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A Note on Geographic Systems and Maps of Montserrat, West Indies

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Abstract

It is often critically important that geospatial data are measured and mapped accurately, particularly for quantitative analyses and numerical modelling applications. Defining a geographic coordinate system requires a non-unique combination of geodetic techniques (e.g. ellipsoids, projections and geoids). The choice of geographic system presents scope for ambiguity and confusion about geographic data, especially those archived without appropriate metadata. Experience has shown that these confusions have been a repeating source of either frustration or inadvertent error for those using geographic data from Montserrat. This is, in part, probably due to common usage of multiple datums and the existence of numerous topographic data sets recorded during the past 150 years. Here, we attempt to provide a brief introduction to geodetic principles and their application to Montserrat geographic data. The differences between common datums are illustrated and we describe variations in magnetic declination as they apply to field use of magnetic instruments. We include a record of the source of the large-scale mapping data sets that have been used and analysed ubiquitously in the literature. The descriptions here are intended as an introductory reference resource for those using geographic data from Montserrat.

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Abbreviated Title: Montserrat Geographic Systems & Maps

Accurate mapping is essential in most areas of geoscience. To understand geospatial data we adopt coordinate systems in which we are able define position and velocity. However, the choice and specification of the coordinate system is not unique and, over the centuries, geodesists have derived a multitude of methods for describing three-dimensional (3D) geographical data. Commonly, this invokes the use of a reference ellipsoid, which models the approximate shape of the Earth's surface; a projection, which translates that ellipsoid into two dimensions (2D); and sometimes a specific reference surface from which height is measured (e.g. sea level). Confusion between different coordinate systems can be – and has been on occasions – a source of significant error when using and comparing geospatial data. The explanations and data given here include a brief summary of the most commonly used systems on Montserrat. Descriptions and derivations of various ellipsoids, geoids and projections are widely available elsewhere (e.g. Robinson *et al.*, 1995). Specifications are also provided here to assist configuration of field tools such as handheld GPS receivers. A summary of the changes in magnetic declination for Montserrat since 1995 is also included. The information herein is intended purely as a practical introduction for those using geospatial data from Montserrat, not as an exhaustive description of cartographic methods.

1. Ellipsoids, Projections and Geoids

There exists a plethora of simple geometrical ellipsoidal models that approximately describe the shape of the Earth. An ellipsoid's shape and size is defined by the lengths of its three mutually perpendicular radii. A *geodetic* ellipsoid is symmetrical around its polar axis such that its shape may thus be defined by just two parameters: the equatorial and polar radii (a and b, respectively). These may be given explicitly or via a flattening factor, f, that relates a to b, where $f = (a-b)/a$. Flattening is also often cited in inverse form: $1/f$. The origin (centre) of any two ellipsoids may be offset in space. An ellipsoid may thus be described by five parameters: the offset of its origin from the Earth's centre of mass (dX, dY and dZ – see Figure 1); the equatorial radius; and either the polar radius or the flattening factor. In some cases, additional parameters may be required (e.g. coordinate axis rotation), but this will not apply herein. Ideally, an ellipsoid would approximate mean sea level (or, more specifically, the geoid – see below) on a global scale. However, this is not the case due to the unevenness that means even globally-defined ellipsoids can vary from mean sea level by over 100 metres in some regions. Accordingly, this has given rise to many different ellipsoid definitions, with models often optimised to fit sea level well over a particular geographical region.

Adopting an ellipsoid as a simplified geometrical representation of the Earth allows for geometrical translation of features on the surface of that ellipsoid onto a 2D plane (i.e. a map). However, in performing such translations (projections), geometrical relationships (e.g. distance, azimuth, shape, area, etc.) cannot *all* be fully preserved on any single map. The method for projecting information from the ellipsoid onto a map thus depends on which properties takes precedence and requires the according compromises. Numerous projections exist, but focus is given here only to those in common use on Montserrat. The Transverse Mercator (TM) method offers a suitable strategy for map projection on Montserrat and is described in brief in the next section. For small areas, such as Montserrat, distortions due to the curvature of the ellipsoid can usually be neglected. It is notable, however, that such assumptions may be inappropriate for precision applications (e.g. ground deformation surveying).

