



**Stellenbosch University
Digital Elevation Model
(SUDEM)**

2016 Edition
(v16.xx)



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Stellenbosch University Digital Elevation Model (SUDEM)

2016 Edition
(v16.xx)

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http://146.232.21.108/Downloads/sudem/SUDEM_Product_Description.pdf



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1 INTRODUCTION

This document gives a short overview of the techniques used for generating the Stellenbosch University DEM (SUDEM) and provides details of the latest version (15.15) that was released in March 2016.

2 ELEVATION DATA SOURCES IN SOUTH AFRICA

Contours and spot heights shown on the South African 1:50000 topographical maps series still remain a primary source of elevation data. These 20m (vertical interval) contours and spot heights were digitised by Chief Directorate National GeoSpatial Information (CDNGI) and are freely available to the public. CDNGI also makes available 1:10000 contours (ranging from 5m to 20m vertical interval) and spot heights, which were digitised from the 1:10000 orthophoto map series. The 1:10000 dataset covers about 43% of South Africa. In addition, the CDNGI developed a 25m DEM (also known as the “ORT-files”) that was interpolated from 50m postings of elevation points. This DEM also covers only parts of South Africa. Other available sources of elevation data covering South Africa include the 1km GTOPO30 DEM, the 30m Shuttle Radar Topography Mission (SRTM), the 30m Global DEM (GDEM) and various large-scale DEM that were developed for specific projects (usually restricted to very small areas).

Contours are not ideal for interpolating DEM 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 increase (i.e. contours with a 5m vertical interval generally produce better DEM than contours with a 20m vertical interval) and as scale increases (i.e. contours with a 20m vertical interval captured at 1:10000 scale usually contain more detail than contours with the same vertical interval captured at 1:50000 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 and orthophoto 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 some areas where input points can be several kilometres apart.

Global DEM (i.e. GTOPO30 DEM, SRTM DEM and GDEM) are generally considered to be unsuitable for some applications (e.g. flood modelling, geomorphometry, civil engineering) due to their relatively low resolutions (30m or less) and quality. For example, the ASTER-GDEM contains anomalies such as residual cloud patterns and stripe effects (Hirt et al. 2010), while the SRTM DEM contains areas with no elevation information (i.e. voids). The vertical accuracy of the SRTM DEM is, however, relatively high (~6m), which makes it an attractive source for regional applications (Rodriguez et al. 2005).

Stereo aerial photography and photogrammetry is the source of most contour and spot height data. The CDNGI has been acquiring very high resolution (0.5m) aerial photography since 2010. This data can be exploited to automatically extract elevation data at very high (<5m) resolutions.

Light Detection and Ranging (LiDAR) provides very accurate elevation data at high resolutions. However, because such data is relatively expensive to collect, it is only available for small parts of South Africa (mainly metropolitan areas). ESKOM has also acquired LiDAR data for many of its transmission lines.

The SUDEM incorporates contours, spot heights, SRTM DEM, photogrammetric-derived DSMs and DTMs, as well as LiDAR data. The next section explains how these sources of data are combined to produce an DEM with optimal quality.

3 DEM, DTM, DSM, NDSM

It is important to understand the differences in elevation models that form part of the SUDEM. A digital elevation model (DEM) is a raster-based data structure that stores elevation values. These elevations can represent the land surface without the heights of land cover included (i.e. a digital terrain model, or DTM), or it can represent terrain and land cover height (i.e. a digital surface model, or DSM). Figure 1 depicts the differences between DTMs and DSMs. A normalised DSM (nDSM) is the difference between a DTM and a DSM (i.e. it only represents the height of land cover).

