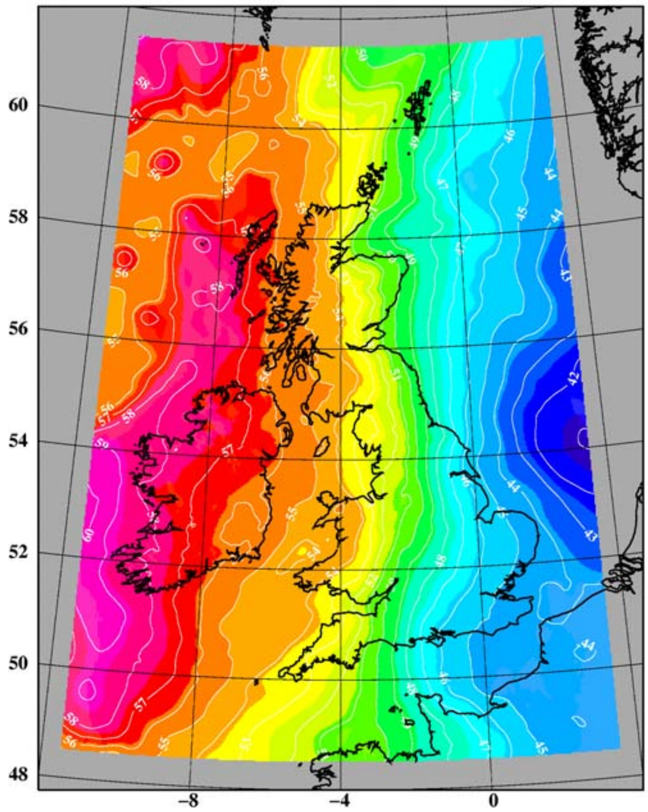
OSGM02™

A new precise geoid model covering all the land areas and inshore waters of the United Kingdom, the Republic of Ireland and the Isle of Man



Developed by:
KMS of Denmark, in association with University College London and the University of Copenhagen

Developed for:
Ordnance Survey Great Britain, Ordnance Survey Ireland, and Ordnance Survey Northern Ireland.

CONTENTS

1 Executive Summary

This report describes the work that has been carried out to produce the OSGM02 geoid, and the quality of the product obtained. The work has been carried out by KMS of Denmark, in association with UCL and the University of Copenhagen, on behalf of a consortium of the Ordnance Surveys of Great Britain, Ireland, and Northern Ireland.

A gravimetric geoid of very high accuracy has resulted from this project which will serve the GPS user and scientific communities with the region it covers for many years to come.

This report is a cut-down version of the final OSGM02 report. A full version may be made available for scientific / academic usage from the geodetic sections at the Ordnance Surveys of Great Britain, Ireland, and Northern Ireland.

OSGM02™ was developed for the consortium consisting of Ordnance Survey Great Britain, Ordnance Survey Ireland and Ordnance Survey Northern Ireland. OSGM02™ was developed by the National Survey and Cadastre of Denmark (KMS), Department of Geomatic Engineering – University College London and Department of Geophysics – University of Copenhagen. The primary data sources for OSGM02™, for whom we are deeply indebted, were;

United Kingdom Hydrographic Office
British Geologic Survey
Dublin Institute of Advanced Studies
Geological Survey of Northern Ireland

2 Gravimetric geoid determination

2.1 Summary of data supplied

The gravity data were supplied by 3 main data centres: The British Geological Survey, Kort og Matrikelstyrelsen (KMS) and Bureau Gravimetrique International. Other institutions contributed as data owners: The Institute of Advanced Studies, Dublin, Republic of Ireland; The Geological Survey of Northern Ireland, Belfast, Northern Ireland; and The Hydrographic Office, UK.

2.1.1 Terrain data

Based on the experience from Scandinavia and other areas, the required horizontal resolution of the terrain information was 100m × 100m average heights. Detailed Digital Elevation Models (DEMs) were provided by the Ordnance Surveys of Great Britain, Ireland, and Northern Ireland.

Great Britain

For the Great Britain (and except the Isle of Man, IoM, see below) the elevation data were organised in a number of 20 km × 20 km tiles covering the whole country. Each tile contained height information on a regular 50 m × 50 m grid in the National Grid coordinate reference system, which is defined by the OSGB36 triangulation. The height information for the IoM consisted of simple data records for each grid node; *easting, northing* and *height*. The IoM elevation data was merged with the elevation data from Great Britain to yield the joint data set of 100m × 100m horizontal spacing by averaging.

Northern Ireland

Two data files with a 50m × 50m elevation grid for Northern Ireland. Information about the data format was also provided. KMS found, nevertheless, good consistency between the received DEM and the measured station heights of gravity points. Consequently, there was no reason to doubt the high quality of the received detailed DEM for Northern Ireland. The use of the Irish Grid planar coordinates in both Northern Ireland and Republic of Ireland made it straightforward to merge the elevation data across the border. Firstly, a joint 50m × 50m DEM for the whole island was created which was then formatted to the required 100m ×100m horizontal spacing DEM by averaging.