A geoid is an equipotential surface that closely aligns with mean sea level around the globe – typically to within a couple of metres of local mean sea level – and can be measured through precise gravitational surveying. Unlike an ellipsoid, the geoid is complex in its shape, with undulations caused by the heterogeneous distribution of mass around the Earth. Recent geoid models have been derived using a combination of data from spaceborne gravity surveys (e.g. GRACE and GOCE). The geoid offset for a specific location – given as the vertical offset between the geoid model and an ellipsoid – may be computed using published model spherical harmonic coefficients or interpolated from gridded geoid data (NGA, 2012).

2. Datums Used On Montserrat

For reasons discussed below, the two most commonly used ellipsoids are the Clarke 1880 and World Geodetic System 1984 (WGS84) ellipsoids. Geographic coordinates are usually expressed either in terms of geodetic latitude and longitude (in degrees) or via a TM projection. Heights are measured relative to a vertical reference surface – usually the ellipsoid or, sometimes, a geoid model. It is important to be sure that a common datum (the combination of ellipsoid, projection *and* vertical reference) is used when considering multiple spatial datasets. Similarly, it is critical that the implications of the projection (i.e. distortion) are considered in analyses where spatial data are manipulated or analysed quantitatively.

Pre-eruption maps of Montserrat are derived from aerial photographs acquired in the 1950s on behalf of the British Government's Directorate of Overseas Surveys (DOS, 1983). The map data derived from these surveys were plotted using the Clarke 1880 ellipsoid and either geodetic coordinates or a customised metric TM projection, referred to herein as the British West Indies (BWI) grid. This datum is used by the Government of Montserrat Lands and Survey Department and was initially adopted by staff and colleagues at the Montserrat Volcano Observatory (MVO; e.g. Kokelaar, 2002). In recent years, the use of the WGS84 and Universal Transverse Mercator (UTM) datum has become more prevalent for representing data gathered on Montserrat as it provides a standardised approach to referencing geographic data. The following summaries describe these systems and appropriate parameters are given in Tables 1 and 2.

2.1 Earth-Centred Earth-Fixed Coordinates

Positions given in Earth-Centred Earth-Fixed (ECEF) coordinates refer to a 3D Cartesian coordinate system, with its origin at the Earth's centre of mass (the WGS84 origin, as shown in Figure 1) and axes aligned as follows: the Z axis is approximately aligned with Earth's axis of rotation (the International Earth Rotation Service, IERS, Reference Pole). The X axis is perpendicular to Z and passes through the IERS Reference Meridian (near the Greenwich Meridian), and the Y axis is mutually perpendicular to Z and X (NIMA, 2004).

Values of position, distance, angle and velocity can be defined explicitly and unambiguously in this system without the need of a reference surface or projection. This can be advantageous when handling position or velocity data outside of a geographic context, as there is no distortion due to projection. However, ECEF coordinates bear no intuitive relation to other features on the Earth and are often not useful for cartographic or geographic applications.

2.2 Ellipsoids

Two ellipsoids have been used predominantly in mapping Montserrat over the past century: the WGS84 ellipsoid and the more region-specific Clarke 1880 ellipsoid. Geodetic coordinates (degrees of latitude and longitude) can be used in conjunction with any ellipsoid but a given position will mark a different position on the ground, depending on the ellipsoid used.

In recent decades, the WGS84 ellipsoid has become an international standard for geodetic applications, against which other systems' parameters are conventionally referenced. The origin of the coordinate system (Figure 1) is taken as the Earth's centre of mass, measured and updated using satellite and orbital measurements, and is coincident with the ECEF origin. The WGS84 ellipsoid was devised as an approximate fit to the global mean sea level (via the geoid), and thus typically results in regional deviations of many tens of metres. The WGS84 ellipsoid reference surface is around 41 m above sea level near Montserrat (Figure 2), for example. Due to changes in the location of the Earth's centre of mass and the accuracy with which it can be measured, the WGS84 has undergone several revisions since it was first realised. While the differences between versions are small – usually negligible for navigation purposes, for example – they can be significant for precision surveying applications.

