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DEM-induced errors in developing a quasi-geoid model for Africa

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Abstract. Errors in digital elevation models (DEMs) will introduce errors in geoid and quasi-geoid models, via their use in interpolating free-air gravity anomalies and (in the case of the quasi-geoid) their use in computing the Molodensky G_1 term. The effects of these errors and those of datum shifts are assessed using three independent DEMs for a test region in South Africa. It is shown that these effects are significant and that it is important to choose the best-possible DEM for use in geoid and quasi-geoid modelling.

Keywords: Digital elevation model – Geoid – Quasi-geoid – Interpolation errors

1 Introduction

The increased use of systems such as Global Positioning Systems (GPS) for surveying and mapping has led to an increased need for precise (quasi-)geoid models to enable GPS-derived heights to be converted to normal heights (or orthometric heights where the geoid is the reference surface). The usual method of computing height anomalies (quasi-geoidal heights) is the so-called remove–restore procedure (Sideris 1994), whereby the contribution of a model geopotential field is removed from a set of free-air gravity anomalies and restored to the residual height anomalies computed from these residual gravity anomalies. The computation of the residual height anomalies can be done in a number of different ways, using least squares (LS) collocation, numerical integration, or its spectral equivalent, Fast Fourier Transform(FFT) (Tscherning 2001). For reasons of computational efficiency the free-air gravity anomalies (or some modified version of them) are almost invariably interpolated onto a regular grid before the computation takes place. As free-air gravity anomalies vary rapidly with position and elevation, it is customary to use Bouguer anomalies (which vary much more smoothly) for the interpolation process (Torge 2001) and to use a digital elevation model (DEM) to convert the Bouguer anomalies back to free-air anomalies at the grid points. The use of the simple Bouguer anomaly for interpolation is not optimal, and it would be preferable to use refined anomalies (incorporating a terrain correction), as these would vary more smoothly in mountainous regions. However, the lack of a high-resolution DEM for the whole of Africa and the desire for computational simplicity has led to the simple Bouguer anomaly being preferred. An alternative would have been to apply the residual terrain model (RTM) approach (Forsberg and Tscherning 1981). This would have avoided the need for direct interpolation of free-air gravity anomalies, but would introduce further computational effort in terms of removing and restoring the terrain effect. The DEM is also used to compute the G_1 correction term in Molodensky's expression for the height anomaly (Amod and Merry 2002b).

There are a large number of potential error sources that can degrade the accuracy of the final product. Amongst these are long- and medium-wavelength errors in the reference geopotential model and errors in the gravity anomaly data. This paper will not deal with the former, but will concentrate on some of the sources of error in the gridded gravity anomalies. These errors include the following.

1. Random observation errors in the gravity measurements.
2. Systematic biases in the gravity data (e.g. Potsdam datum used instead of IGSN71 datum).
3. Biases in the height datum (e.g. Mean Sea Level (MSL) not used as the basis for heights) – this affects both the gravity anomalies and the DEM.
4. Biases in the horizontal datum (e.g. local datum used instead of GRS80/WGS84) – this affects both the gravity anomalies and the DEM.

5. Random errors in the DEM (caused by errors in creating the DEM).
6. Interpolation errors – this affects both the gravity anomalies and the DEM.

This paper focuses on the errors associated with the DEM and their impact on the height anomalies generated using the DEM. The study arose out of a project to compute a geoid model for Africa – the African Geoid Project (Merry and Blitzkow 2001). A regular grid of free-air gravity anomalies is needed in order to use a computer-efficient technique such as convolution for the computation. For the African Geoid Project, Bouguer anomalies were interpolated onto a regular grid and then converted to free-air anomalies using DEM values for the heights at these grid points. At this point in time the only available continental DEM is the 30" GLOBE model (Hastings and Dunbar 1998). However, there are serious questions about the quality of this DEM (Berry at al. 1999), which may have a serious impact on the quality of the African geoid model and on the proposed precise quasi-geoid model for South Africa (Merry and Amod 2001).

2 Effects of DEM Errors

There are no simple models relating errors in a DEM to errors in either height anomalies, ζ, or geoidal heights, N. An empirical approach has been used in this study, whereby three separately compiled DEMs for a test region have been used to compute height anomalies for the same region. The discrepancies in the height anomalies are a measure of the effect of the discrepancies in the DEMs.

The chosen test area consists of the region bounded by the latitude limits of 32° and 35° south and the longitude limits of 18° and 21° east. This region was chosen for the following reasons.

