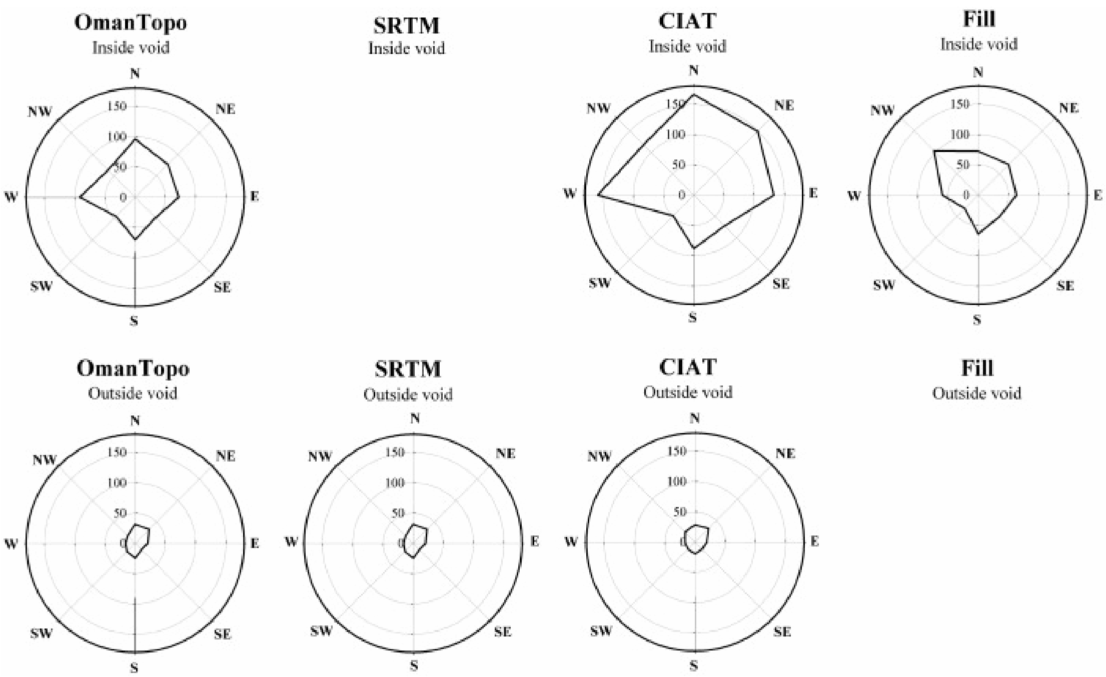

Fig. 6. Standard deviations of the ΔGPS values derived from the four surfaces, inside and outside the void areas in the SRTM model, according to the bearing of the slope at the GPS location.

initial impression that the Russian topographic maps overestimated the true elevation was confirmed by the analysis, which determined mean elevations of the maps to be 84 m higher than the GPS positions. Nevertheless, inside the SRTM data voids, the ΔGPS values obtained from the fill surface showed a much lower standard deviation (69 m) than those from the CIAT surface (128 m), indicating that the fill surface represented the relative topography better than the CIAT DEM. The OmanTopo surface inherited most of the accuracy from the fill surface, resulting in a standard deviation of the ΔGPS values of 76 m (Table 2). Nevertheless, for the area corresponding to the no data cells in the SRTM model, OmanTopo's ΔGPS values had a much higher standard deviation than for the area that was covered by the SRTM. The surface developed in this study does, however, provide a much more accurate fill for the SRTM voids than the DEM published by CIAT.

Table 3.
Mean values and standard deviation of the ΔGPS values, according to steepness of slope, for the four surfaces

Slope		**OmanTopo**		**SRTM**		**CIAT**		**Fill**	
		Inside void (m)	**Outside void (m)**	**Inside void (m)**	**Outside void (m)**	**Inside void (m)**	**Outside void (m)**	**Inside void (m)**	**Outside void (m)**
Low (0–10°)	Mean	+ 8.2	− 6.5	–	− 6.5	+ 87.3	− 2.2	+ 11.7	–
	Std. dev.	58.8	14.1		14.1	123.8	14.7	57.3	
Moderate (10–20°)	Mean	− 10.9	− 0.1	–	− 0.1	− 15.4	+ 5.4	+ 79.7	–
	Std. dev.	43.4	20.5		20.5	97.0	18.4	42.2	
Steep (20–30°)	Mean	− 22.5	− 7.0	–	− 7.0	− 38.0	+ 7.0	+ 98.8	–
	Std. dev.	66.0	38.5		38.5	123.1	36.8	67.2	
Very steep (30–60°)	Mean	− 21.9	− 61.6	–	− 61.6	+ 60.6	+ 15.5	+ 90.1	–
	Std. dev.	106.4	58.1		58.1	140.2	57.7	87.5	

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In part, the fairly large ΔGPS standard deviation might arise from the method used to calculate it. We compared point measurements with mean values for each raster cell. Since the spatial resolution of the grid was 81 m, the cell size corresponds to an area of about 0.65 ha, which is represented by only one value in the grid. Within a level raster cell, accuracy could be measured reliably by comparing a GPS position with the DEM surface. For sloping land, however, the GPS position would be at one specific elevation within the range spanned in the cell. For a slope of 14°, the average inclination of the raster cells covered by GPS control points, the range of altitude that can be expected is about 29 m. For a slope of 45°, the maximum elevation range within one cell amounts to 115 m (Fig. 7). Consequently, we have to expect higher standard deviations of the ΔGPS values inside the void areas, since slopes are generally steeper than outside the voids. In fact, the average slope at GPS positions outside the voids is 13°, compared to 25° inside the voids. This corresponds to potential elevation ranges per raster cell of 26 and 53 m, respectively. For the cardinal directions (N, E, S, W), these numbers are slightly lower (18 and 38 m), since the distance between the center of the square raster cell and the edge in slope direction is shorter than for the other directions (NE, SE, SW, NW).