The Clarke 1880 ellipsoid differs in both shape (more oblate) and origin (offset by about 540 m) from the WGS84 ellipsoid (Table 1, Figure 1). The Clarke 1880 ellipsoid surface is about equivalent to sea level in the Lesser Antilles region and the British Ordnance Survey adopted it for 20th Century mapping work. Significant horizontal and vertical offsets can exist between coordinates referenced to the Clarke 1880 ellipsoid versus the WGS84 ellipsoid. For example, a point in Montserrat defined by geodetic coordinates (lat./ long.) on the Clarke 1880 ellipsoid would be about 400 m northeast of the point with the same coordinates on the WGS84 ellipsoid. The offset is due to the difference in ellipsoid shape and origin and the exact difference depends on the three-dimensional position of the point in question. Furthermore, the vertical difference between the two ellipsoids also varies spatially. In Montserrat, the offset is around 38 m (WGS84 is higher); variations are illustrated in Figure 2. These examples highlight the importance of explicit datum referencing to avoid position ambiguity or errors.

2.3 Projections

The common map projection employed for Montserrat is the TM projection. The TM method figuratively uses a cylinder, wrapped around the ellipsoid, with its central axis parallel to the ellipsoid's equatorial plane. The great circle at which the ellipsoid meets the cylinder is the 'central meridian' on the ellipsoid. The projection is then performed by 'unwrapping' the cylinder from the ellipsoid, translating features on the ellipsoid onto a 2D plane (see illustrations by Robinson *et al.*, 1995). Distortion caused by this type of projection is minimised along the chosen central meridian and it is therefore ideal to select a central meridian close to the region of interest. Northing and Easting coordinates may then be measured, in units of length, eastward from the central meridian and northward from the equatorial plane, respectively. Often, an arbitrary offset is applied to the Easting coordinate so that positions west of the central meridian do not have negative values. TM projections can thus be readily tailored to specific cartographic requirements, as desired, and can be applied to any ellipsoid. The BWI grid is an example of a TM projection used for mapping parts of the West Indies region (e.g. DOS, 1983), typically in conjunction with the Clarke 1880 ellipsoid (Table 2).

The UTM system is a series of standardised TM projections that cover the globe in a series of sixty numbered 'zones'; each zone has its own central meridian, spaced six degrees of longitude from the next zone. Any position in the world can be identified by values of Easting, Northing and UTM Zone number, and whether the point is in the northern or southern hemisphere. Subdivision of latitudinal zones in the UTM system (denoted by letters) is somewhat redundant as long as the hemisphere is specified. The UTM system uses the WGS84 ellipsoid (Table 2). Montserrat falls within UTM Zone 20Q (also 20-North or 20N – the latter raising ambiguity with latitude Zone N).

It is notable that the choice of TM projection does not inherently define the vertical reference surface (ellipsoid or geoid) against which elevation is measured. However, two common pairings have generally been used on Montserrat: the Clarke 1880 ellipsoid with BWI TM grid *or* the WGS84 ellipsoid with UTM grid.

2.4 Geoids & 'Sea Level'

The Earth Gravitational Model 1996 (EGM96; NGA, 2012) is used as the reference geoid for the WGS84. Earlier and more recent geoid models exist, with varying sophistication and accuracy. The WGS84 geoid provides a separate alternative as a standard vertical reference surface with the attraction that it is, by definition, close to the average ocean surface level. Figure 2 shows the vertical offset of the WGS84 EGM96 geoid from the WGS84 ellipsoid around Montserrat. The geoid has not generally been used as a vertical reference for Montserrat geographic data owing partly to the additional complexity of computing or interpolating geoid offsets (e.g. Figure 2). However, it is necessary to recognise that multiple vertical datums exist in the WGS84. Heights referenced to the geoid (EGM96) are often used for larger-scale mapping and/or spaceborne surveying such as the Shuttle Radar Topography Mission (SRTM) global topography model. A third convention for measuring topographic height is mean sea level. Sea level can be measured using one or more tide gauges in the area of interested. Commonly, however, heights given 'above sea level' (asl) refer directly to the geoid height (NIMA, 2000). This introduces ambiguity in the use of the term 'sea level'. There are currently no reference tide gauge sea level measurements on Montserrat.

2.5 Maps of Montserrat

The most widely available published map of Montserrat (DOS, 1983) is referenced to the Clarke 1880 ellipsoid and has coordinates expressed in the BWI TM grid (Easting and Northing, in metres, height in feet) and in geodetic coordinates (latitude and longitude, in degrees and minutes). DEMs derived from this map (described later), along with various archived georeferenced data from Montserrat, use the same system. Since about 2009, MVO have adopted the WGS84 ellipsoid as a reference and use the UTM grid (Zone 20Q, Easting and Northing in metres, ellipsoidal height also in metres). Datum parameters (given in Table 2) may be used to correctly configure instruments, such as handheld GPS receivers, and software appropriately.