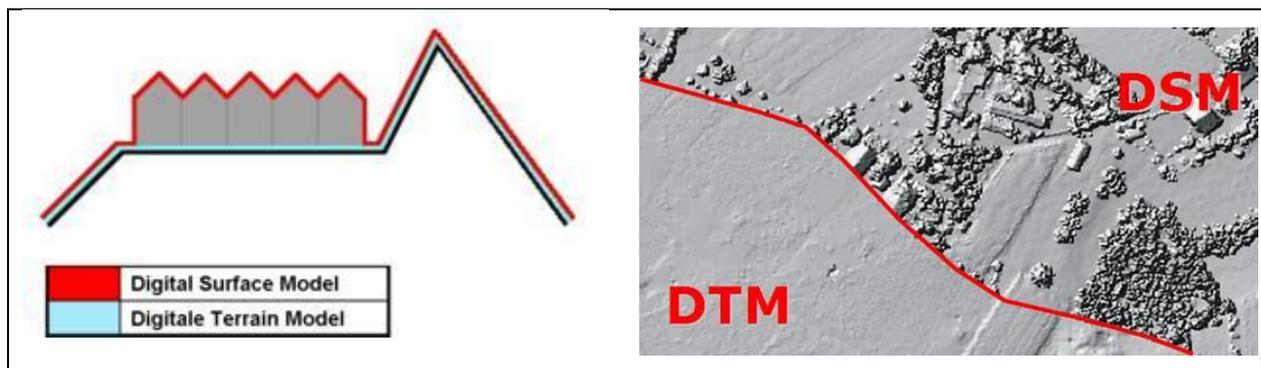


Figure 1 Differences between digital surface and terrain models

4 SUDEM PRODUCT LEVELS

The 2016 edition of the SUDEM includes four products that involve various levels of processing. A summary of these products is provided in Table 1.

Table 1 SUDEM processing levels and products

Level	Description	Model	Resolution (m)
1	Only contours and spot heights are used in the interpolation process. This results in a 5m resolution digital terrain model (DTM).	DTM	5
2a	Contours and spot heights are supplemented with SRTM data in areas with low to moderate terrain. This results in a DTM, but in some areas tall and large surface objects do influence elevations.	DTM (DSM)	5
2b	Also known as the "Enhanced Level 2 product", the L2b product consists of the Level 2a product substituted (fused) with the Level 3 product (where available).	DSM (DTM)	5
3a	Elevations are extracted from 0.5m stereo aerial imagery. The Level 2 product is used only where extraction failures occurred (e.g. shadows). The result is a 1-2m resolution digital surface model (DSM). Although several automated correction procedures are applied, the product may have some remaining anomalies, especially in waterbodies.	DSM	2*
3b	All remaining anomalies in the Level 3a product are manually removed.	DSM	2*
4	The 1-2m DSM (Level 3b product) is converted to a DTM by removing all objects with heights of more than 0.5m. This involves an automated and manual editing process.	DTM	2*

* Available at 1m resolution on request

Figure 2 describes the SUDEM processing procedure and the resulting products. The first step involves interpolation using spot heights and contours as input, which results in a generalized digital terrain model (DTM) at 5m resolution (Level 1 product). Most of the generalization occurs in flat areas (e.g. valley bottoms) where contours tend to have low densities. In the next step (Step 2) the 30m SRTM DEM is corrected (e.g. void and gap filling) and interpolated to 5m resolution. Level 1 product is then fused with the 5m SRTM DEM in Step 3, which results in a 5m DTM with much better detail in flat areas. Given that the SRTM DEM includes heights of objects on the terrain, the resulting Level 2 product is in some areas a digital surface model (DSM). In Step 4 of the SUDEM development procedure highly accurate elevations are extracted from 0.5m stereographic aerial photographs to produce a very detailed (1-2m resolution¹) DSM called the Level 3 product. The Level 2 product is used to for correcting errors caused by shadows etc. This DSM is then analysed in Step 5 to identify surface objects (Level 3b product), which is then subtracted from the DSM to produce a DTM (Level 4 product) in Step 6. In the final step (Step 7) the latter product is resampled to 5m resolution and incorporated into the original Level 2 product.

¹ 1m resolution DSMs are extracted in some urban areas where higher detail is required for building extraction purposes.

