Developing a very high resolution DEM of South Africa

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DEMs are used in many applications, including hydrology [1, 2], terrain analysis [3], soil science [4], disaster risk mitigation [5], image pre-processing [6] and climate surface generation [7]. The use of DEMs in geographical information systems (GIS) has increased in recent years, mainly due to the greater availability of free DEMs covering most of the globe.

Notable near-global DEMs include the 30 second arc (~1 km) GTOPO30 DEM, the 90 m shuttle radar topography mission (SRTM) DEM and the 30 m advanced spaceborne thermal emission and reflection radiometer global DEM (ASTER-GDEM). Although these near-global DEMs have been used extensively for many applications worldwide, they are generally considered to be unsuitable for use at large mapping scales or local applications due to their relatively low resolutions and quality [8]. These DEMs have also been shown to include many anomalies, such as residual cloud patterns and stripe effects in the ASTER-GDEM [9] and areas with no elevation information (i.e. voids) or abnormally high or low values (i.e. outliers) in the SRTM DEM [10].

The increased availability of very high resolution (VHR) DEMs, mainly as a result of improvements in technologies such as lidar and VHR earth observation satellites, has also opened up new application possibilities. Such DEMs are invaluable in disaster management [11], building footprint extraction [12], geomorphology [13] and floodplain mapping [14]. However, such data is not available for most of South Africa [8], mainly due the high costs associated with lidar data acquisitions and the extraction of elevations from stereo VHR satellite imagery.

Much effort has gone into producing very accurate and detailed topographical maps of South Africa [15]. The contours and spot heights shown on these maps are extremely valuable sources of elevation data. Contours are, however, not ideal for interpolating DEMs as their densities vary with slope gradient. Areas of low relief are particularly problematic as contours are often spaced far apart (horizontally), reducing the reliability of interpolations in such areas. Contour density is further reduced as the vertical interval of the contours increases (i.e. contours with a 5 m vertical interval generally produce better DEMs than contours with a 20 m vertical interval) and as scale increases (i.e. contours with a 20 m vertical interval captured at 1:10 000 scale usually contain more detail than contours with the same vertical interval captured at 1:50 000 scale). To alleviate the problem of low contour densities in areas of moderate terrain, additional spot heights are often shown at strategic locations on topographical maps. Although the quality of a DEM can be improved by incorporating these elevation points in the interpolation process, the combined density of input points (i.e. contour vertices and spot heights) is often insufficient to represent subtle changes in terrain (e.g. floodplains and river banks), particularly in areas where input points can be several kilometres apart. DEMs interpolated from contours are, however, very accurate in areas with relatively steep terrain (i.e. where contour densities are high), because large numbers of known elevations are usually available in such areas.

