OSGM15 and OSTN15:
Updated transformations for UK and Ireland

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OSTN and OSGM are the transformations that link 3D positions measured using GNSS with the national coordinate and height reference systems of Great Britain, Ireland and Northern Ireland. This article explains the background to the changes and presents OSTN15 and OSGM15, the latest transformations that incorporate new gravity data and iron-out discrepancies – mostly at the outer edges of the models.

The Ordnance Surveys of Great Britain (OS), Ireland (OSi) and Land & Property Services (LPS, formally Ordnance Survey Northern Ireland) have collaborated to improve the OSGM02 geoid model covering the UK and Ireland. The new model is OSGM15. OS has also updated the horizontal transformation grid for GB, OSTN02, to OSTN15. The horizontal transformation polynomial for Ireland and Northern Ireland is unchanged.

Coordinate systems and transformations

There are several coordinate systems in use across the UK and Ireland. The primary system for use with satellite positioning is ETRS89 (European Terrestrial Reference System 1989). As the name suggests, ETRS89 is for use over the whole of Europe and facilitates a standard coordinate system across the entire region. ETRS89 is realised and accessed through continuously operating reference station (CORS) networks – 'OS Net' in GB and 'Active GNSS stations' in Ireland and Northern Ireland.

Mapping data is on more "traditional" datums – OSGB36 National Grid in GB and Irish National Grid in Ireland and Northern Ireland. Similarly height data is related to mean sea level based datums – ODN (Ordnance Datum Newlyn) plus island specific datums in GB, Belfast datum in Northern Ireland and Malin Head datum in Ireland. So, to get from/to ETRS89 and the mapping datums a coordinate transformation is required and a geoid model is required to transform heights.

In GB the mapping transformation is a grid look-up model. OSTN15 covers the whole of GB at 1km resolution with a set of transformation shifts (Δeastings, Δnorthings) at each intersection. Bi-linear interpolation of the values from each corner of a km square is used to compute the transformation shifts at a specific point.

In Ireland and Northern Ireland the mapping transformation is expressed as Δlatitude and Δlongitude via a third order polynomial.

The geoid model OSGM15 is common across the whole region. In Ireland and Northern Ireland there are two separate files, based on a latitude/longitude graticule, one for Malin datum and the other for Belfast. In GB the OSGM15 offsets are incorporated into the OSTN15 1km grid with an additional flag parameter to indicate the height datum they relate to.

Strictly speaking OSGM15 is not a true geoid model, but is rather a 'height corrector surface' since the gravimetric geoid surface has been fitted to the local sea level based datums. However, it is common practice for such models to be referred to as "geoid models" so the "GM" is retained.

Reasons for the updates

There were two main drivers for the change in the models – an improvement to the realisation of ETRS89 across the region and an improvement to the gravity data and fitting of the OSGM geoid model.

There is now, for the first time, a homogeneous, "zero order", realisation of ETRS89 across the whole region. This is from the "EUREF IE/UK 2009" GNSS campaign, which has been ratified (by "EUREF" a sub-commission of the International Association of Geodesy) as the official extension of ETRS89 across the UK and Ireland. The reason for EUREF IE/UK 2009 was that in GB a number of the original ETRS89 stations from the earlier EUREF GB 2001 definition had been lost, so, whilst some of the original stations still remained for continuity, it was decided to build a purpose designed zero order network of 12 new points. In Ireland and Northern Ireland the ETRS89 realisation had not been submitted to EUREF for ratification. So, it made sense to combine the campaign for the whole region.

The update to ETRS89 required an update to the OSTN transformation to minimise the change in OSGB36 coordinates. This by itself, would have also required a small update to the OSGM geoid model, but in GB the OSGM02 model also required improvement in its fitting to the height datum in the Scilly Isles, north-west Scotland and also on the Scottish islands especially the Outer Hebrides. The data in the west of Ireland required improvement post OSGM02. Also, additional gravity data from the GRACE (Gravity Recovery And Climate Experiment) satellite mission was available to be incorporated into the gravimetric model.