1. DEM models from three independent sources are available.
2. There is good gravity coverage, both on hills and in valleys, so that gravity interpolation errors are minimised.
3. The region is mountainous, so that the effects of DEM errors both on the interpolation of free-air anomalies and on the computation of the G_1 term should be noticeable.
4. There are a number of GPS/levelling benchmarks in the region, which provide an independent check on the quality of the results.

2.1 Data sets

The three digital elevation models available are as follows.

1. CDSM: this model, covering most of South Africa, with a grid spacing of 30", is based upon a much finer grid produced by the South African national mapping agency – the Chief Directorate of Surveys and Mapping. The original grid, at a 400-m grid spacing on a Transverse Mercator projection of the Cape datum, was produced photogrammetrically, and subsequently converted to the WGS84 datum on a 30" grid (Duesimi, pers. Commun. 2002).
2. GLOBE: this global data set, at 30" grid spacing, has been compiled by the US National Geophysical Data Centre (Hastings and Dunbar 1998). The part of the data set for Africa is largely based upon the National Imagery and Mapping Agency's DTED Level 0. This data set (at least for Africa) has been compiled from medium-scale maps produced by national survey agencies. As far as can be established, no datum conversion (to WGS84) has been carried out.
3. UCT: this is a much more local DEM, which only covers the western part of South Africa, at a grid spacing of 1'. The DEM was compiled at the University of Cape Town, by direct interpolation from 1:50 000 contour maps (Merry 1981). The horizontal datum is the Cape datum.

For the purposes of comparison, a common grid spacing of 1' was chosen. For the UCT and GLOBE DEMs the required data could be extracted directly. In the case of the CDSM data, the grid points, although 30" apart, were not on exact multiples of 30", and a further interpolation had to be performed in order to obtain a DEM on the desired 1' grid points. This has introduced a further error into this DEM, to be discussed later.

All three data sets use the same height datum – the South African Land Levelling Datum (LLD) – which is estimated to be some 15–20 cm below MSL (Merry 1990). The CDSM DEM refers to the WGS84 horizontal datum, the UCT model refers to the Cape datum, and GLOBE is presumed to refer to the Cape datum.

The land gravity data used for this study were provided by the South African Council for Geoscience and refer to IGSN71 c (Fourie, Pers. Commun.1997). The datum for horizontal positions is the Cape datum and the height datum is the LLD. The data spacing is roughly 5 km (2.7'). Simple Bouguer anomalies were computed from these data and used to interpolate a 2' grid using kriging. A 1' grid was also generated, for use in calculating the G_1 term.

Part of the test area includes the sea off the southwestern coast of Africa. Rather than use the sparse and unreliable sea gravimeter measurements in this region, the 2' free-air anomaly data set computed from satellite altimetry and provided by the Danish National Survey and Cadastre (Andersen and Knudsen 1998) was used.

2.2 Height anomaly and G_1 calculation

The technique used for the computation of the height anomalies follows that of Merry and Blitzkow (2001).

1. Bouguer anomalies are computed at all the data points.

2. These anomalies are interpolated onto a regular 2' grid, using kriging.
3. The gridded Bouguer anomalies are converted to gridded free-air anomalies using each of the three DEMs in turn

$$\Delta g_f = \Delta g_B + 0.1119 H_i \tag{1}$$

4. Residual anomalies are formed by subtracting the contribution of the EGM96 geopotential model

$$\Delta g_r = \Delta g_f - \frac{GM}{a \cdot r} \sum_{n=2}^{360} (n-1) \left(\frac{a}{r}\right)^n \times \sum_{m=0}^{n} [(C_{nm} \cos m\lambda + S_{nm} \sin m\lambda) \cdot P_{nm}(\cos\theta)] \tag{2}$$

5. The residual anomalies are used in a 2-D convolution with a spherical Stokes kernel to determine residual height anomalies.

$$\zeta_r = \frac{R\Delta\phi\Delta\lambda}{4\pi\gamma} [S(\psi) * \Delta g_r \cos\phi] \tag{3}$$

   Here, * denotes the convolution operator and $\Delta\phi$ and $\Delta\lambda$ are the grid intervals in latitude and longitude.
6. These residual height anomalies are added to the height anomalies generated by the EGM96 model, in order to obtain final height anomalies.

$$\zeta = \zeta_r + \frac{GM}{\gamma r} \sum_{n=2}^{360} \left(\frac{a}{r}\right)^n \times \sum_{m=0}^{n} [(C_{nm} \cos m\lambda + S_{nm} \sin m\lambda) \cdot P_{nm}(\cos\theta)] \tag{4}$$

For the G_1 term, the following steps are carried out (Amod and Merry 2002b).