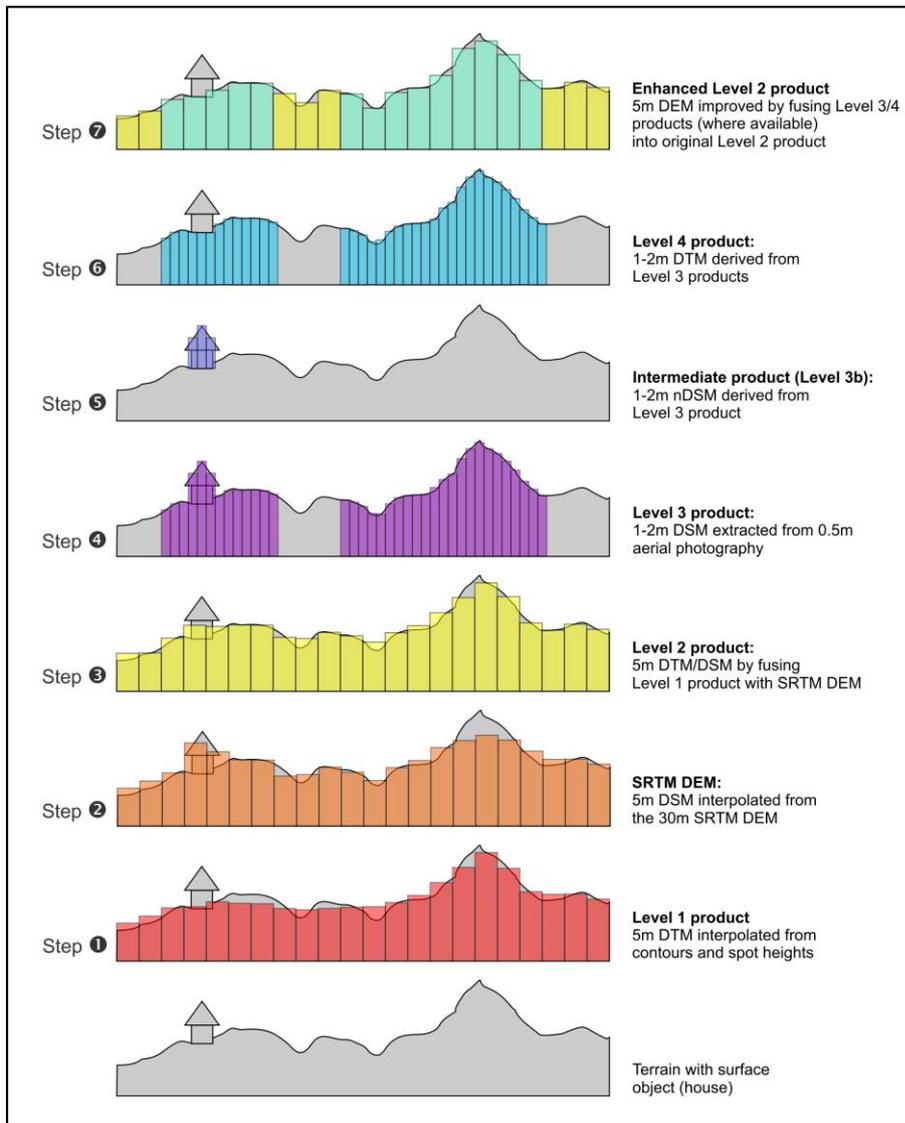


Figure 2 SUDEM development procedure and product levels

Details about the different products are provided in the next subsections.

4.1 LEVELS 1 & 2

4.1.1 Data used

Five sets of input data were used to develop the 2016 edition of the SUDEM. Preference was given to large scale (i.e. 1:10000) contours and spot heights, while smaller scale (i.e. 1:50000) data were only used in areas where large scale data were unavailable. Two products were developed from this data. The Level1 product was interpolated using only contours and elevation points, while the Level2 product combines contours and elevation points with the 30m SRTM DEM. Our experiments showed that DEM quality in areas of moderate terrain can be significantly improved when the SRTM DEM is used in combination with contours and elevation points in relatively flat areas. The ASTER-GDEM was also considered for this purpose, but our accuracy assessments indicated significant deviations from our reference data. This observation is supported by others who have found that the SRTM DEM is superior to ASTER-GDEM. In addition to the contours, spot heights and SRTM DEM, LiDAR and the Level 3/4 product data was used where such data is available.

4.1.2 Input data verification and error correction

A large proportion of the effort in developing the SUDEM was related to data verification and error correction. The main problems experienced with the input data were related to (1) attribute errors in the digitized contours and spot heights; (2) spatial errors such as gaps and mismatching contours at the edges of map sheets; (3) voids in the SRTM DEM; and (4) voids and artefacts in the DSMs and DTMs extracted from aerial photography (Level 3/4). This section provides an overview of the procedures followed to correct these errors.

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 and implemented 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 find errors. Each profile is normalised (i.e. the horizontal distance 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 "corrects" errors by examining each profile. These corrections are then verified by an operator. Thousands of the contours that were used as input to the SUDEM interpolation required attribute corrections. Thousands of spatial edits were also required.