Update to ETRS89 realisation

The EUREF IE/UK 2009 campaign realised a new ETRS89 across the whole region resulting in 12 zero order stations in GB, 10 in Ireland and 6 in Northern Ireland. The stations in the campaign are shown in Figure 1.

The final accuracy of the new stations is 2mm horizontal and 6mm vertical.

In GB the updated coordinates have been used as fiducial stations for a complete recomputation of the OS Net stations. This is the first time that OS Net has been computed as a whole network since 2001 (when it was simply the "Active GPS Network"). The re-computation has also made use of the latest absolute phase centre offsets models for both terrestrial and satellite antennas. Table 1 shows the differences between the new and old OS Net coordinates.

Table 1. Differences (in m) between old and new OS Net coordinates.

	East	North	Up	2D
Min	-0.025	-0.010	-0.050	0.002
Max	0.030	0.021	0.053	0.034
RMS	0.015	0.008	0.018	0.017

The 2D differences between old and new coordinates for Active stations in Northern Ireland are shown in Table 2.

Table 2. 2D coordinate changes (in m) for Northern Ireland stations.

Station	2D coordinate change
BELF	0.007
ENIS	0.009
FOYL	0.007
KLRE	0.017
MRKT	0.023
OMGH	0.014

Since the ratification of the EUREF IE/UK 2009 coordinates, LPS has installed four new reference stations, which were not included in the campaign; Queen's University (QUB1), Thomastown (THMS), Ballypatrick (BPTK) and Bangor (BNGR). Unfortunately the original Belfast station (BELF) has since been destroyed. All the new stations have been processed against the original fiducials so are aligned to the EUREF IE/UK 2009 realisation of ETRS89.

OSTN upgrade

OSTN02 was aligned to the older EUREF GB 2001 realisation of ETRS89. OSTN15 has been aligned to the EUREF IE/UK 2009 realisation of ETRS89 by applying a transformation to the OSTN transformation data set ETRS89 coordinates to shift them to the new ETRS89 realisation. The transformation was computed from common points in both EUREF campaigns.

Table 3 shows the expected differences between OSTN02 and OSTN15. These were computed by passing the same OS Net station coordinates through each transformation. Table 4 shows the expected final impact on user generated OSGB36 coordinates by comparing the old OS Net coordinates passed through OSTN02 with the new ones passed through OSTN15.

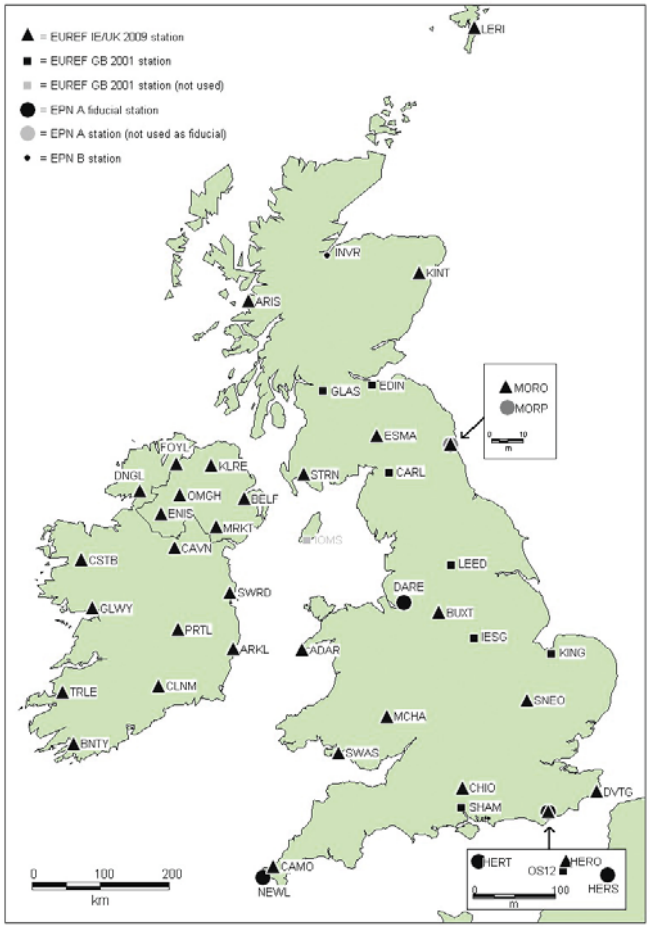

***Figure 1**. EUREF IE/UK 2009 stations*

Table 3. Differences (in m) between OSTN02 and OSTN15.