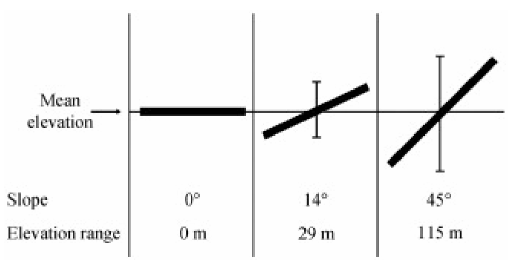

Fig. 7. Effect of raster cell inclination (slope) on the elevation range spanned in one raster cell. The elevation ranges given apply to the directions NE, SE, SW and NW. For the cardinal directions, they are 0 m, 20 m and 81 m, respectively.

For the areas outside the SRTM voids, the bearing-specific uncertainties were small (Fig. 6) and distributed among the different aspects in a similar manner as reported previously (Jarvis et al., 2004). Analysis of the areas inside the data voids, however, shows the quality of our new method. Even though the size of the ΔGPS standard deviations differs between OmanTopo and CIAT, the distribution pattern between the bearings is similar for both DEMs. The biggest standard deviations of the ΔGPS values occur at bearings N, W, NE and E. The steepest slopes inside the voids face to the N, NE and E (on average 36.4°, 28.7° and 27.9°, respectively), which makes the large standard deviation in western direction surprising. It is striking that the bearing-specific bias of the fill surface does not correspond to the DEMs derived from the shuttle mission (SRTM, CIAT, OmanTopo). It is highest in NW, N, and NE direction, but also has a strong southern component, which might originate from the Russian surveying and mapping techniques. In filling the SRTM voids with this dataset, however, the TIN-based method removed this bias, so that the bearing-specific distribution of ΔGPS standard deviations corresponds in its shape to the respective distribution for the CIAT surface. This shows that the TIN-based delta fill surface method successfully combined the absolute elevations of the SRTM surface with the relative elevations of the fill surface without introducing the error of the fill surface into the DEM.

The data analysis revealed that the SRTM model contains several cells in Musandam, at the northern edge of the Oman Mountains, which were assigned negative elevations between − 1 and − 84 m. Most of these cells lie directly at the coast in an area with very steep shorelines. We assume that the shoreline mask used to clip the land surface from the original SRTM dataset (Slater et al., 2006) was inaccurate in this region. For the OmanTopo surface, we corrected this.

The CIAT surface approximately retained the resolution of the unfinished SRTM dataset, which is slightly coarser than that of the finished SRTM DEM. The CIAT product is good for areas, for which the SRTM delivered reliable data. CIAT diminished the vertical bias of the SRTM DEM for the region and also took care of the anomalously low elevations in Musandam. For the areas that are void in the SRTM dataset, however, the approximation achieved by OmanTopo is much better.

This study shows that our method, which realizes the transition between the incomplete dataset and the fill surface by using TINs, yields useful results. It is particularly useful for datasets, about which only little is known. The delta fill surface method described by Grohman et al. (2006) relies on knowledge of the average difference between the incomplete DEM and the fill surface. This requires that this difference be calculated, based on a complete DEM. Digitizing topographic maps is a time-consuming process. The TIN-based approach allows us to restrict the digitizing to the areas that are to be filled plus a small buffer zone around them. The average difference between the surfaces remains unknown, but is irrelevant to this method. Knowledge of the ellipsoid or geoid, above which the fill elevations are calculated is also unimportant and complicated adjustments do not have to be carried out, since the TIN-based method only considers the relative elevations of the fill.

Moreover, it can account for varying differences between the incomplete DEM and the fill surface over the whole extent of the DEM and even within a specific void. The delta fill surface method assumes an average bias of the fill surface, or the specific void, and interpolates the values at the void edge to merge into the frame. In the case of varying biases within the hole, this can create unrealistic inclinations near the void edges. Our TIN-based approach simply uses a linear interpolation created by the TIN to realize a smooth transition between the surfaces.

For older maps, arbitrary variations in absolute height must be expected. We assume that the Russian military used aerial photographs taken by planes and manually drew contour lines using stereographic techniques. Such maps will almost unavoidably have varying biases at different map locations. If they are to be merged with other datasets, they require estimation of the pixel-specific difference between both elevation models. Our TIN-based approach provides this.

The surveys conducted by the Russian military produced a wealth of topographic information. It seems that the relative vertical accuracy of these surveys, especially in mountainous terrain, has not been matched by any other survey at that scale, the results of which are publicly available. The Russian data is relatively easily available and at least one commercial GIS data provider has begun to include DEMs derived from these maps into his stock.

6. Conclusions

The TIN-based delta surface is a versatile tool to fill the voids in the SRTM dataset, even with fill surfaces that have varying absolute elevation errors. Traditional paper maps constitute a wealth of topographic information that may for many regions be superior to all available DEMs, making such maps the most suitable datasets for filling the SRTM data voids.

The TIN delta fill method would be a valuable contribution to the CIAT dataset, which is already very accurate in the areas covered by SRTM data, but could benefit from this new method to help improve DEM quality in the SRTM voids.

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