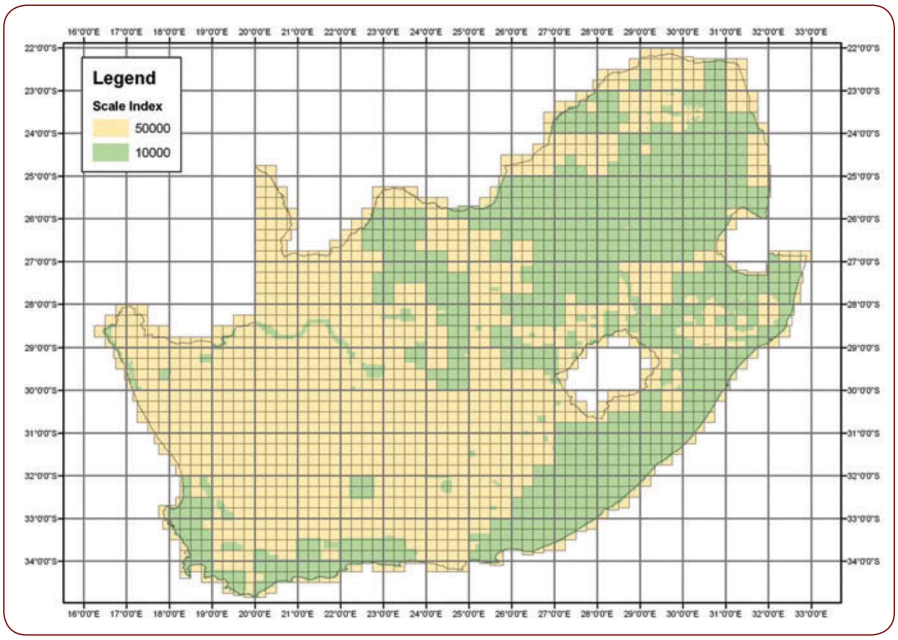

Fig. 1: Areas for which 1:10 000 and 1:50 000 contour data is available.

Supplementing contour data with other sources of elevation information in areas of moderate or flat terrains would significantly improve the detail and accuracy of interpolated DEMs. However, the seamless integration of different elevation sources is difficult as artefacts are often created in areas where there is a disagreement between sources [16, 17, 18, 19]. This paper reports on a fusion method for combining the SRTM DEM with a DEM interpolated from contours and spot heights to produce a seamless, very high resolution (VHR) DEM of South Africa. The paper outlines the methods used in developing the DEM and evaluates the results using a combination of quantitative and qualitative methods.

Methods and materials

Available data sources

Contours and spot heights shown on the South African 1:50 000 topographical map series is a valuable source of elevation data as it is the only official large-scale topographical data set covering the country. These 20 m (vertical interval) contours and spot heights are freely available from the Chief Directorate National GeoSpatial Information (CDNGI). Recently, CDNGI has also made available contours (ranging from 5 m to 20 m vertical interval) and spot heights captured from the 1:10 000 orthophoto map series. This data set currently covers 43% of the country (see Fig. 1).

Both the 1:50 000 and 1:10 000 contours and spot heights were used in developing the VHR DEM. Preference was given to the 1:10 000 contours and spot heights, while the 1:50 000 data was only used in areas where large-scale data was unavailable (Fig. 1). The SRTM DEM data ("research-grade" version), was used in combination with the contours and elevation points in relatively flat areas. The ASTER-GDEM (version 2) was also considered for this purpose, but quality assessments indicated significant deviations from reference data. Many of these deviations were due to the inclusion of surface features such as buildings and trees, which is characteristic of surface models derived from stereo optical imagery.

Data corrections

Much of the effort expended in developing a VHR DEM of South Africa relates to data verification and error correction. The main problems experienced with the input data involved (1) attribute errors in the digitised contours and spot heights; (2) spatial errors such as gaps and mismatching contours at the edges of map sheets; and (3) voids and outliers in the SRTM DEM.