Spot heights that are likely incorrect were identified by comparing their heights to the height of its closest (corrected) contour. If the absolute height difference is more than twice the vertical interval of the

contour, then the spot height was 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 spikes in the SRTM DEM.

4.1.3 Interpolation algorithm

The SUDEM was developed using a combination of algorithms. The ANUDEM algorithm was used for interpolating a DEM from contours and spot heights. This DTM, called the Level1 product, was employed to identify and correct the errors in the SRTM DEM (i.e. voids and spikes). Once corrected, the SRTM DEM was fused with the Level1 DEM using a newly-developed algorithm which ensures that the SRTM DEM is only applied in areas with low densities of contours and spot heights. Although it is recognised that the SRTM DEM is not a true DEM², the fusion procedure reduces the effect of surface objects.

4.1.4 DEM resolution

Hengl (2006) suggests the use of Equation 1 to calculate the appropriate cell size when interpolating DEM from contours. When applying Equation 1 on contours of various intervals and scales, and in various types of terrains within South Africa, the “optimal” resolution varied between 5m and 50m. Consequently, it was decided to produce the DEM at a 5m resolution to ensure that no topographical variation is lost as a result of cell size. Producing the SUDEM at 5m resolution will also enable the incorporation of other DEM (e.g. those that were created using stereo images and LiDAR) at a resolution that is manageable.

$$p = \frac{A}{2 \cdot \sum l} \quad \text{Equation 1}$$

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

4.1.5 Limitations & future improvements

SUDEM 2016 has a number of limitations which users should take into consideration. This section provides an overview of these limitations and how they will be addressed in future editions.

4.1.5.1 Contour and spot height errors

² 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).

Although much time and effort was spent on identifying and correcting attribute errors in the contour and spot height data, some errors may have gone unnoticed or uncorrected. All remaining attribute errors will be corrected in future versions. The spatial errors that occasionally occur in the contour data were described in Section 5. These errors can only be corrected manually and is a very time-consuming and laborious process. Many of these errors (e.g. gaps) do not have a significant impact on the quality of the interpolated DEM (because interpolation is a gap-filling process). However, most of the major errors were corrected in preparation of SUDEM 2016. Minor errors will be corrected as they are identified. Users are encouraged to bring such errors to our attention³.

4.1.5.2 Interpolation artefacts

Contours are discrete representations of a continuous surface (terrain) and are consequently not ideal sources of terrain data. Interpolating from contours will always produce artefacts (e.g. banding, tiger stripes, and wave effects). Although several techniques were employed to limit these artefacts, some are still present in both the SUDEM products (in particular Level 1). Users may choose to employ filtering techniques to reduce the effect of these artefacts. However, this will reduce the integrity of the data. Research is currently being carried out to find alternative methods to reduce these artefacts.

4.1.5.3 SRTM errors

Only major errors (e.g. voids and spikes) in the SRTM DEM were corrected in SUDEM 2016. Other errors, such as banding and striping, were not corrected. Methods to minimise such errors are currently being developed and will be incorporated in future releases.

4.1.5.4 Hydrological errors

Although some interpolation algorithms (such as ANUDEM) can produce hydrologically-corrected (HC) DEM, they often produce artefacts such as artificially deep river channels and gorges, particularly in areas of relatively moderate terrain. Because these artefacts can have a significant impact on some applications (e.g. geometrical and terrain correction of imagery), none of the SUDEM products were hydrologically corrected. However, a HC version of each product can be supplied by removing sinks and peaks from the original DEM. These products, signified by a processing level indicator B, are available on request, but should be regarded as an experimental version as work is currently in progress to develop a more robust correction methodology by using ancillary data (e.g. stream networks and water bodies).

4.2 LEVELS 3 & 4

³ Kindly email the locations (i.e. latitude and longitude) of suspected errors to avn@sun.ac.za.

The SUDEM Level 3 product is a 1-2m resolution digital surface model (DSM), while the Level 4 product is a digital terrain model (DTM). The Level 3 product was extracted from the CDNGI 0.5m aerial photography. A new algorithm (not yet published) was developed to optimize the accuracy of the DSM. The algorithm incorporates several pre-processing steps to prepare the imagery for point cloud extraction. A minimum of 54 points are generated for each 2x2m pixel and statistical measures are used to remove outliers and to extract elevations that are highly accurate.