3. Converting Between Coordinate Systems

It is often desirable or necessary to convert geospatial data from one coordinate system to another. For example, quantitative analyses might be performed using ECEF coordinates and then converted to geographic coordinates for visualisation. Conversion formulae are derived from the geometrical form of each reference system, and are described widely in the literature. There also exist numerous programs and web-based tools for performing coordinate transformations. The software tools named here do not represent an exhaustive list of available options but are given as a starting point. A comprehensive database of reference systems is maintained online by Butler *et al.* (2012).

The ArcGIS software package (ESRI, Redlands, California) and open source equivalents (e.g. QGIS; www.qgis.org) are popular and powerful interfaces for handling and manipulating geospatial data. Such data may be explicitly assigned to a map datum and the software is generally capable of relating or converting data between multiple coordinate systems. ArcGIS and many similar programs use the Geospatial Data Abstraction Library (GDAL, 2012) to perform datum translations. GDAL may be freely downloaded and used as a standalone, multi-platform program. Programs such as GDAL and proj (Evenden, 2003) perform command-line and batch-mode conversion that allows straightforward incorporation into other programs and scripts. Coordinate systems are often indexed using a unique European Petroleum Survey Group (EPSG) code, as listed by Butler *et al.* (2012) and in Table 2. The following example command uses the 'cs2cs' command in proj to convert a position on Montserrat (near the volcanic vent) from Clarke 1880 BWI TM to WGS84 UTM 20Q coordinates:

Input:

```
cs2cs +init=epsg:2004 +to +init=epsg:32620
380915      1847084     700
```

Output:

```
587842.27   1847829.34  661.98
```

In this example, EPSG codes (Table 2) are used as shorthand for the two map datums. Datum parameters and other details (such as output precision) can be specified explicitly and input values can be typed (as in this example) or given as an input file. Extensive documentation is available for these and other conversion programs and the reader is directed there for further information.

4. Digital Maps of Montserrat

Digital Elevation Models (DEMs) are grids, rasters or point files containing topographic height information. They are an extremely useful resource for many geospatial applications. In the context of Montserrat, DEMs have been essential for measuring topographic changes during the Soufrière Hills Volcano (SHV) eruption as well as for providing constraint on numerical models of eruptive processes. The following descriptions briefly document the origin of large scale Montserrat DEMs that have been widely used by the volcanology community.

The British Ordnance Survey's Directorate of Overseas Surveys (DOS) used photogrammetric survey data – collected in the mid 20th Century – to generate a series of published topographic maps. In 1986 G.Wadge manually digitised the latest edition (DOS, 1983) from original DOS acetate contour sheets. DEM accuracy is affected by error in photogrammetric topography retrieval – exacerbated by dense vegetation on the island – and digitisation error. The latter was estimated at about 1/3 of the 50-foot contour interval (G. Wadge, pers. commun.). The resulting '1995', or 'pre-eruption', DEM (at 10 m grid intervals, available at www.nerc-essc.ac.uk/~gw) has since been used extensively by the research community. The original DEM was generated using the Clarke 1880 ellipsoid and BWI TM grid.

The accumulation of erupted volcanic material since 1995 has resulted in major changes in the island's topography and coastline. Various surveying work has been conducted throughout the eruption to measure and record these changes at different spatial and temporal scales (e.g. Jones, 2006; Wadge *et al.*, 2008). An airborne LiDAR survey was commissioned by MVO in 2010 and yielded the most extensive and detailed topographic survey recorded since the start of the eruption. The survey was conducted using a helicopter-mounted scanner with on-board high-rate GPS tracking which was later processed using ground control GPS data supplied by MVO. The survey covered most of the island to the south of the Centre Hills, except for regions above about 750 m (asl), which could not be surveyed due to low cloud cover. The 2010 DEM has 1-metre grid intervals and we estimate an RMS point error of 0.17 m from independent GPS measurements. The original DEM data used WGS84 UTM 20Q coordinates with heights referenced to the WGS84 (EGM96) geoid, later converted to ellipsoid height values.