Republic of Ireland

The elevation information was represented with a grid spacing of 10 m ×10 m. There were however a few areas in Republic of Ireland where the elevation data were not available. The data sets were thinned and patched up to yield a joint 50m × 50m DEM. Finally, this DEM was further averaged to yield a DEM with the required horizontal spacing of 100m ×100m.

The missing elevation data in Republic of Ireland created a special problem. It was necessary to close the data gaps. It was decided to interpolate the heights from a coarser 30” x 30” gridded elevation data set obtained via the Internet from the National Geophysical Data Center (NGDC) in the US. These coarse grid elevations were used to interpolate the heights to a 100m ×100m grid in the Irish Grid planar coordinates.

100 m ×100 m DEM

In summary, two DEMs with a horizontal spacing of 100m × 100m were created; one for Great Britain and the IoM and one for Northern Ireland and the Republic of Ireland.

Gravity station heights and the interpolated DEM heights

The gravity data contains station height information. The consistency between the interpolated DEM heights and the gravity station heights was assessed as part of the quality control procedure. In general, there was good consistency between the interpolated heights from the DEM and the station heights. All the large outliers were closely studied. However, if there was no obvious reason for the removal of the corresponding gravity data point, the data were left unchanged. Only the data with obvious errors were removed.

Other Terrain Models

The use of DEMs in geoid modelling by the technique of the Residual Terrain Modelling (RTM) involves the use of a coarse DEM as well as the use of a model for the reference topography (which is even coarser). For a particular gravity station, the coarser DEM is used for modelling (by prism integration) the gravitational attraction of the distant topography. The 100m × 100m DEM is used to model the attraction of the near topography. In the OSGM02-project the coarser DEM had a resolution of 1000m ×1000m. Two such models were created, one for the Great Briatin and the IoM and one for Northern Ireland and Republic of Ireland.

One detail concerns the use of the gravity data from the parts of The Netherlands, Belgium, France and the Faeroe Islands. These data were all treated as marine data (i.e. with zero heights). This assumption had only a negligible effect on the geoid on land in the British Isles, and avoided the problems of edge effects and missing heights along the borders of the computational region for the gravimetric geoid.

2.1.2 Gravity data

Sources of gravity data

Gravity data for the OSGM02-project came from several different sources. Table 2.1.2.1 lists the agencies that supplied the data and the data owners (if explicitly known).

Agency supplying the gravity data	Data owner	Type of gravity data	Number of raw gravity points
Kort- & Matrikelstyrelsen (KMS), Denmark	The Institute of Advanced Studies, IAS, Dublin, Republic of Ireland	Republic of Ireland land gravity data	17784
	National Survey Authorities	Land gravity data from Belgium, the Netherlands & the Faeroe Islands	5190
	BGS	Marine data around the British Isles	24721
	KMS	KMS99, gravity anomalies from ERS1 and ERS2 satellite altimetry	146445
British Geological Survey, BGS, UK	BGS	UK except Northern Ireland land gravity data	156882
		Marine gravity data (grids)	10170
	The Hydrographic Office, HO	Marine gravity data (unadjusted)	328974
	Geological Survey of Northern Ireland, Belfast	Northern Ireland land gravity data	11554
Bureau Gravimetrique International, BGI, France	IGN, France	Land gravity data from France	84280
	IGN, France	Marine gravity data from France	12617

Table 2.1.2.1 Sources of the gravity data for the OSGM02-project.

Other sources of gravity information

Other sources of gravity information relevant for the OSGM02 project were the EGM96 global gravity model (Lemoine et al., 1996), and KMS99 - the improved version of KMS98 – a global marine free-air gravity anomaly field from satellite altimetry (Andersen and Knudsen, 1998).

Pre-processing and screening for large outliers

In many cases the absolute gravity value *g* for a gravity station was also provided. Thus, it was possible to examine the inner consistency between the information in a data record: the station height, the free-air gravity anomaly and the Bouguer gravity anomaly, and to examine what normal gravity formula has been used (e.g. GRS67 or GRS80). Lack of internal consistency between constituents of a data record is a clear indication of erroneous gravity data. As it is most often unclear which constituent of a data record is erroneous, the internally inconsistent records could not be "repaired". They were simply removed from the data set. This was only done in a few, limited cases.

Station heights could however be verified independently for the land gravity data. This was done by a comparison of station heights with the interpolated heights from the high resolution DEM in the area, on land, and for marine data, especially in the open ocean in the western part of the area, KMS99 gravity anomalies from satellite altimetry were an excellent source of "independent" gravity information for outlier detection. Only obvious errors were removed.

Another aspect of the pre-processing of the gravity data was the transformation to the common system based on the GRS80 ellipsoid; i.e. GRS80-ellipsoid geographical coordinates and the GRS80 normal gravity formula (truncated to the 2^{nd} order term in height).