The product is currently only available for selected areas, but can be produced on demand for anywhere in South Africa. The Level 3 product provides significantly more detail than the other SUDEM product levels (see Figure 3)

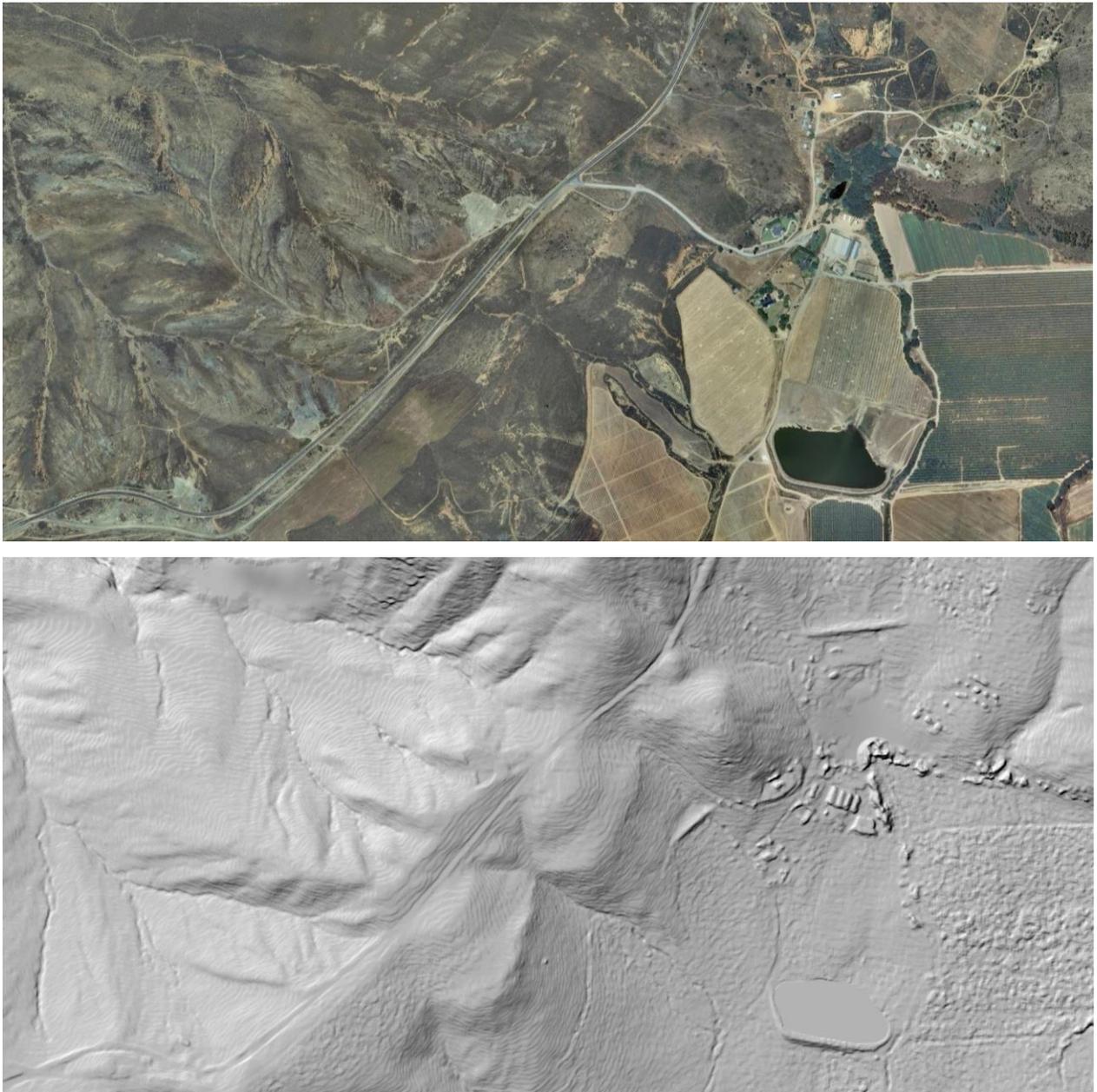


Figure 3 Comparison of SUDEM Level 3 (bottom) to an aerial photograph (top)

The Level 4 product is generated by converting the Level 3 product to a DTM. This is done using a newly developed algorithm that identifies pixels representing the terrain (i.e. are on the ground). These pixels are then used to interpolate a new DEM that accurately depicts the terrain surface.