Space-borne topographic surveying provides an attractive alternative to airborne and ground-based surveying methods, providing wide, contemporaneous. Generating of DEMs using satellite radar interferometry can be impeded by degradation of active volcanic terrain – a problem that will be reduced in data from recent, high-repeat rate satellite missions (e.g. Ferrucci & Tait, 2011). DEM data from such endeavours are typically adjusted to fit existing topographic data (e.g. SRTM) and thus adopt the cartographic conventions of the original DEM. Georeferenced satellite topography and imagery data (e.g. radar intensity images, Wadge *et al.*, 2011) commonly use the WGS84 UTM systems, with either geoid or ellipsoid vertical reference.

Bathymetric data around Montserrat have been compiled and updated in a similar fashion: original data were derived from 1:50000 scale British Admiralty sea charts based on 19th and 20th Century surveys. Numerous additional surveys conducted since 1998 have been used to map bathymetric changes around Montserrat, particularly the evolution of submarine deposits offshore from the Tar River Valley (due east from SHV). Le Friant *et al.* (2004; 2010) documented the details of various bathymetric surveys. An estimate of near-shore bathymetry –

usually inaccessible to large survey ships – was given by Wadge *et al.* (2010). The map in Figure 2 shows a current DEM, combining data from recent surveys.

5. Magnetic Declination

Magnetic declination (the difference in angle between magnetic and true north) changes in space and time. It is important to account properly for declination in work that requires the use of a magnetic compass (e.g. surveying, wind vane installation, etc.). In Montserrat, a correction of about 14°W is required, and this has changed at an average (not constant) rate of about 3'W/yr during the course of the eruption. Figure 3 shows the variation of magnetic declination on Montserrat since 1995, estimated using the International Geomagnetic Reference Field (IGRF-11; Finlay *et al.*, 2010). Magnetic inclination (dip of the magnetic field from horizontal) is usually not as critical for standard surveying purposes; on Montserrat, magnetic inclination dips at about 40° and changes by about 0.2°/yr (becoming shallower). Alternative magnetic field models and further information are available from NOAA (2012).

6. Summary

This note is intended as a brief introduction, to highlight and document geodetic practices as they have been used in geoscience on Montserrat. We have included a rudimentary description of the fundamental geodetic tools used for handling and manipulating geospatial data and highlight the importance of understanding the influence of their use and mis-use. We have also indicated the conventions that have been used most commonly by researchers during the course of the eruption on Montserrat.

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Table 1. Parameters for two ellipsoids commonly used on Montserrat (from Butler *et al.*, 2012).

Name	Offset (*to* WGS84)			Equatorial radius, *a* (m)	Inverse flattening ratio, *1/f*
	dX (m)	dY (m)	dZ (m)		
WGS 1984	-	-	-	6378137.000	298.257223563
Clarke 1880	174	359	365	6378249.145	293.465000000

Table 2. Parameters that define the two TM projections most commonly used for Montserrat geographic data (from Butler *et al.*, 2012).