	East	North
Min	-0.017	-0.009
Max	-0.006	0.002
RMS	0.012	0.004

Table 4. Differences (in m) old OS Net + OSTN02 and new OS Net +OSTN15.

	East	North
Min	-0.037	-0.015
Max	0.019	0.018
RMS	0.009	0.007

The format of the OSTN15/OSGM15 transformation parameter file is unchanged from OSTN02/OSGM02. The main difference between the two files, apart from the updated parameters, is that the inbuilt 10km offshore cut-off in OSTN02/OSGM02 has been removed from OSTN15/OSGM15. In OSTN02/OSGM02 transformation parameters beyond 10km offshore were set to zero. The OSTN15/OSGM15 transformation grid is fully populated.

The on-shore parameters are computed from the OSTN dataset of over 4,200 points with an observed difference between OSGB36 and ETRS89. A Triangulated Irregular Network (TIN) is fitted to the dataset to express the datum shifts as "surfaces" (one for east shift and another for north). The 1km transformation grid is overlaid onto the surfaces and the transformation parameters at

each km intersection are interpolated.

The accuracy of the onshore transformation remains the same as it was for OSTN02. Within Great Britain, OSTN15 defines OSGB36. I.e. OSTN15 in combination with the ETRS89 coordinates of the OS Net stations, rather than the fixed triangulation network, define the National Grid. This means that, for example, the National Grid coordinates of an existing OSGB36 point, refixed using GNSS from OS Net and OSTN15, will be the correct ones. The original archived OSGB36 National Grid coordinates of the point (if different) will be wrong, by definition, but the two coordinates (new and archived) will agree on average to better than 0.1m (0.1m rmse, 68% probability). Out from the GB landmass the offshore parameters are based on an extrapolation of the TIN using boundary points outside the grid created from a seven parameter "Helmert" style transformation between ETRS89 and OSGB36. So, the accuracy of OSTN15 degrades from 0.1m to the 3m level as the transformation is extrapolated from the land based core dataset and is increasingly based instead on the simpler seven parameter transformation.

The removal of the 10km cut-off means a transformation is now available across the whole area within a single application. Previously, users would have to switch to the seven parameter transformation at the 10km boundary. Of course having the transformation available across the whole area does not mean it should be used everywhere. So, there is now an inbuilt transformation "boundary" based on the UK EEZ line (**https://en.wikipedia.org/wiki/Exclusive_economic_zone#United_Kingdom**), see Figure 2. Parameters beyond this line are flagged as datum number 16, "Outside transformation area" as a warning to users that they have passed the "sensible" boundary beyond which the transformation should not be used.