5 ACCURACY ASSESSMENT

To determine the accuracy of SUDEM products, the elevation values were systematically compared to reference elevations. Highly accurate (mm) surveyed points, obtained from the City of Cape Town, were used as reference data. To determine vertical accuracy, the mean absolute error (MAE) was calculated using Equation 1 (Bolstad & Smith). The standard deviation (STD DEV) and 90 percentile of error were also determined. The results of the accuracy assessments are summarized in Table 2.

$$MAE = \frac{\sum |x_i - x_j|}{n} \quad \text{Equation 1}$$

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.

Table 2 Vertical error of the SUDEM products

PRODUCT	MAE (m)	STD DEV (m)	90 percentile (m)
30m SRTM DEM	3.22	2.88	6.42
5m SUDEM Level 1	1.57	1.76	3.25
5m SUDEM Level 2	1.77	1.21	3.06
1-2m SUDEM Level 3/4	0.35	0.25	0.66

It is clear from the results that the SUDEM products performed significantly better than the SRTM DEM. Although the Level 2 product has a slightly higher mean absolute error than the Level 1 product, it seems to be a good compromise between vertical accuracy and level of detail, particularly in flat terrain where contours are sparse. The standard deviation and 90 percentile of the Level 2 product is also lower than the Level 1 product, which indicates that it is more consistent in its accuracy. This was confirmed by a comprehensive qualitative assessment (visual interpretation) where the Level 2 product showed more detail than the Level 1 product in areas with moderate terrain. An example where this is apparent is provided in Figure 4.

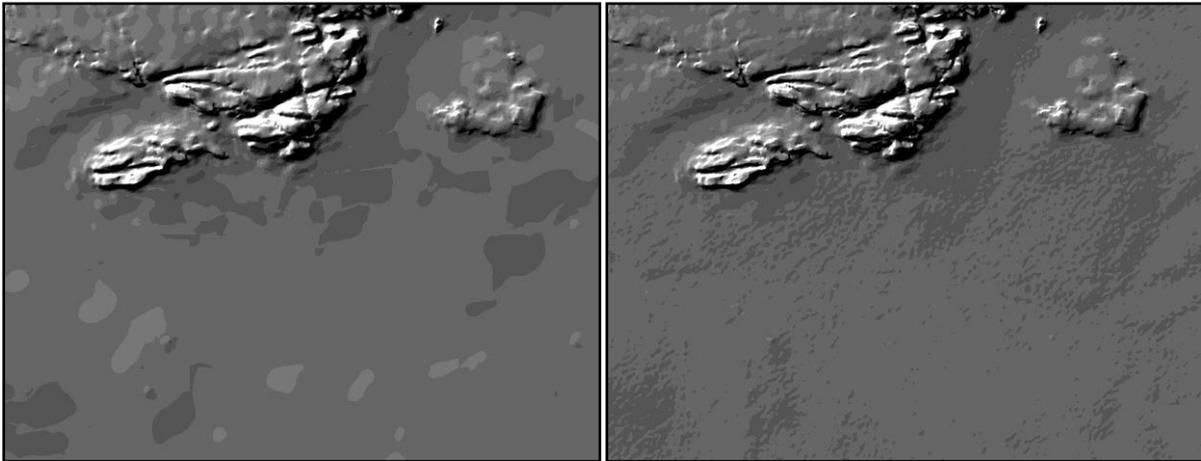


Figure 4 Hillshade of the Level 1 (left) and Level 2 (right) products for an area of moderate terrain demonstrating the higher detail of the Level 2 product

The qualitative assessment also revealed that some of the artefacts (e.g. banding, tiger stripes, and wave effects), that are frequently present in contour-interpolated DEM (and visible in the Level 1 product), are reduced when the SRTM fusion is performed (see Figure 5). Additional methods to further reduce these artefacts are currently in development.