After the pre-processing of the gravity data (the transformations and the removal of erroneous data) the remaining data were inspected for their areal coverage. The "distant zone" land gravity data from France, The Netherlands, Belgium and The Faeroe Islands were basically treated as if they were marine gravity data.

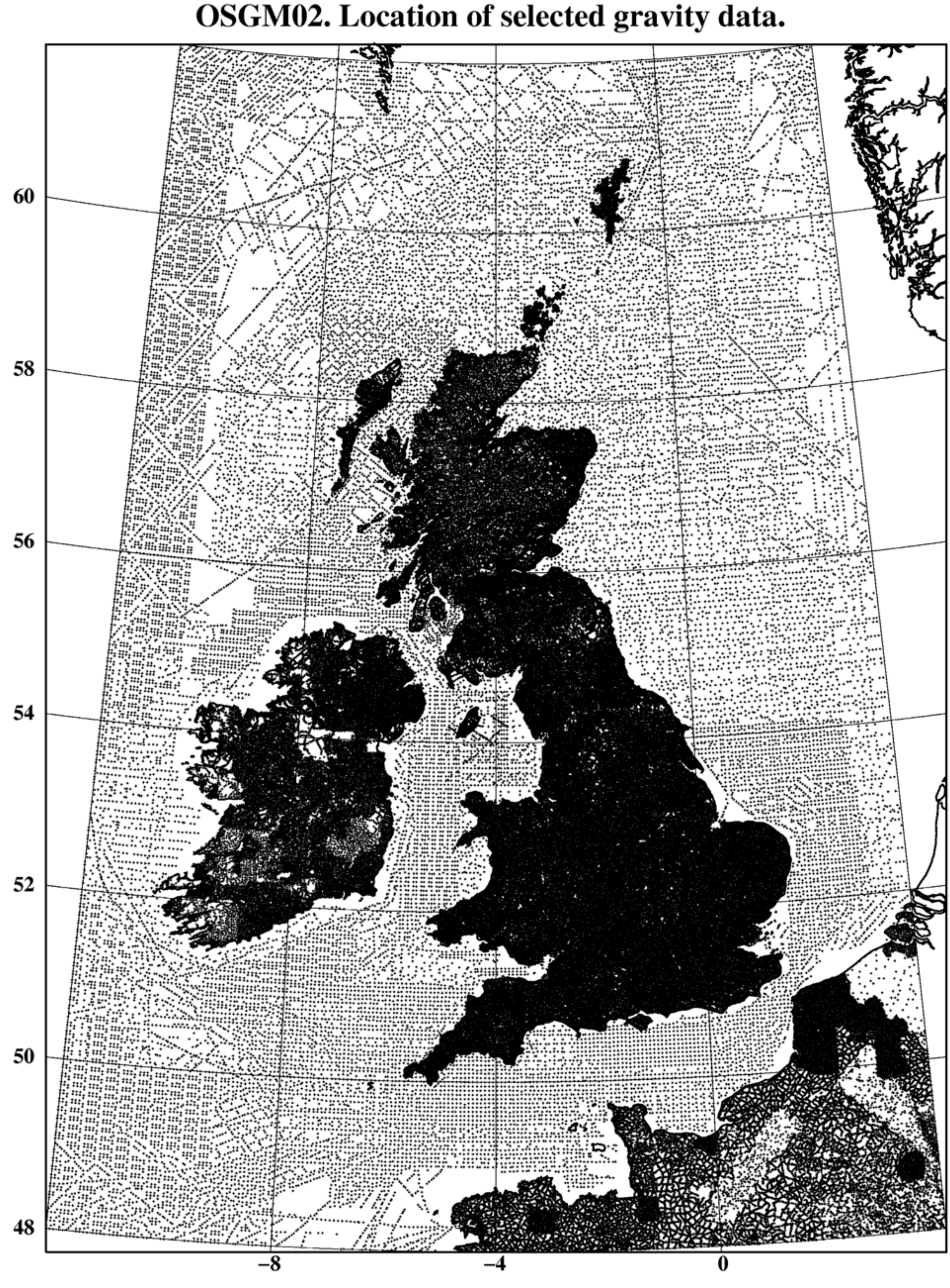


Fig. 2.1 OSGM02 gravimetric geoid. Station locations for the selected gravity data.

2.2. Gravimetric geoid determination methodology

The OSGM02 geoid is determined by first computing a gravimetric geoid model from the given gravity and DEM data – the major computational step – and then the subsequent fitting of the gravimetric geoid to the GPS-levelling control.