1. Bouguer anomalies are interpolated onto a 1' grid and converted to free-air anomalies using the CDSM DEM (considered to be the most reliable).
2. Each of the DEMs, together with the 1' free-air-anomaly grid, are used in a 2-D convolution to obtain the G_1 anomaly term on a 2' grid.

$$G_1 = \frac{\Delta\phi\Delta\lambda}{2\pi} \left[(h\Delta g_f) * \frac{1}{\ell^3} - h\left(\Delta g_f * \frac{1}{\ell^3}\right) \right] \tag{5}$$

   Here, h is the height and ℓ is the horizontal distance.
3. These anomalies are used in a 2-D convolution with a spherical Stokes kernel to determine their contribution to the height anomalies.

$$\zeta_{G_1} = \frac{R\Delta\phi\Delta\lambda}{4\pi\gamma} [S(\psi) * G_1 \cos\phi] \tag{6}$$

In order to reduce any edge effects, the height anomalies and the G_1 contributions were only computed for the central window ($-34° < \phi < -33°$; $19° < \lambda < 20°$), although the entire gravity anomaly data set was used ($-35° < \phi < -32°$; $18° < \lambda < 21°$).

2.3 Tests

The following four tests and comparisons were carried out.

1. Each of the three DEMs was used in turn to compute free-air gravity anomalies from which residual height anomalies were computed. These were then compared to each other.
2. Each of the three DEMs was used to compute the G_1 term and its contribution to the height anomalies. These results were compared to each other.
3. In order to assess the effect of a horizontal datum shift, the CDSM DEM was shifted in each of latitude and longitude by 300 m and the free-air gravity anomalies and residual height anomalies were re-computed.
4. In order to assess the effect of a height datum bias, the CDSM heights were all changed by 5 m and re-used to compute free-air gravity anomalies and height anomalies.

3 Results

The statistics of the three DEMs covering the 3° by 3° region are summarised in Table 1. The grid resolution of the data used in Table 1 is 1 minute.

The mountainous nature of the terrain is evident in the large standard deviation (σ) values for all three models. Although they cover a very similar range of values, there are large discrepancies at individual grid points. These are due to errors of interpolation and to the models being referenced to different datums. The height bias of more than 5 metres in the UCT model is of some concern, as the height datum is nominally the same for all three models. The CDSM and UCT DEMs, although referenced to different horizontal datums, show much better agreement with each other than with the GLOBE DEM. This highlights the concerns that have been expressed regarding the quality of the GLOBE DEM.

Table 1. Summary statistics for DEM models

DEM model	Maximum (m)	Minimum (m)	Mean (m)	Standard deviation (m)
CDSM	1984	0	562	443
GLOBE	2033	1	564	442
UCT	1980	0	557	445
CDSM–GLOBE	+707	−709	−1.7	95
CDSM–UCT	+508	−403	+5.6	45
GLOBE–UCT	+910	−908	+7.3	118

3.1 Residual Height Anomalies

The DEMs described in the previous section were used to generate free-air gravity anomaly data sets and subsequently to determine residual height anomaly fields. The results are summarised in Table 2.

The differences between the three sets of residual height anomalies mirror, to some extent, the differences between the three DEMs. Again, the CDSM and UCT results agree better with each other than with the GLOBE result. The impact of the height bias in the UCT model manifests itself as a 5-cm bias in the height anomalies. How significant are these discrepancies? Assuming for the moment that the CDSM DEM is the most accurate (it is the most recent, and is derived directly from a photogrammetric model), then individual errors of up to 20 cm could occur if the GLOBE model is used, with the standard deviation being around 6 cm. For a continental-scale geoid determination such as that proposed for Africa, these errors are reasonably small compared to other potential error sources (long-wavelength errors in EGM96 possibly exceeding 50 cm; errors due to the complete lack of gravity data in some regions, extending over thousands of square kilometres). However, for South Africa, where relative height anomaly accuracies of 5 cm + 1 ppm are achievable (Amod and Merry 2002a), these errors are not insignificant.

3.2 G_1 correction term

The convolution of Stokes' function with residual gravity anomalies is only part of the process leading to Molodensky height anomalies. The G_1 correction term is particularly significant in mountainous regions and relies heavily upon a detailed accurate DEM. A further test was carried out in which the G_1 contribution to ζ was computed using the three DEMs. These results are summarised in Table 3.