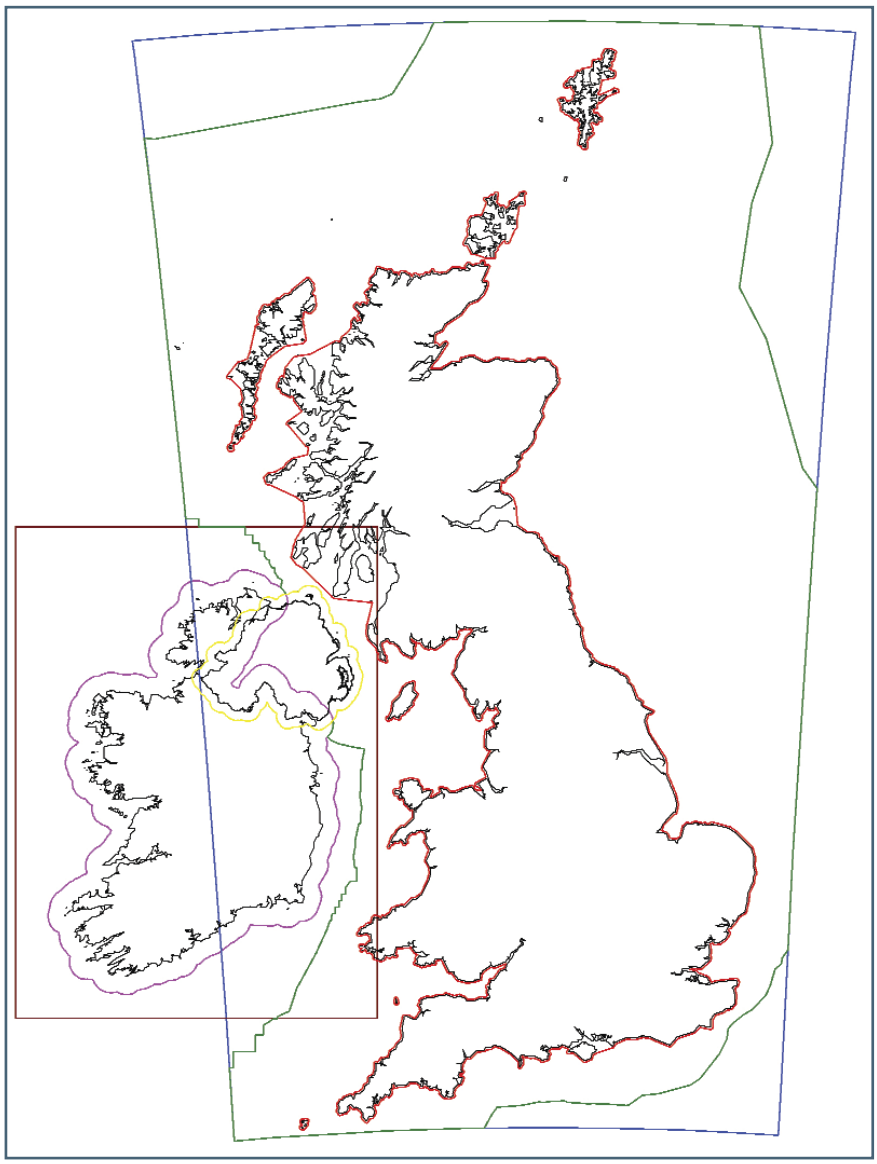

Figure 2. Map of transformation extents.

- = Extent of Irish OSGM15 files
- = Extent (10km buffer) of Belfast OSGM15 datum built into OSGM software
- = Extent (20km buffer) of Malin OSGM15 datum built into OSGM software
- = Extent of OSTN15/OSGM15 file
- = Extent of OSGM15 "Newlyn Offshore" datum (flag 15)
- = Extents (2km buffer) of Great Britain OSGM15 land based datums: Newlyn, St Marys, Douglas02, Stornoway15, Lerwick, Newlyn (Orkney)

OSi/LPS Polynomial Transformation

In Ireland and Northern Ireland analysis of the changes to the ETRS89 realisation following the EUREF IE/UK 2009 campaign showed that a recomputation of the OSi/LPS Polynomial Transformation was not necessary. The changes observed were not significant enough to warrant adjusting the transformation and so it remains the same.

OSGM upgrade – OSGM15 in GB

OSGM02 was fitted to the height datums in GB via observed geoid separations at benchmarks. The majority of these observations on the GB mainland for fitting to ODN were from a single campaign ("The FBM Project") and were aligned to a different realisation of ETRS89 than the one used for OS Net coordinates. OSGM15 is now aligned to the same realisation as OS Net (from the EUREF IE/UK 2009 campaign) via transformations based on common points in the FBM Project campaign and old OS Net coordinate set. The realignment has resulted in approximately a 0.025m shift in the vertical.