For the OSGM02 geoid a remove-restore technique is used. The basic anomalous gravitational potential T is split into three parts: a global field from the EGM96 spherical harmonic model, complete to degree and order 360, a short-wavelength contribution from topography, and a "residual" signal

$$T = T_1 + T_2 + T_3$$

The anomalous potential is a function of both position and height. If T is evaluated at the geoid (height zero, inside the topography) we obtain the classical geoid N – the goal of OSGM02:

$$N = \frac{T(\varphi, \lambda, 0)}{\gamma}$$

For mathematical stringency the OSGM02 gravimetric geoid model has been computed rigorously as a *quasi-geoid* ζ. The quasigeoid may loosely be described as the geoid height referring to the surface of the topography

$$\zeta = \frac{T(\varphi, \lambda, H)}{\gamma}$$

The difference between geoid and quasigeoid is the same as the difference between orthometric and normal heights, i.e.

$$\zeta - N = H_P - H_P^* \approx -\frac{\Delta g_B}{\gamma_o} H$$

The basics of the above equations may be found in fundamental physical geodesy textbooks such as Heiskanen and Moritz (1967).

To compute the *effects of the topography (T_2)*, the RTM (Residual Terrain Model) method has been used: topography has been taken relative to a smooth mean height surface, produced by filtering the DEM of the British Isles. The RTM reference height surface used has approximately 66 km resolution, to correspond roughly with EGM96. The filtering was done by taking 9 x 9 moving averages over the coarse 4' x 6' mean height grid

The gravity terrain effects have been computed by *prism integration* using the basic 100m DEMs in an inner zone, and averaged 1 km height grids in the outer zones.

Gravity terrain effects have been computed for all land and marine data, even though the marine terrain effects are very small, except close to the coast (only terrain information on land was used, as marine terrain effects make little difference for land geoid applications).

The "restore" terrain quasi-geoid effects ζ_2 were computed by FFT methods on the basic 0.8' x 1.2' height grid.

The modified Stokes integral was evaluated by the multiband spherical FFT technique (Forsberg and Sideris, 1993), as implemented in the GRAVSOFT programme SPFOUR.

By addition of the three quasigeoid contributions (ζ_1, ζ_2, and ζ_3) the final quasigeoid is obtained, and subsequently converted to the final gravimetric geoid N in a grid by the formula for ζ-N. The end result is the OSGM02 gravimetric geoid.

2.3. The results of the gravimetric OSGM02 geoid computation

The small standard deviations of the residual gravity data shows that excellent smoothing has been obtained. It is apparent that the mean value in the mountains is not zero, as it should be. This is most probably due to the suspected errors in the EGM96 model. The gravimetric geoid model will take into account these biases.

From the reduced gravity data, a grid was made by least squares collocation, assigning standard deviations as follows:

Land gravity data: 0.5-1 mGal
Marine gravity data: 2 mGal
Marine gravity data interpolated from BGS grids: 3 mGal
Satellite altimetry: 5 mGal

A reduced gravity grid was predicted on a 0.8' x 1.2' resolution in latitude and longitude, corresponding to approximately 1.5 km, for the area 48°-62° N, 12°W-4°E.

The reduced gravity grid was subsequently converted to a reduced quasigeoid grid, using spherical FFT with 100% zero padding, transforming a basic grid of 2048 x 1600 data points. In the final solution Stokes' harmonics were 100% removed to degree 12, tapered to 0% at degree 15, as tests showed that the gravimetric geoid became significantly better the smaller the modification of Stokes' function. This is consistent with the assumed errors in EGM96, meaning that the local data "overrides" correctly the possible biases in EGM96 in the mountains of Scotland and northern England.