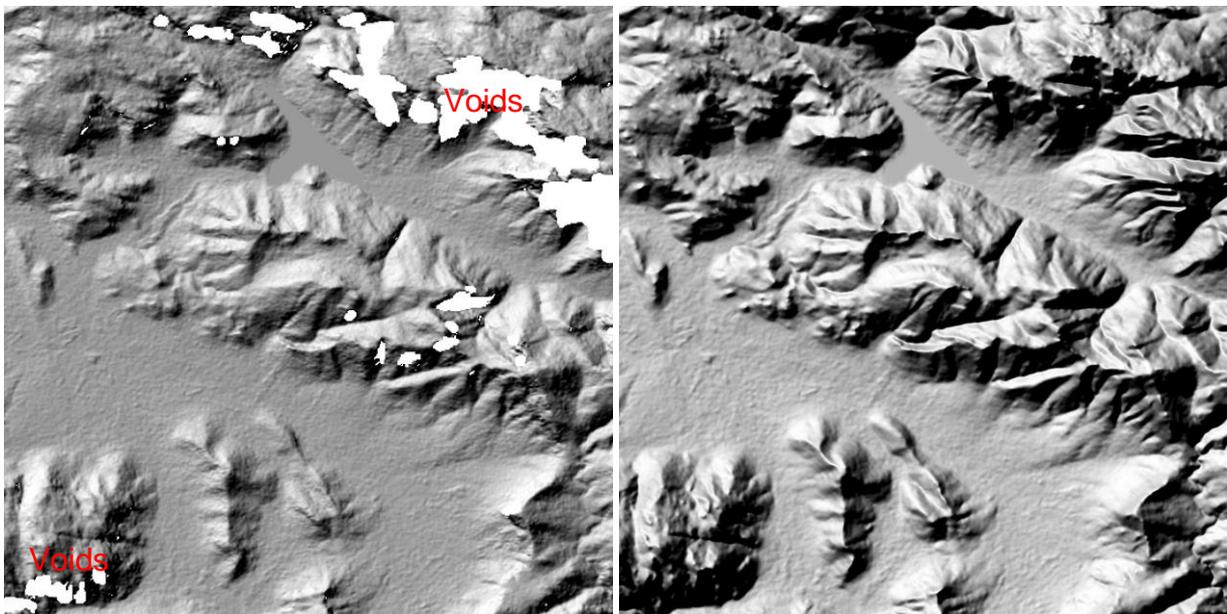


Figure 5 Hillshades of the 30m SRTM DEM (left) and 5m SUEM Level 2 (right) products

From the quantitative and qualitative assessments it is clear that the SUEM products are significantly more accurate than the SRTM DEM. The higher resolution of the SUEM also enables the inclusion of more terrain detail. There is, however, much room for improvement and it is our intention to further enhance the SUEM by incorporating other sources of information, specifically DTMs derived from high-resolution stereo aerial photographs (Level 4) and LiDAR data. These improved editions of the SUEM are expected to be released annually.

6 WEB ACCESS

The hillshade of the SUDEM Level 2 product is available for online use. There are a number of ways to do this:

Option 1:

1. In ArcMap click the dropdown arrow next to the 'Add data' button.
2. Select 'Add Data From ArcGis Online...'
3. In the new window search for SUDEM. Then simply select the SUDEM hillshade and click 'Add'.

Option 2:

1. In ArcMap click the 'Add Data' button.
2. Click the 'Look in' drop-down arrow and navigate to the 'GIS Servers'. This will provide a list of servers you have previously used.
3. Double-click 'Add WMS Server'.
4. Enter the URL pathname provided below to establish a connection and Click OK.
<http://146.232.21.108/arcgisweb2/services/sudemhs/MapServer/WMServer>
5. Double-click the WMS service you want to use (__sudemhs on 146.232.21.108), select 'sudemhs' and click 'Add' to open it in ArcMap.

For those using QGIS:

1. Simply select 'Layer' and then 'Add WCS layer...'
2. Click on the 'New' button, then paste the URL below in the box that opens.
<http://146.232.21.108/arcgisweb2/services/sudemhs/MapServer/WCServer>
3. Give the layer a name e.g. 'Sudemhs' and click OK.
4. Click 'Connect', the layers will show in the box, select them and click 'Add'.
5. The hillshade should be added to your QGIS display.

7 SAMPLES

Table 3 lists a range of samples that can be downloaded and used in a GIS for visualization and analysis. The samples are all in TIFF format.