Table 5 shows the expected differences between OSGM02 and OSGM15 and also the accuracies of the OSGM15 datum realisations. The variation of the differences across Great Britain are shown spatially in Figure 3.

A much better fit to ODN has been achieved in north-west Scotland and to the local height datums of the Islands by researching and surveying new benchmarks. A great contribution to the selection of suitable new

points came from extensive research carried out by the late John Hallam, formerly of BGS.

On the Stornoway datum for the Outer Hebrides, OSGM15 now achieves a smoother and consistent fit along the whole island chain and is more closely aligned to the datum mark in Stornoway. However, this has resulted in a bigger jump from OSGM02 heights in the southern part of the island chain.

On the Scilly Isles, St Mary's datum the previous fit of OSGM02 was to just one point which was not on St Mary's island. OSGM15 is fitted to two new points on St Mary's island and is therefore more closely aligned to the local datum. This has resulted in a height change of approximately 0.35m.

In OSGM02 the Newlyn (ODN) datum extended up to the 10km offshore boundary imposed in the file. In OSGM15 ODN extends to 2km offshore. Since the gravimetric geoid is computed for the whole 700km × 1250km OSTN15/OSGM15 area, but is of course just fitted to Newlyn on the GB mainland – anything offshore is considered an extrapolation of ODN. So, beyond the 2km line this datum is now flagged as "Ordnance Datum Newlyn (Offshore)" to indicate the extrapolated Newlyn datum. Figure 2 shows the transformation extents.

OSGM02 contained some datums for small islands off the north and west of Scotland – Fair Isle, Flannan Isles, North Rona, Sule Skerry and Foula. All these island datums were fitted using single points and testing against OSGM15, which showed that their historic datums were poorly defined so they have been removed from the model. The St Kilda datum has also been removed for the same reason. In OSGM02 the fit on St Kilda was based on three points of varying quality fitting to an assumed mean sea level of unknown origin. OSGM15 highlighted a large discrepancy between the fitted St Kilda surface and both the gravimetric geoid and the fitted ODN surface. In OSGM15 heights in these areas now come from the ODN fitted geoid and are flagged as "Ordnance Datum Newlyn (Offshore)".

To avoid steps in the model where an island datum meets Newlyn (Offshore) each island had a 15km buffer placed around it in addition to the 2km cut off for the island's datum. In the zone between the two buffers a custom surface was fitted between the island datum at 2km and Newlyn (Offshore) at 15km – this achieves a gentle transition from one datum to the other. The transitions were checked by sampling cross-sectional profiles for both the island datum, the underlying Newlyn (Offshore) datum and the interpolated sections. An example profile for the Shetlands is shown in Figure 4.

As a consequence of the loss of some datums and the addition of new ones, the OSGM15 datum flags in the file are changed from OSGM02. Where a datum flag was used in OSGM02 the flag value is the same in