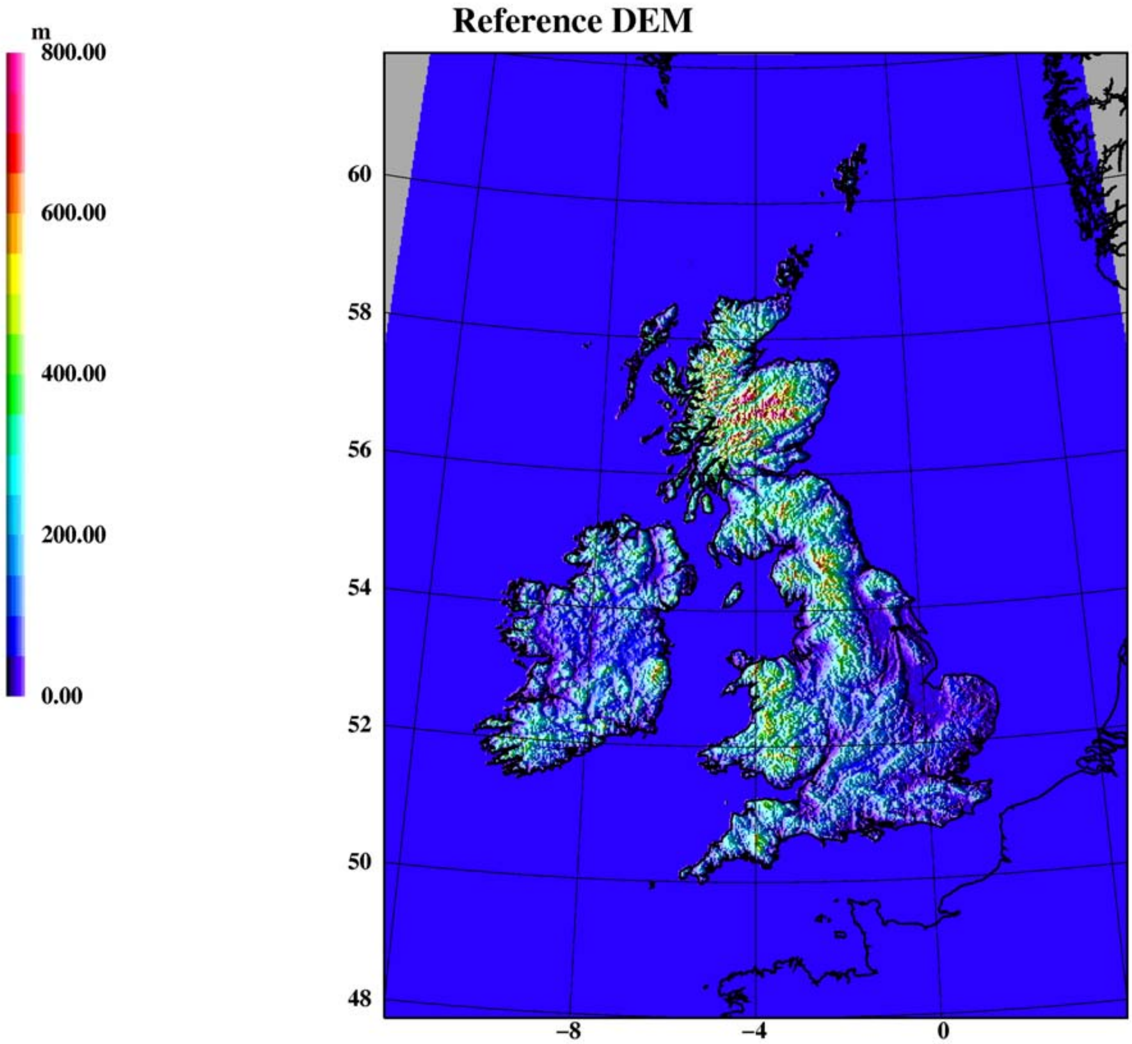


Figure 2.3.1: The 0.8’ x 1.2’ DEM of the British Isles, from merging OSGB, OSI, OSNI and Isle of Man heights.