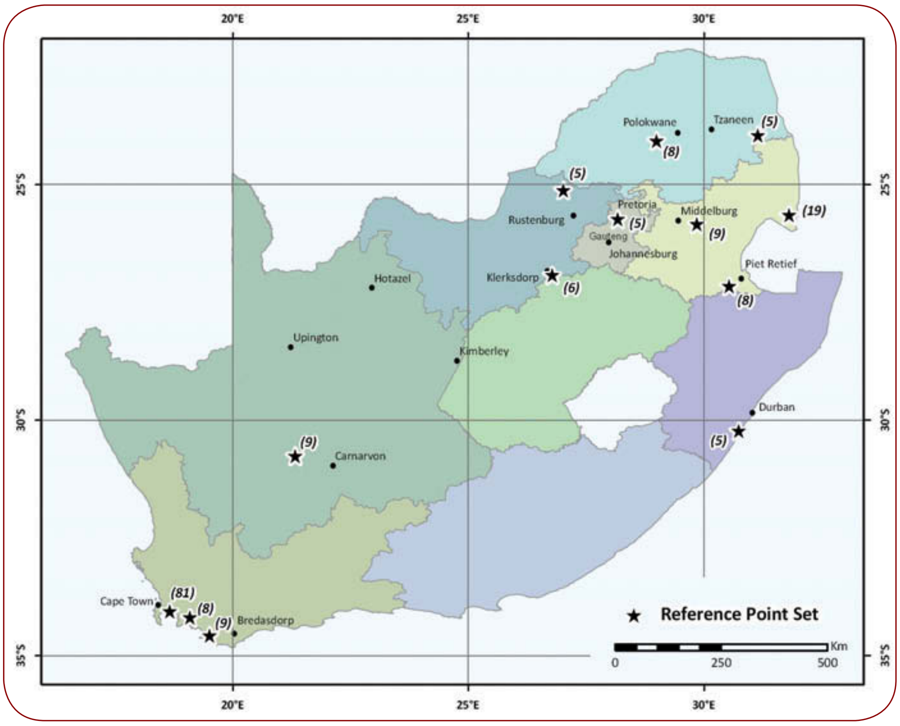

Fig. 2: Location (and number) of reference points used for accuracy assessment.

Attribute errors refer to cases where the elevations stored in the "Height" field of contours and spot heights were incorrectly captured from the original maps. An algorithm was developed to identify and correct such errors. The algorithm examines vertical profiles (cross sections) created at regular intervals (determined by the extent of the smallest contour) within a specified area to identify potential errors. Each profile is normalised (i.e. the horizontal distances between contours are unified) and tested against a set of topological rules. The algorithm not only identifies incorrect contours (or sequences of contours) but also suggests the correct elevation by examining each profile. These suggestions were verified and implemented by an operator. About 1% (2926 of 3 479 217) of the contours considered for input to the interpolation process required attribute corrections. Thousands of spatial errors (e.g. edge mismatches, duplicate contours, missing contours, multipart contours) were also corrected.

Spot heights likely to be incorrect were identified by comparing their heights with the height of the closest (corrected) contour. Absolute height differences of more than twice the vertical interval of the closest contour were labelled as "likely incorrect". These points were excluded from the interpolation process. Voids in the SRTM DEM were filled using elevation values interpolated from the corrected contours and spot heights. A similar procedure was used to remove elevation outliers in the SRTM DEM.

DEM resolution determination

Hengl [20] suggests the use of Eqn. 1 for calculating the appropriate cell size when interpolating a DEM from contours. When applying Eqn. 1 on contours of various intervals and scales, and in various types of terrains within South Africa, the "optimal" resolution varied between 5 m and 50 m. Consequently, it was decided to produce the DEM at a 5 m resolution to ensure that no topographical variation is lost as a result of cell size. Producing the SUDEM at 5 m resolution will also enable other DEMs (e.g. those that were created using stereo images and lidar) to be incorporated in the future. Eqn. 1 is:

$$p = \frac{A}{2 \cdot \sum l} \qquad (1)$$

where
p is the pixel size;
A is the total size of the study area;
l represents contour length.

Interpolation and fusion algorithms

The VHR DEM was developed using a combination of interpolation

algorithms. The ANUDEM algorithm, as implemented in the ArcGIS 9.3 Topo to Raster function, was used for interpolating a DEM from contours and spot heights *(d_i)*. This DEM was employed to identify and correct the errors in the SRTM DEM (i.e. voids and outliers). A second DEM *(d_j)* was interpolated from the corrected SRTM DEM using a regularised spline interpolation algorithm. The SRTM-interpolated DEM *(d_j)* was fused on a cell-by-cell basis with d_i using Eqn. 2 which ensures that the SRTM DEM is only applied in areas with low densities of contours and spot heights (i.e. areas with low slopes). Eqn. 2 is:

$$DEM = \left(d_i \frac{ln(s)}{ln(s)_{max}}\right) + \left(d_j \left(1 - \frac{ln(s)}{ln(s)_{max}}\right)\right) \quad (2)$$

where

DEM is the fused DEM;

d_i is the contour-interpolated DEM;

d_j is the SRTM-interpolated DEM;

s is the generalised slope in degrees.

Eqn. 2 was automated in ArcGIS using the Python programming language. Parallel processing on a high-performance computer cluster of 30 dual-core machines was required to generate the DEM in a reasonable time frame.