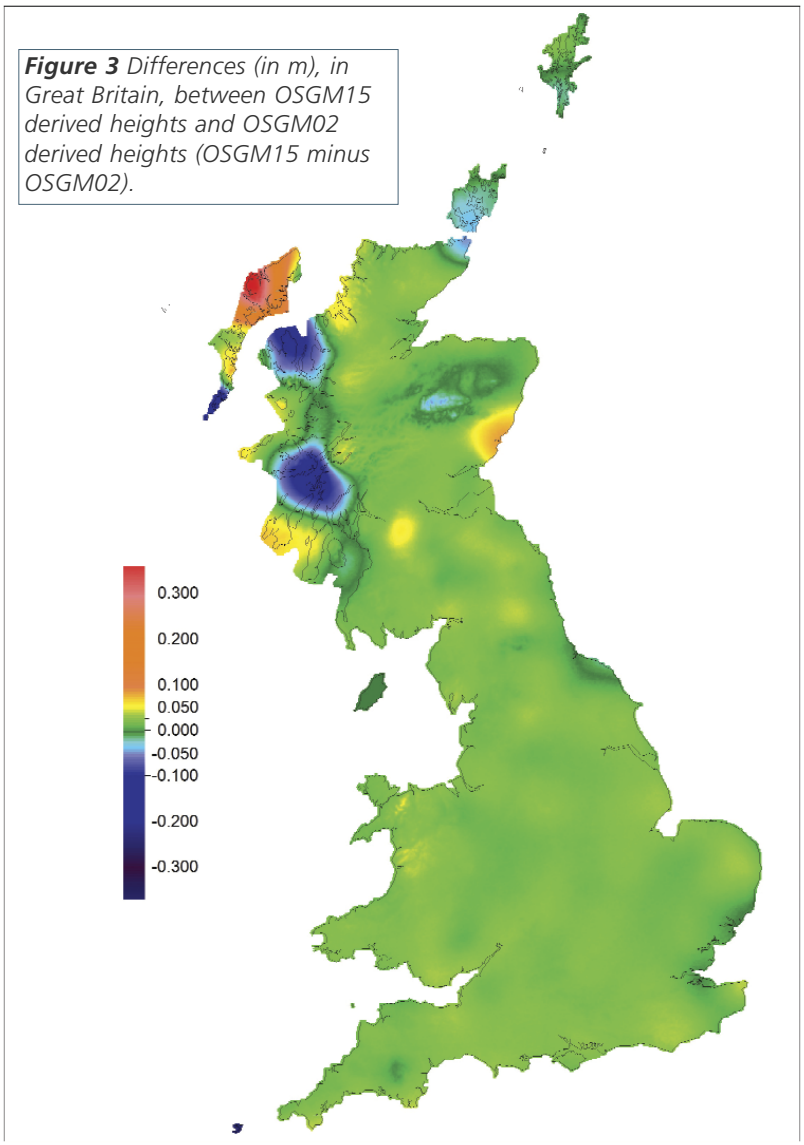

Figure 3 *Differences (in m), in Great Britain, between OSGM15 derived heights and OSGM02 derived heights (OSGM15 minus OSGM02).*

Table 5. Differences (in m) between OSGM02 and OSGM15 in GB and also accuracy values of OSGM15.

Datum:	Newlyn	St Marys	Douglas02	Stornoway15	Lerwick	Newlyn (Orkney)
RMS difference:	0.026	0.365	0.000	0.175	0.013	0.021
Accuracy:	0.008	N/A single offset		0.030	0.011	0.018 0.017

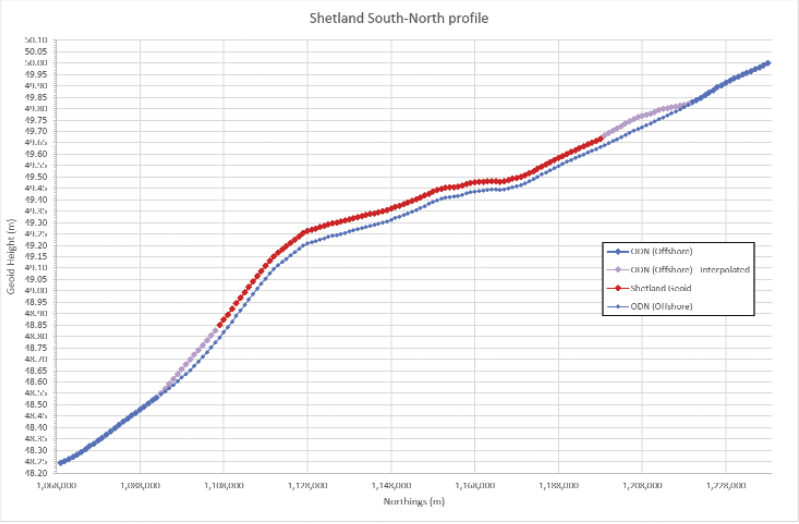

Figure 4*. Example cross section used to check height datum transition.*

OSGM15. Flags in OSGM15 are:

1 = Ordnance Datum Newlyn, UK mainland.
2 = St Marys datum, Scilly Isles.
3 = Douglas02 datum, Isle of Man.
4 = Stornoway15 datum, Outer Hebrides.
6 = Lerwick datum, Shetland Isles.
7 = Newlyn (Orkney), Orkney Isles.
15 = Ordnance Datum Newlyn (Offshore) – new flag in OSGM15.
16 = Outside transformation area – new flag in OSGM15.