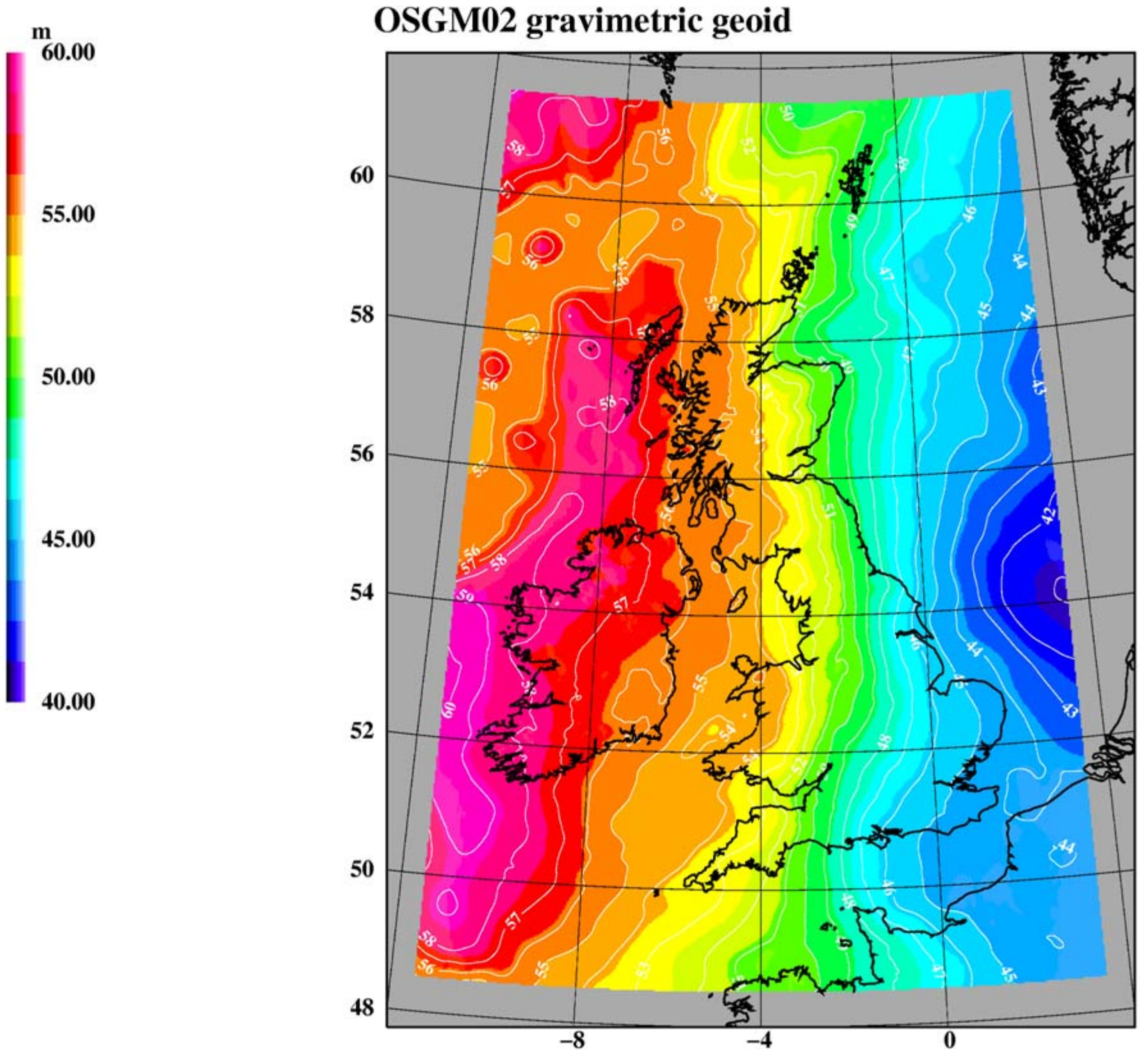


Figure 2.3.8: The final gravimetric OSGM02 geoid, referred to a global vertical datum.

3 Geoid fitting

3.1 Geoid fit methodology

The gravimetric geoid scheme provides an estimate of a geoid in a global datum. The GPS user is interested in geoids referring to a *local* datum such as Newlyn or Malin Head.

The purpose of the geoid fit step is to modify the gravimetric geoid to fit the local GPS control. For this control a GPS-levelling N-value may be obtained by

$$N_L = h - H$$

Here h is the GPS ellipsoidal height (in a national system, ideally ETRS89 consistent) and H the orthometric height in the local datum. The above equation will give an N_L-value which may be in error due to levelling errors or land uplift between the epochs of GPS and levelling. Fitting a gravimetric geoid to N_L-values may therefore no longer produce a geoid in terms of an equipotential surface, but rather produce a “height reference surface”, for use in GPS height conversion.

After a number of tests, it was decided to employ a rather “stiff” collocation interpolation surface with a fixed correlation length of 50 km. For the a priori standard deviations of N_L assumed values in the range from 2 cm (precise levelling) to 10 cm or more (some tertiary levelling on the islands, see below) means that the influence of the collocation interpolation is relatively small. One can therefore state that on the shorter wavelengths the OSGM02 geoid will be controlled by the gravimetric geoid, whereas on the longer wavelengths OSGM02 is controlled by the levelling.

Due to the different datums involved it was decided not to try and force one fitted geoid model over all the British Isles, but rather make the fitted geoids in “patches” covering mainland UK, Ireland and the various other island datums.

3.2 Summary of the GPS-levelling data supplied.

The raw information for fitting the gravimetric geoid consists of points where both GPS heights in ETRS89 and orthometric heights in the local datum are available.
Statistics and summary information for all data sets are summarised in Table 3.2.1 below.

Area	Via agency	Points	Datum	Comments
Republic of Ireland	OSI	133	Malin	Points supplied were a mixture of tertiary spirit levelling, trigonometric heighting and orthometric heighting from GPS block adjustment. 23 points were subsequently rejected from the data set.
Northern Ireland	OSNI	38	Belfast	Two points were rejected from the data set.
GB mainland	OSGB	179	Newlyn	All points at FBMs.
Inner Hebrides	OSGB	18	Newlyn*	Additional points supplied to compensate for sparse coverage in this area of the FBM network.
Outer Hebrides	OSGB	8	Stornoway	Points of varying quality, some of which had been levelled by trigonometric heighting.
Isle of Man	OSGB	3	Douglas	Points of varying quality, two of which had been levelled by trigonometric heighting.
Shetlands	OSGB	13	Lerwick	Points of varying quality, some of which had been levelled by trigonometric heighting.
Orkneys	OSGB	15	Newlyn*	Points of varying quality, some of which had been levelled by trigonometric heighting. One point had been rejected after discussion with OSGB.
St Kilda	OSGB	3	St Kilda	Points of varying quality, two of which had been levelled by trigonometric heighting.
Scilly Isles	OSGB	1	St Mary's	
Lundy	OSGB	0		No data supplied.

Table 3.2.1: Summary statistics for GPS/levelling points.

3.3 Fitting to GPS Points (main areas)

The estimated accuracies of OSGM02 for each regional vertical datum are included in table 3.3.1. The figures quoted assume precise ellipsoidal heights are used, for lower quality GPS observations additional error budget must be included.