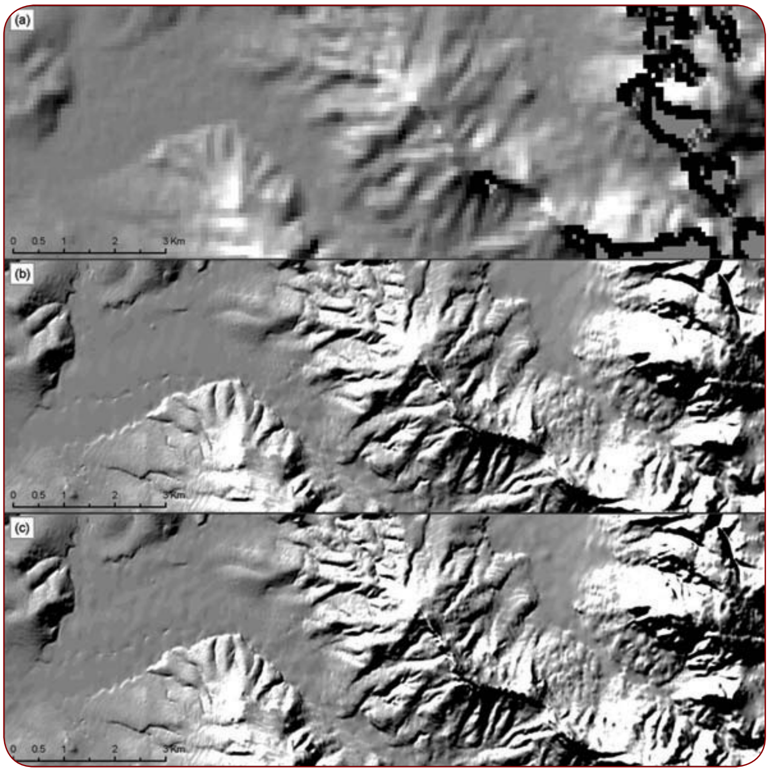

Fig. 3: Hillshades of the (a) SRTM DEM, (b) contour-interpolated DEM, and (c) fused DEM.

DEM assessment

The vertical accuracy of the fused DEM was quantitatively determined using highly-accurate (centimetre) lidar points as reference. A total of 177 reference points were randomly selected from a range of lidar campaigns covering diverse terrain types and geographical areas in South Africa (see Fig. 2). Surveyed points such as trig beacons were not considered as reference as most of these were used in the interpolation process.

To quantify the vertical accuracy, the mean absolute error *(MAE)* and root mean square error *(RMSE)* were calculated using Eqn. 3 and 4 respectively [21]. These equations are:

$$MAE = \frac{\Sigma|x_i - x_j|}{n} \quad (3)$$

where *MAE* is the mean absolute error;

x_i is the DEM's elevation value;

x_j is the reference point's elevation value; and *n* is the number of reference points.

$$RMSE = \sqrt{\frac{\Sigma(x_i - x_j)^2}{n}} \quad (4)$$

where *RMSE* is the root mean square error; x_i is the DEM's elevation value; x_j is the reference point's elevation value; and *n* is the number of reference points.

A visual assessment of the resulting DEM was also carried out. This assessment mainly focused on determining whether there is a marked improvement in detail between the fused DEM and those used as input (i.e. the contour-interpolated DEM and SRTM DEM). Any notable artefacts in the respective DEMs were also examined by interpreting hillshaded visualisations of the respective DEMs.

Results

The results of the vertical accuracy assessment are summarised in Table 1. It is clear that the fused DEM performed significantly better than the SRTM DEM regarding MAE and RMSE. The difference in elevation error between the fused and contour-interpolated DEMs is negligible (0,1 m for both MAE and RMSE). The MAE of the SRTM DEM was found to be significantly higher (219%) than those of the contour-interpolated and fused DEMs. This result compares well with the findings of Rodriguez et al. [22], who determined that the absolute error of the SRTM DEM is about 6 m. The very high RMSE of the SRTM DEM indicates that elevation differences between the SRTM DEM and the reference data were highly variable (i.e. some reference points deviated considerably) and that many of the sample points deviated by more than 43 m. In contrast, the contour-interpolated and fused DEMs had relatively low RMSEs.