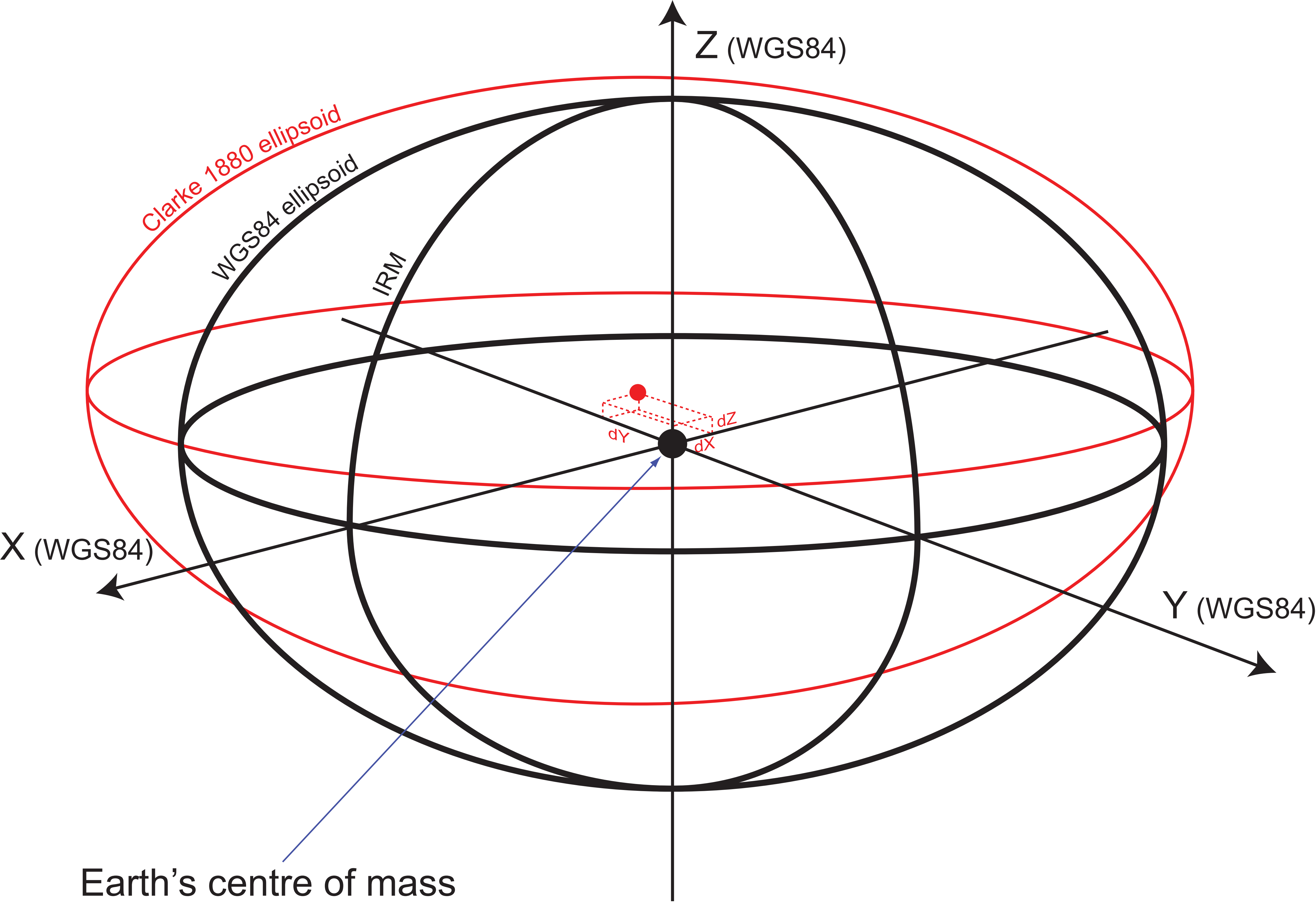
Parameter	**BWI grid**	**UTM Zone 20N (= Zone 20Q)**
Ellipsoid	Clarke 1880	WGS 1984
Projection	Transverse Mercator	Transverse Mercator
Central Latitude	0°	0°
Central Meridian	62° West	63° West
False Easting (m)	400000	500000
False Northing (m)	0	0
Scale Factor	0.9995	0.9996
EPSG Code	2004	32620