Regional Datum	Standard Error (m)
Great Britain	0.02
Republic of Ireland	0.03
Northern Ireland	0.02

Table 3.3.1: Statistics of geoid fit for final OSGM02

3.4 Intra-datum relationship with the European (EVRS) datum

One area of future work is to determine the off-set of the Belfast and Malin datums to the European Vertical Reference System (EVRS) on the NAP (Normaal Amsterdams Peil) datum. In principle this can be done by establishing a link via the Newlyn datum. International sources such as *http://evrs.leipzig.ifag.de* (the home page of the EVRS) quote a relationship between EVRS and OSDN that gives heights in the United European Levelling Network (UELN) as being on average 0.02 m above Newlyn heights, with a range from 0.05 m below to 0.12 m above. However, this relationship between EVRS and Newlyn appears to be based upon establishing the link across the English Channel using a geoid model, and therefore cannot be regarded as definitive or reliable.

3.5 Island datums (and sub-datums).

3.5.1 The Orkneys

Orthometric height data for the Orkney Islands is related to the Newlyn datum, although in the course of this project it became apparent there are unacceptable inaccuracies in the links to the mainland. For this reason, the Orkneys have been treated by using a separate "patch" in the geoid fitting, effectively treating the datum in this area as separate from Newlyn.

The gravimetric geoid was then fitted to the tie points. The correlation length was again set to 50 km. Spirit levelled data points were given a priori weights of 50mm, trigonometric heighting points were assigned 100mm, and the points on Westray, Papa Westray and North Ronaldsay (after discussion with the Ordnance Survey) were de-weighted to 0.2m. The statistics resulting from this procedure are shown in Table 3.5.1.1.

Mean	Standard error	Minimum	Maximum
0.027	0.084	-0.092	0.199

Table 3.5.1.1: The Orkneys – statistics of geoid fit.

3.5.2 The Shetlands

Orthometric height data in The Shetland Islands is related to a datum established at Lerwick. Due to the fact that this datum is completely separate from the Newlyn datum, a separate patch was created for the Shetlands.

There were 13 points available in the data set for the Shetland Islands, with the orthometric heights obtained by both spirit levelling and trigonometric heighting.

Although the spread of values is wide, no individual outliers were identified, and therefore all 13 points were used in the fit. The EUROGAUGE point was constrained with an *a priori* sigma of 0.001m, and all other points were weighted at 0.03 m. The correlation length was 50 km.

Mean	Standard error	Minimum	Maximum
-0.003	0.030	-0.053	0.045

Table 3.5.2.1: The Shetlands – statistics of post-fit geoid fit.

3.5.3 The Outer Hebrides

Orthometric height data in the Outer Hebrides is related to a datum established at Stornoway. Due to the fact that this datum is completely separate from the Newlyn datum, a separate patch was created for the Outer Hebrides.

There were 8 points available in the data set for the Outer Hebrides, with the orthometric heights obtained by both spirit levelling and trigonometric heighting.

Mean	Standard error	Minimum	Maximum
0.008	0.088	-0.108	0.143

Table 3.5.3.1: The Outer Hebrides – statistics of geoid fit (m).

3.5.4 The Isle of Man

Orthometric height data on the Isle of Man is related to a datum established at Douglas. There were 3 points at which GPS and levelling data was available, and these were used to derive a correction surface.

Fitting was carried out using a 50 km correlation length, which over the area concerned was closely approximate to a similarity transformation. Of the three points used, two points found by trigonometric heighting were given weights of 0.100 m; the one point that had been spirit levelled was given a weight of 0.050 m.

The statistics of the post-fit residuals are shown in Table 3.5.4.1.

Mean	Standard error	Minimum	Maximum
-0.002	0.027	-0.028	0.025

Table 3.5.4.1: Isle of Man – statistics of geoid fit (m).

3.5.5 The Scilly Isles

Orthometric height data on the Scilly Isles is related to a datum established at St. Mary's. There was only one point at which GPS and levelling data was available.

From this single point, a simple shift of –0.71 m is derived.

Heights in the St. Mary's datum can therefore be determined by applying this shift to the gravimetric geoid.

3.5.6 St. Kilda

Orthometric height data for St Kilda is on a locally established datum. There were 3 points at which GPS and levelling data was available, and these were used to derive a correction surface.

Fitting was carried out using a 50 km correlation length, which over the area concerned was closely approximate to a similarity transformation. Of the three points used, two points found by trigonometric heighting were given weights of 0.100 m; the one point that had been spirit levelled was given a weight of 0.050 m.

The statistics of the post-fit residuals are shown in Table 3.5.6.1.

Mean	Standard error	Minimum	Maximum
0.006	0.055	-0.040	0.067

Table 3.5.6.1: St.Kilda – statistics of geoid fit (m).