Hillshaded visualisations of the SRTM DEM, contour-interpolated DEM and the fused DEM are shown in Fig. 3. It is clear that the latter two DEMs include more detail in mountainous areas and areas with moderate terrain. The relatively less detail of the SRTM DEM is mainly attributable to its significantly lower resolution (2001), while the effect of the voids in the SRTM DEM is clearly visible in the eastern parts of Fig. 3a. Some interpolation artefacts (e.g. banding, tiger stripes, and wave effects) are noticeably visible in Fig. 4b. Such artefacts are frequently present in contour-interpolated DEMs [17]. It seems that these artefacts are slightly less prominent in Fig. 4c, which suggests that the fusion process reduces such artefacts, particularly in flat areas. This is likely due to the averaging effect of the fusion algorithm. More work, however, is needed to reduce the occurrence of these artefacts.

It was found that the fused DEM included more detail than the contour-interpolated DEM in areas of moderate terrain (Fig. 4) and that no noticeable detail is lost in mountainous areas after the SRTM DEM is fused with the contour-interpolated DEM. This result suggests that the fusion technique optimises the detail of both input DEMs and that the relatively low resolution of the SRTM DEM does not have a negative impact on the visual quality of the fused product.

Apart from the artefacts caused by the contour-interpolation, no significant abnormalities were found to have been caused by the fusion process. The use of the first derivative of elevation (slope) as a factor in the fusion process enabled a smooth transition from using the contour-interpolated DEM in areas of moderate to high terrain to using the SRTM DEM in areas of relatively low relief.

Product	MAE (m)	RMSE (m)
SRTM DEM	4,6	43,4
Contour-interpolated DEM	2,1	10,1
Fused DEM	2,2	10,2

Table 1: Vertical error of the fused DEM compared to the contour-interpolated and SRTM DEMs.

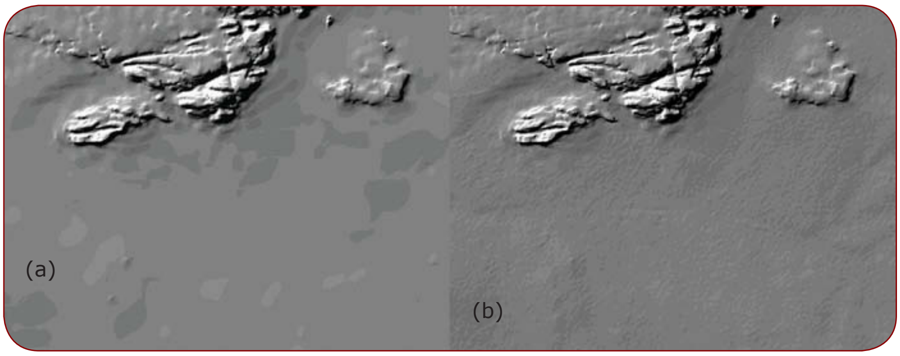

Fig. 4: Hillshade of the (a) contour-interpolated DEM and (b) fused DEM for an area of moderate terrain.

It is clear from the quantitative and qualitative assessments that the quality of the fused DEM is significantly better than that of the SRTM DEM. Although it is recognised that the SRTM DEM is not a true digital terrain model (DTM)[1], it was found that the fusion procedure reduces the effect of surface objects. This is particularly important for hydrological studies in which the inclusion of surface objects can have a significant impact on flow direction and volumes. More work is needed to improve the hydrological qualities of the fused DEMs. Although some interpolation algorithms (such as ANUDEM) can produce "hydrologically-corrected" DEM, they often produce

Note. 1: The SRTM DEM was developed using C-band radar technology. Objects on the ground (e.g. buildings) are consequently included in the signal, which results in a digital surface model (DSM) instead of a digital terrain model (DTM).