The following flags from OSGM02 are no longer used:

0, Outside model boundary.
5, St Kilda.
8, Fair Isle.
9, Flannan Isles.
10, North Rona.
11, Sule Skerry.
12, Foula.

OSGM upgrade – OSGM15 in Ireland and Northern Ireland

Table 6 shows the differences between OSGM02 and OSGM15 in Ireland and Northern Ireland.

Table 6. Differences (in m) between OSGM02 and OSGM15 in Ireland and also accuracy values of OSGM15.

Datum:	Malin Head	Belfast
RMS difference:	0.093	0.018
Accuracy:	0.023	0.014

The differences between OSGM02 and OSGM15 on the Malin datum can be largely attributed to improvements in the extreme West of Ireland. The difference between the OSGM02 model and the OSGM15 model in Ireland is, on average, at the less than the 2cm level. However, the new model in some places contains significant variations. An area around Leitrim/Cavan/Monaghan contains differences around the 20cm level, while the most pronounced differences occur in the most Westerly parts of Galway and Mayo. These differences are higher than expected given the accuracy of the models and to give further assurance of the validity of these changes OSi observed some further test points targeted specifically in these areas.

There is a correlation between these areas and the density of the terrestrial gravity data that was used in the OSGM02 model. The improvement to the gravitational geoid model in these areas can be attributed in part to the new gravity field data now available from the GRACE mission. In addition much of the available orthometric height data in the extreme West is of a lower standard having been derived from a transformation from Poolbeg datum to Malin datum rather than by spirit levelling. These effects combine to produce significant deviations between the 2002 and the 2010 models.

The raw OSGM15 data for Ireland is released as two files – one for Belfast datum and the other for Malin datum. Within the updated transformation software limits have been placed on the extents of the datums. Belfast extends 10km offshore and into Ireland and Malin extends 20km offshore and into Northern Ireland. See Figure 2.

Availability of new models

All the transformations have been coded into a software application – "Grid InQuest II", which allows for individual coordinate input and output via a GUI and also batch input/output via text files. A command line interface and dll, along with examples of their use in a variety of programming languages, are also included. Users wishing to incorporate the pre-prepared .dll into other applications should refer to the Grid InQuest II user guide. Grid InQuest II download packages for Windows (32 bit and 64 bit), Linux (32 bit and 64 bit) and OSX are available from **https://bitbucket.org/PaulFMichell/gridinquestii**

The raw data files have been released to software and equipment vendors. Any developer wishing to request the raw data files should contact one of the following:
Ordnance Survey (GB): **GeodeticEnquiries@os.uk**
LPS: **peter.downie@finance-ni.gov.uk**
OSi: **control@osi.ie**

The new models and updated coordinates of the national CORS networks will be available by August 26th 2016 and website transformation tools will also be updated at this time. A tool will also be available to allow coordinates and heights from the OSTN02/OSGM02 models to be converted to OSTN15/OSGM15 values by first back transforming to ETRS89, via OSTN02/OSGM02, and then forward transform through OSTN15/OSGM15.

The EPSG Geodetic Parameter Dataset maintained by the International Association of Oil & Gas Producers (IOGP) has been updated to give new EPSG codes to the OSTN15 and OSGM15 models. EPSG codes are commonly used to uniquely identify datums, projections, transformations etc especially within GIS systems. E.g. OSGB36 datum can be referenced as EPSG::27700.

Concluding remarks

The coordinate, transformation and geoid model updates bring improved accuracy and homogeneity of the ETRS89 realisation and mapping coordinates and height datums to users across the whole region. Increased compatibility of data is also a benefit for initiatives such as INSPIRE.

"…improved accuracy and homogeneity of the ETRS89 realisation and mapping coordinates and height datums to users across the whole region."