3.5.7 The Inner Hebrides (and mainland Great Britain).

The main data set for Great Britain consisted of 179 points established at fundamental bench marks (not including Wicken FBM (1984), which had already been eliminated as an outlier), detailed in table 3.2.1. Although the Inner Hebrides are on the Newlyn datum, it was recognised that there were likely to have been problems associated with the links to separate islands, and it was also the case that no FBMs were present in the extreme west of the Scottish mainland. A strategy was therefore established to avoid the problems that would have resulted from an uncontrolled extrapolation of the fitting procedure westward to the Inner Hebrides.

This involved introducing a further 18 tie points in the Inner Hebrides (particularly on Mull and Skye) and on the western fringes of the mainland. A total of 197 points was therefore used.

In the next step, the gravimetric geoid was again fitted to the tie points. The correlation length was again set to 50 km, but on this occasion the weights applied were 0.05 m for all new points, and 0.02 m for the rest of the FBM points in Great Britain.

It is noted that the standard error, and the range from maximum to minimum values, have increased considerably when compared with the equivalent diagram and statistics for the solution that only used the fundamental bench marks. It is extremely important to note, however, that these statistics are essentially dominated by a localised effect in the region of the Inner Hebrides.

Mean	Standard error	Minimum	Maximum
-0.001	0.013	-0.080	0.048

Table 3.5.7.1: Great Britain including the Inner Hebrides – statistics of geoid fit.

3.6 Comparison with OSGM91

As the final correction surface for the mainland of Great Britain is the one derived in Section 3.5.7, where the gravimetric geoid was fitted to the FBM network and additional points in the Inner Hebrides and western highlands of Scotland, comparisons can now be made with the previous geoid model, OSGM91.

This was done by deriving geoid heights (or, more correctly, GPS-correction values) from the Grid InQuest software package, entering at several locations a height of zero above ETRS89 and using the resulting height below OSDN as the negative of the geoid height in OSGM91.

To gain an overall impression of the comparison between the two geoid solutions, values of OSGM91 and OSGM02 were derived on a 0.5° grid across the whole of the country. In general, the Grid InQuest package returns an error message if the location selected is outside the area of applicability. However, it was found in practice that values were obtained for some off-shore areas that were unlikely to have formed part of the solution when deriving OSGM91.

What follows therefore constitutes an initial examination of the differences between the two geoid solutions: more extensive editing of the results would be necessary to arrive at a definitive comparison.

For the whole of Great Britain, on the 0.5° grid, the mean value of δN is 0.004 m. This value is not significant given the discrete nature of the sampling. The standard error is 0.092 m, with a maximum and minimum of 0.336 and –0.234 respectively.

Topographic type	Lat.	W. Long	E. Long	Mean (m)	St. Dev (m)	Max. (m)	Min (m)
Highland	57°N	4°W	3°W	0.000	0.043	+ 0.065	- 0.061
Moorland	54°N	2°W	1°W	- 0.073	0.012	- 0.050	- 0.094
Fenland	52.5°N	0°W	1°E	0.024	0.013	0.040	- 0.005

Table 3.6.1: Values of δN along representative sections of latitude.

A full study was beyond the scope of this contract, but this area will doubtless be the subject of further academic study.

4 Conclusions

A new geoid model – OSGM02 – has been computed. This is the first time all the available high-resolution gravity and DEM data for the region has been fully utilised.

A gravimetric geoid model has been computed from 100m spaced DEM data and gravity data spaced approximately at 1.5 km. The model has been computed by remove-restore techniques, using spherical FFT and RTM prism integration, using EGM96 as reference field. The gravimetric geoid was computed rigorously as a quasi-geoid, then converted to a classical geoid consistent with the use of Helmert orthometric heights.

The computed gravimetric geoid model shows excellent fits to the UK fundamental network GPS-levelling data (32 mm r.m.s. after removal of a 4-parameter trend surface to model the long wavelength effects) as well as in Northern Ireland. In the Republic of Ireland and the UK islands less accurate results are obtained, most likely as a consequence of noisier GPS-levelling data used for comparisons.

The final OSGM02 model has been fitted to the available GPS-levelling data in patches corresponding to the different vertical datums (Newlyn, Malin Head, Belfast and minor island datums). The fits have been done with rather “stiff” collocation estimators, with correlation length of 50 km and assumed a priori standard deviations of the GPS-levelling at 2-10 cm. In this way a series of OSGM02 geoid patches have been obtained, reflecting at short distances the details and strength of the gravimetric geoid, and at longer distances the trends of the levelling networks.

The overall error of the final OSGM02 geoid surface is estimated at 2 cm r.m.s. in the UK and 3-4 cm r.m.s. in other areas, mainly limited by the accuracy of the GPS-levelling constraints.

It should be pointed out that the final OSGM02 geoid patches represent fits to local levelling networks, which are likely to have tilts due to systematic errors and land uplift. The OSGM02 geoid surfaces are therefore not equipotential surfaces.

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