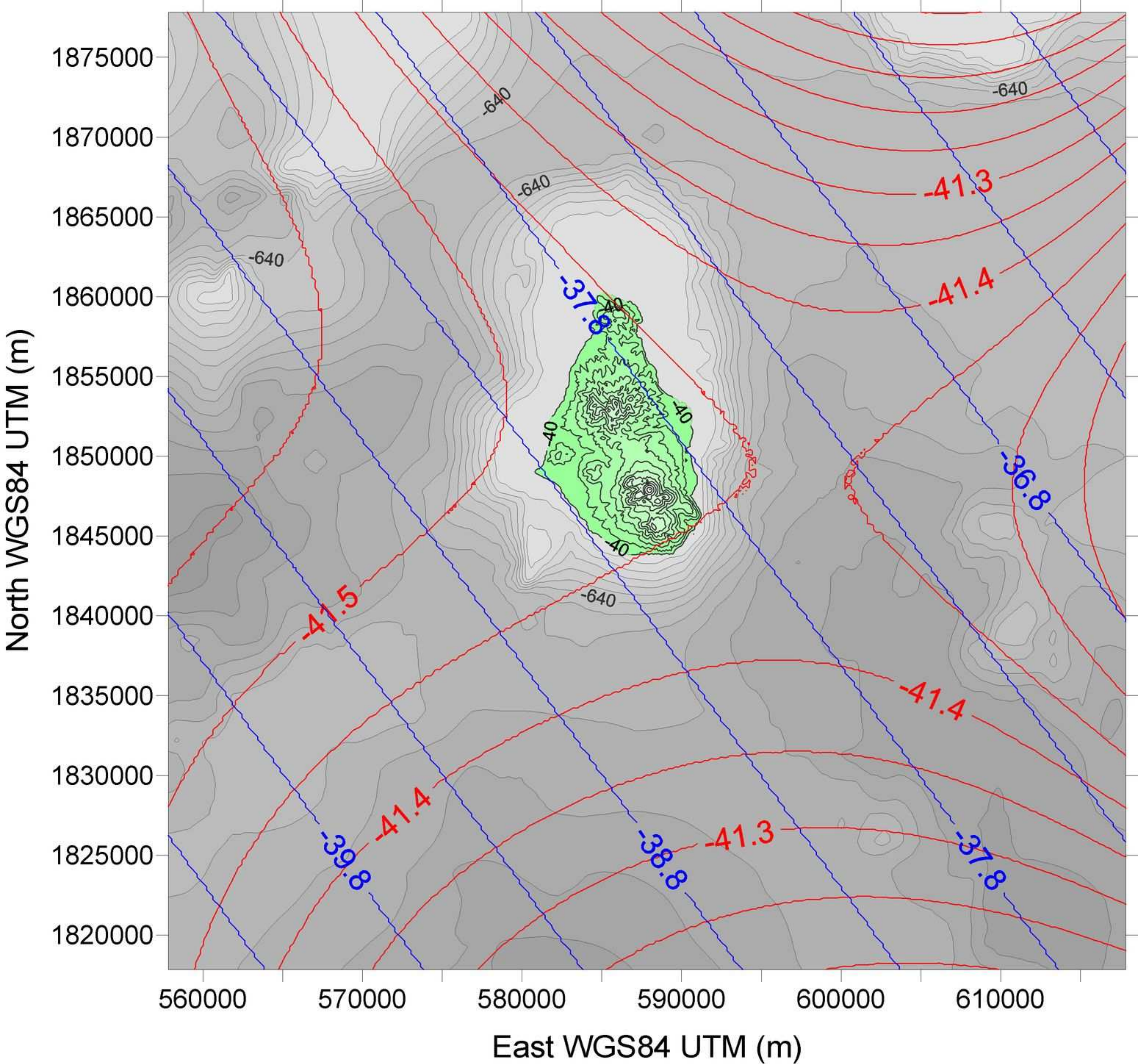
Figure Captions

Figure 1. Cartoon illustration of typical geodetic ellipsoids. The WGS84 ellipsoid (black) has its origin at the Earth's centre of mass (black dot). The rotational pole, *Z*, and the prime meridian, *X*, are defined by the IERS reference pole and meridian (IRM), respectively, as described in the text. The equatorial and polar radii define the flatness of the ellipsoid. Ellipsoids are conventionally defined by parameters relative to the WGS84 frame. Here, the Clarke 1880 ellipsoid (red) has an origin that is offset in each of the *X, Y* and *Z* dimensions (red dot), as defined in Table 1. The radius and flattening of the ellipsoids also differ. The flattening and offset in this figure is exaggerated for illustrative purposes. The WGS84 *X, Y* and *Z* axes also form the orthogonal Earth-Centred Earth-Fixed coordinate axes.

Figure 2. Map of Montserrat and surrounding bathymetry (grey contours with 100 m intervals; see text for description of DEM). Vertical offsets from the WGS84 ellipsoid are shown for the Clarke 1880 ellipsoid surface (blue contours, 50 cm intervals) and the WGS84 (EGM96) geoid (red contours, 5 cm intervals). The complexity in the geoid model derives from local and regional heterogeneities of mass distribution in the Earth. All height contours are measured in metres from the WGS84 ellipsoid surface (negative values are below the ellipsoid). The coastline of Montserrat is thus shown by a contour at -40 m, rather than at 0, because of the ellipsoid-geoid vertical offset. Horizontal coordinates are given as metres in Easting and Northing using the WGS84 UTM Zone 20Q datum (see Table 2).