The G_1 contribution is generally small (less than 10 cm), with a root-mean-square (RMS) contribution of around 5 cm. The differences between the results for the three DEMs are also small, with the CDSM and UCT DEMs agreeing better with each other than with the GLOBE model. Considering that the G_1 term uses height differences, it appears that although there might be significant differences between the three models, in a relative sense they are reasonably consistent. Certainly, as far as the G_1 term is concerned, the CDSM and UCT DEMs provide very similar results.

3.3 Change in horizontal datum

The DEM and the gravity anomaly data sets do not necessarily refer to the same horizontal datum. For example, although the gravity data refer to the Cape datum, the CDSM DEM refers to the WGS84 datum. What would be the impact of this bias? For this test the CDSM DEM has been shifted by approximately 300 m in latitude and in longitude and re-interpolated onto a 2' grid. The 300-m shift is larger than would be necessary for a shift between the Cape and WGS84 datums – this magnitude of shift has been selected so as to encompass the maximum possible shift that may be expected for any African datum.

The original CDSM and the shifted CDSM DEMs have been used to compute free-air gravity anomalies that in turn have been used to compute residual height anomalies. A summary of these results is given in Table 4, with the 'Difference' in this table being the statistics of the grid of differences between the two results.

The shift in horizontal position introduces a bias of around 1 cm in the residual height anomalies, with an RMS discrepancy of 2 cm. However, individual discrepancies can reach 6 cm. In the context of a

Table 2. Summary statistics for residual height anomalies

DEM model	Residual height anomaly			
	Maximum (m)	Minimum (m)	Mean (m)	Standard deviation (m)
CDSM	+0.636	−0.675	−0.074	0.313
GLOBE	+0.687	−0.625	−0.076	0.290
UCT	+0.620	−0.739	−0.128	0.313
CDSM–GLOBE	+0.176	−0.181	+0.002	0.058
CDSM–UCT	+0.141	−0.013	+0.054	0.023
GLOBE–UCT	+0.269	−0.148	+0.052	0.070

Table 3. Summary statistics for G_1 contribution to ζ

DEM model	G_1 contribution to ζ			
	Maximum (m)	Minimum (m)	Mean (m)	RMS (m)
CDSM	+0.070	+0.018	+0.050	0.050
GLOBE	+0.096	+0.019	+0.062	0.063
UCT	+0.071	+0.015	+0.047	0.048
CDSM–GLOBE	+0.008	−0.039	−0.013	0.015
CDSM–UCT	+0.015	−0.009	+0.003	0.004
GLOBE–UCT	+0.051	−0.013	+0.015	0.018

Table 4. Summary statistics for effect of datum shift on ζ

Model	Effect of datum shift on ζ			
	Maximum (m)	Minimum (m)	Mean (m)	RMS (m)
CDSM	+0.636	−0.675	−0.074	0.321
CDSM shifted	+0.615	−0.703	−0.088	0.330
Difference	+0.064	−0.034	+0.013	0.022

continental geoid model for Africa, these effects are insignificant.

3.4 Change in height datum

Height biases are another potential source of error. The South African LLD has a bias of around 20 cm (Merry 1990). It is unlikely that other vertical datums in Africa will have biases exceeding 50 cm. However, the DEMs may themselves have larger biases. For example, for the test area, there are biases between the DEMs of up to 7 m (Table 1). Assuming that biases would not generally exceed 5 m, such a bias (minus 5 m) has been introduced into the CDSM DEM. This is equivalent to reducing the free-air gravity anomalies by 1.5 mGal. The effect of this shift on the residual height anomalies is summarised in Table 5, with the 'Difference' in this table being the statistics of the grid of differences between the two results.

The result of reducing the heights by 5 m (equivalent to 1.5 mGal) is an almost constant reduction in the height anomalies of 9 cm. It is unlikely that such a large bias (5 m) would exist for a vertical datum, but (at least for a limited region) such a bias does exist between different DEMs. The equivalent bias in the gravity datum is 1.5 mGal. If the gravity survey has been properly connected to IGSN71 the bias is likely to be a lot smaller. However, inconsistencies in gravity datums can and do occur. As an example, the same gravity data set for a survey in southern Angola was supplied to the author by two different intermediary agencies. There is a bias of 14.5 mGal between the two sets. The difference is undoubtedly due to the difference between the Potsdam and IGSN71 gravity datums, but which is correct? If the wrong set is chosen, the impact on the geoid in that region could exceed 50 cm.