Table 3 SUDEM samples available for download

Product	Description	Link	Size (MB)
Level 2	Cape Town (3319C)	http://146.232.21.108/Downloads/sudem/SUDEM_Level2_3319C.zip	420
Level 2	Cederberg	http://146.232.21.108/Downloads/sudem/SUDEM_WCDEM_AOI_mask.zip	799
Level 3/4	Moorreesburg Level 3 and 4 comparison	http://146.232.21.108/Downloads/sudem/SUDEM_Level34_Moorreesburg.zip	650
Level 3	10x10km DSM and hillshade	http://146.232.21.108/Downloads/sudem/SUDSM_Level2_10x10km.zip	107
Level 3	3x3km urban area, with 1m & 2m resolution comparison	http://146.232.21.108/Downloads/sudem/SUDEM_Level3_1m_and_2m.zip	44

8 FORMAT

The SUDEM products are stored in TIFF format, but can also be supplied in other formats (e.g. ERDAS IMG, ESRI GRID, ESRI File GeoDatabase). The Level 2 product is normally supplied in geographical coordinates (Hartebeesthoek Datum), but if needed can be projected to a map projection. The Level 3 and 4 products are distributed in the South African Coordinate System (i.e. Gauss, LO). Given that elevations are continuous, it is important that the SUDEM is reprojected to the correct resolution using the Cubic Convolution resampling method. Using Nearest Neighbour (or even Bilinear) resampling can cause artefacts.

9 SUDEM PRICES

Developing the SUDEM is very costly. The intention is to do more research on developing even more accurate and higher resolution DEMs of South Africa (and other countries). The funds raised from selling the SUDEM will go towards this end.

All products can be ordered per square km, with a minimum order of 300km². The costs are much lower when ordering larger areas (e.g. per 1:50 000 sheet). The price structure of the SUDEM is provided in Table

4. The cost for the entire 5-m resolution Level 2 data set is R1 million. Costs are significantly reduced when supplied at 10m. The Level 3 and 4 products are generated on order.

Table 4 SUDEM prices (excl. VAT) [single user license]

Area/Product	10m resolution (Level 2)	5m resolution (Level 2)	2m* resolution (Level 3)	2m* resolution (Level 4**)
Per square km (min order of 300km ² rectangular area)	R15.00	R20.00	R50.00	R80.00
Per 1:50 000 map sheet (e.g. 3318dd)	R5,000.00	R7,500.00	R25,000.00	R40,000.00
Per quarter degree square (e.g. 3318d)	R12,500.00	R18,750.00	R75,000.00	R120,000.00
National	R750,000.00	R1,000,000.00	R5,000,000.00	R8,000,000.00

* 1m resolution on request at a premium; ** When ordering the Level 4 product, the Level 3 product is provided free of charge; Level 3 and 4 products are generated on order.

The cost for the Level 3 (DSM) product is R50 per square km², but as with the Level 2 product, the cost drops substantially as larger areas are ordered. The Level 4 (DTM) product is slightly more expensive, but includes the Level 3 product free of charge. Very large orders are heavily discounted (up to 50%). Students and researchers can apply for an academic discount of up to 30% on the Level 2 product.

10 UPDATE HISTORY: LEVEL 2A PRODUCT

Version 15.15 (released March 2016)

- Replaced 90m with 30m SRTM DEM
- Increase extent to include Lesotho and Swaziland, as well as parts of other neighbouring countries to improve the use of the DEM near the border
- Fixed some artefacts due to missing contours
- Introduce new packaging as non-overlapping tiles
- Introduce 10m down-sampled version

Version 14 (released March 2014)

- Improved fusion algorithm

Version 13 (released March 2013)

- Replaced coastline with one digitized from 0.5m aerial photographs
- Fixed some artefacts along coastline
- Include LiDAR data of Cape Town area
- Introduce L3 (DSM) data

Version 12 (released March 2012)

- Added 90m SRTM DEM to input data
- Introduced fusion of interpolated and SRTM DEM data
- Corrected contour errors
- Fixed some artefacts due to missing contour data

Version 11 (released March 2011)

- Extent expanded from Western Cape to full South African coverage
- Increased resolution to 5m from 20m
- Added 1:10 000 (5m) contours and spot heights to input data

11 UPDATE HISTORY: LEVEL 2B (ENHANCED) PRODUCT

Version 16.01 (for release in March 2016)

- Fusion of Level 2b products (where available)
- Improved fusion technique for seamless integration

12 UPDATE HISTORY: LEVEL 3/4 PRODUCT

Version 16.01 (for release in March 2016)

- Improvements in DSM editing

Version 15.16 (released August 2016)

- Improvements in DTM extraction algorithm/workflow

Version 15.15 (released March 2016)

- Improvements in performance of algorithm

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