Figure 3 Magnetic declination at 16°42'N 62°11'W (southwest flank of SHV) between 1995 and 2015, according to the IGRF-11 model. These corrections may be used to calibrate field compasses or adjust uncorrected azimuth data.


Z (WGS84)
Clarke 1880 ellipsoid
WGS84 ellipsoid
IRM
dZ
dY
dX
X (WGS84)
Y (WGS84)
Earth’s centre of mass


North WGS84 UTM (m)
1875000
1870000
1865000
1860000
1855000
1850000
1845000
1840000
1835000
1830000
1825000
1820000
East WGS84 UTM (m)
560000
570000
580000
590000
600000
610000
-640
-640
-640
-640
-640
-40
-40
-40
-40
-41.3
-41.4
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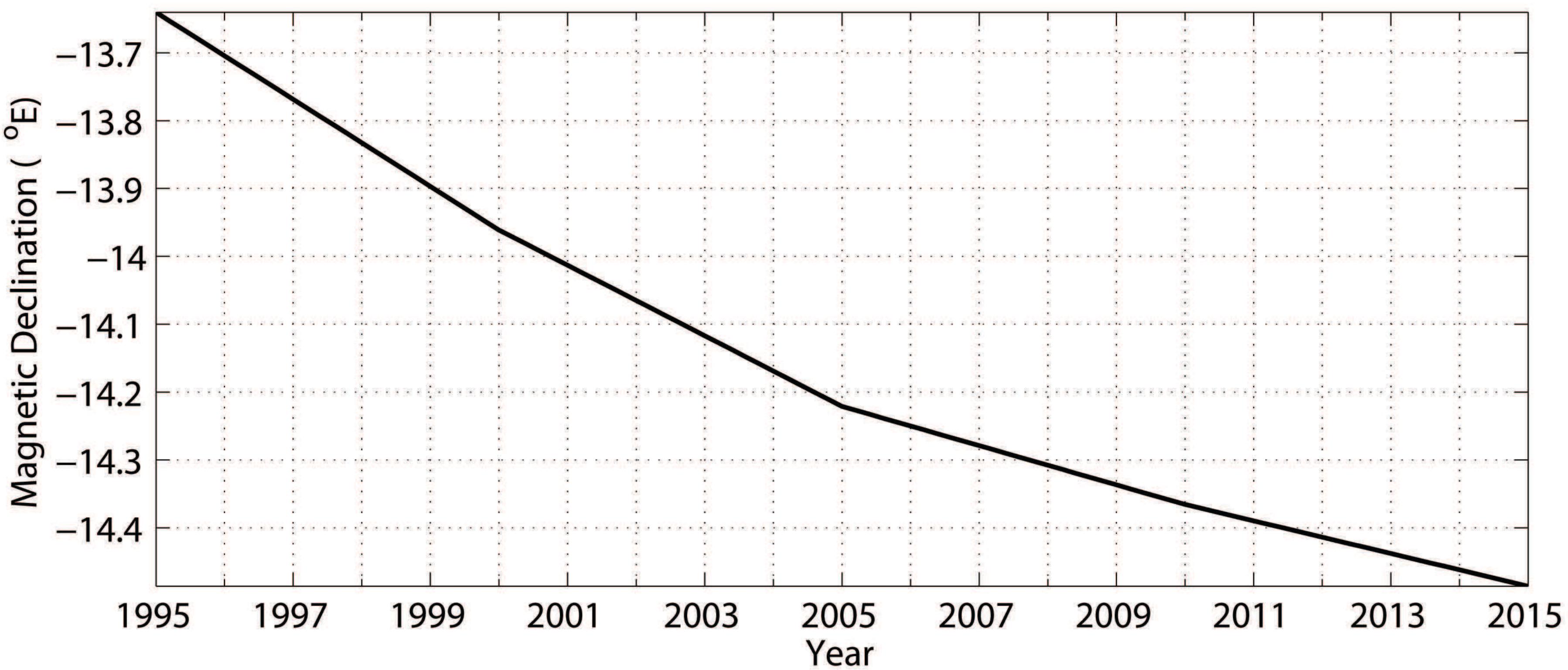
-39.8
-38.8
-37.8



Magnetic Declination (°E)
−13.7
−13.8
−13.9
−14
−14.1
−14.2
−14.3
−14.4
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year