3.5 DEM interpolation errors

The three DEMs investigated here stem from different source data. However, even if the original source data are the same, interpolation of these data onto another grid can introduce further errors. As mentioned previously, the CDSM data were provided on a 30" grid, but the grid intersections were not exact multiples of 30". A further interpolation had to be carried out in order to match the grid points with those of the GLOBE and UCT DEMs. The chosen interpolation procedure was kriging. However, alternative interpolation procedures (inverse distance squared, TIN) were also investigated. It was somewhat alarming to see that significant differences (RMS of the order of 20 m) occurred when the same data were interpolated onto the same grid, using different algorithms. Obviously, more reliable results would be obtained if the original mesh size was considerably smaller.

3.6 Comparison with GPS/levelling

Some 11 precise levelling benchmarks, occupied with GPS, are available within the test region. The GPS measurements tie the benchmarks to the national GPS network and to the new national datum, Hart94. This datum is tied to the International Terrestrial Reference Frame(ITRF) via the very-long-baseline interferometry(VLBI) site at Hartebeesthoek (Wonnacott 1997) and is for all practical purposes the same as WGS84. In the comparison, full height anomalies are computed using each DEM model (including the EGM96 and the G_1 contributions). These three sets of gridded data are then used to interpolate height anomalies at each of the benchmarks. The resultant values are then compared to the values derived from GPS/levelling. These results are summarised in Table 6.

There is a significant bias between the gravimetric quasi-geoid models and the GPS/levelling quasi-geoid. A large part of this is due to biases in the levelling datum (LLD) and in the GPS height datum. It is known that the LLD is some 15–20 cm below MSL (Merry 1990). More recently it has been established that there are systematic errors of the order of 30 cm in the Hart94 ellipsoidal heights in the southwestern part of South Africa (Chandler 2001). If we take these into account

Table 5. Summary statistics for effect of height shift on ζ

Model	Effect of −5-m height shift on ζ			
	Maximum (m)	Minimum (m)	Mean (m)	Standard deviation (m)
CDSM	+0.636	−0.675	−0.074	0.313
CDSM shifted	+0.546	−0.767	−0.166	0.313
Difference	+0.093	+0.081	+0.092	0.001

Table 6. Comparison of height anomalies

Model	Comparison of height anomalies				
	Maximum (m)	Minimum (m)	Mean (m)	Standard deviation (m)	Range (m)
GPS/levelling ζ	+33.125	+31.473	+32.218	0.446	1.652
GPS/levelling–CDSM	−0.338	−0.489	−0.405	0.045	0.151
GPS/levelling–GLOBE	−0.311	−0.517	−0.421	0.067	0.206
GPS/levelling–UCT	−0.290	−0.422	−0.344	0.043	0.132

then the negative bias of around 40 cm in Table 6 becomes a positive bias of 5–10 cm, well within the error budget of the EGM96 geopotential model.

Apart from this bias, all three models agree well with the GPS/levelling results. However, the fit of the GLOBE model is significantly worse than that of the CDSM and UCT models. This implies that the GLOBE DEM may be of lower accuracy in the test region.

4 Discussion

A reliable and accurate DEM is essential if a reliable and accurate geoid or quasi-geoid model is to be determined. This is especially so if a DEM is used as part of the process of interpolating free-air gravity anomalies onto a regular grid. For the test region, the effects of the DEM errors are as follows:

1. An RMS error in height of 120 m introduces an RMS error in height anomaly of 7 cm.
2. The same height error introduces an RMS error in the G_1 term of 2 cm.
3. A horizontal datum bias of 300 m introduces a bias of 1 cm in the height anomaly.
4. A vertical datum bias of 5 m introduces a bias of 9 cm in the height anomaly.

These results are based upon very limited testing in a small geographical region in South Africa. This is a particularly mountainous region, and the DEM errors (and correspondingly the ζ errors) should generally be smaller in other parts of Africa. However, it is also possible that they could be larger.

In the case of South Africa, DEM models other than GLOBE exist and can and should be used. Although precise DEMs are available for most of the developed world, this is not the case for Africa, where the only available continental model is GLOBE, which has been shown to be unreliable. An alternative is urgently needed. Fortunately, a candidate is waiting in the wings. The Shuttle Radar Topography Mission (SRTM), undertaken in 2000, promises a near-global DEM grid at 90-m spacing with an accuracy of better than 16 m (National Aeronautics and Space Administration 2002). At the time of writing, an SRTM DEM for North America is available, and one for Africa should become available within the next year. It is eagerly awaited.

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