REFERENCE FRAMES IN PRACTICE – FIG WORKING GROUP 5.5

Paul A. Cross, Phil B. H. Davies, Alan H. Dodson and Matthew B. Higgins

ABSTRACT

This paper describes the background to and objectives of the FIG Commission 5 Working Group 5.5 on Reference Frames in Practice. The fundamental objective of WG-5.5 is to prepare, and make easily accessible, tutorial style information that is readily understandable by practicing surveyors and general practitioners in the geomatic professions. The major focus of the paper is to introduce the Technical Fact Sheets and Local Information Sheets that will become the products of Working Group 5.5. Technical Fact Sheets are short documents that explain, in readily understandable English, basic theoretical concepts and practical applications and issues and which summarize the activities of organisations with specific responsibilities in this field. Local Information Sheets will describe the current situation in individual countries. The emphasis is on the provision of a brief background with contact information and to be a conduit between practicing surveyors and the information they require. Attachments to the paper give samples of the Technical Fact Sheet and Local Information Sheet products.

BACKGROUND

The FIG Commission 5 Working Group 5.5 on Reference Frames in Practice was established at the FIG Congress in Brighton UK in 1998 under the Chairmanship of Paul Cross, with Matt Higgins as Vice Chair. Its purpose is to develop further the wishes of Commission 5 to provide a useful service to practicing surveyors (and others) in the general field of reference systems.

It carries on from the former Working Group 5.2 (Reference Systems and Heighting) that was established in Melbourne in 1994 under the chairmanship of Matt Higgins and that reported at the Brighton Congress (see paper entitled "Reference Systems and Heighting and the FIG" in the Brighton proceedings).

OBJECTIVES

The fundamental objective of WG-5.5 is to prepare, and make easily accessible, tutorial style information that is readily understandable by practicing surveyors and general practitioners in the geomatic professions. The following broad topic areas have been identified:

- Formal definitions and applications of different types of coordinate systems, reference frames and height systems.
- General methods of transforming between reference frames and height systems, including the role of the geoid.
- Related activities undertaken by international organisations (such as standards bodies and scientific organisations).
- Up to date practices in all FIG (and other) countries regarding reference frames and height datums used for standard geomatics products (such as maps, geographical information and positions of permanent markers).
- Practical procedures for transformations between these reference frames and height datums, and others that might also be needed to used in these countries (e.g. global geocentric systems such as WGS84).

It is emphasized that WG-5.5 is not seeking to undertake fundamental research into reference frame definition. That is seen as the work of, for instance, the International Association of Geodesy (IAG). Nor is it seeking to make formal recommendations for reference frame definition, specification and adoption. That is the role of international standards organisations or perhaps other bodies of FIG. WG-5.5 simply seeks to make accessible and readily understandable the relevant activities of others in this general field.

WG-5.5 PRODUCTS

It is proposed to develop two sets of WG-5.5 products and to place these on the Commission 5 World Wide Web site. The two products are (a) Technical Fact Sheets and (b) Local Information Sheets.

Technical Fact Sheets

Technical Fact Sheets are short documents (typically one to three pages) which explain, in readily understandable English, basic theoretical concepts, and practical applications and issues, and which summarize the activities of organisations with specific responsibilities in this field. The following are initial candidates for Technical Fact Sheets:

- WGS84
- Global and Local geoid models
- Types of coordinates
- Map projections
- Classical (local) astrogeodetic datums
- ITRF
- Rigorous (seven parameter) 3D transformations
- Practical transformation procedures
- Role of standards organisations (e.g. in GIS metadata)
- Role of IAG
- Role of CERCO
- Commercial activities (OPENGIS)
- Approaches of GPS manufacturers and software developers

Sample Technical Fact Sheets have been developed for the first two items in the above list and are attached as Appendices A and B. The information in those Appendices demonstrate the level of content intended for Fact Sheets but it should be remembered that the actual products will be World Wide Web based and therefore more interactive than can be demonstrated in this paper.

Local Information Sheets

The second type of product to be developed by WG-5.5 is the Local Information Sheet. These will typically be about one page long and will describe the current situation in individual countries. It is expected that the information will normally be provided to the Commission 5 representative in that country by the appropriate official organisation such as the national mapping agency. Local Information Sheets will contain the following information:

- Formal references to detailed (and easily accessible) technical papers describing the history and current state of reference systems and height datums in that country.
- A very brief summary of the standard geomatic products available in that country and of associated reference system information.
- A web address or other contact method, from which the reader can find the latest information regarding relevant transformation methods and associated parameters.
- Any relevant comments indicating special issues relating to that country (e.g. whether transformation parameters are freely available and/or whether or not commercial products are available to undertake transformations). Also any known future policies (e.g. with respect to moving to a global geocentric frame) could be summarized.

The emphasis of Local Information Sheets is on the provision of a brief background with contact information. It is not intended to give (for instance) transformation parameters (as these a likely to become out of date very rapidly and because WG-5.5 does not want to be responsible for their correctness). Local Information Sheets are meant to become a conduit between practicing surveyors and the information they require.

A sample Local Information Sheet has been developed using the UK as an example and is attached as Appendix C.

MEETINGS TIMETABLE

The first task has been the preparation of this paper for the FIG Working Week in South Africa in May 1999. The purpose of this paper is to publicize the activities of WG5.5 and to encourage participation by, and contributions from, interested parties. It was seen as important that this paper include samples illustrating the concepts of the Fact Sheet and Local Information Sheet so that comments can be sought on the structure and level of detail before preparing more of them.

The Working Group will have its main working meeting during the FIG Working Week in Prague (22-27 May 2000). All group members will be encouraged to attend the Prague meeting at which progress can reviewed and a detailed work plan for the remaining two years can be drawn up. In Prague the location for a meeting in 2001 will be identified if necessary (most probably the FIG Working Week in Seoul).

The Working Group will prepare a final report for the FIG Congress in Washington DC in 2002, which will include lists of Technical Fact Sheets and Local Information Sheets as well as recommendations regarding the future of the Working Group.

MEMBERSHIP

An initial membership has been drawn from people who were known to be interested in this field but there is a clear need for a broad membership representing all sectors of our industry and from a wide geographic coverage of the globe.

Membership of the Working Group is open to anyone with a genuine interest in its aims. Members must, however, be prepared to undertake one or more of the following activities.

- Suggest topics for Technical Fact Sheets and comment on their overall coverage and structure.
- Prepare initial drafts for one or more fact sheets (and edit following comments – see below).
- Seek and synthesize comments on draft fact sheets from (a) technical experts (for correctness) and (b) practicing surveyors (for understandability).
- Collect data (on a regional basis) regarding local reference frames and transformations (particularly in cases in which Commission 5 representatives have been unable to respond).

It is not intended to form any sub-committees.

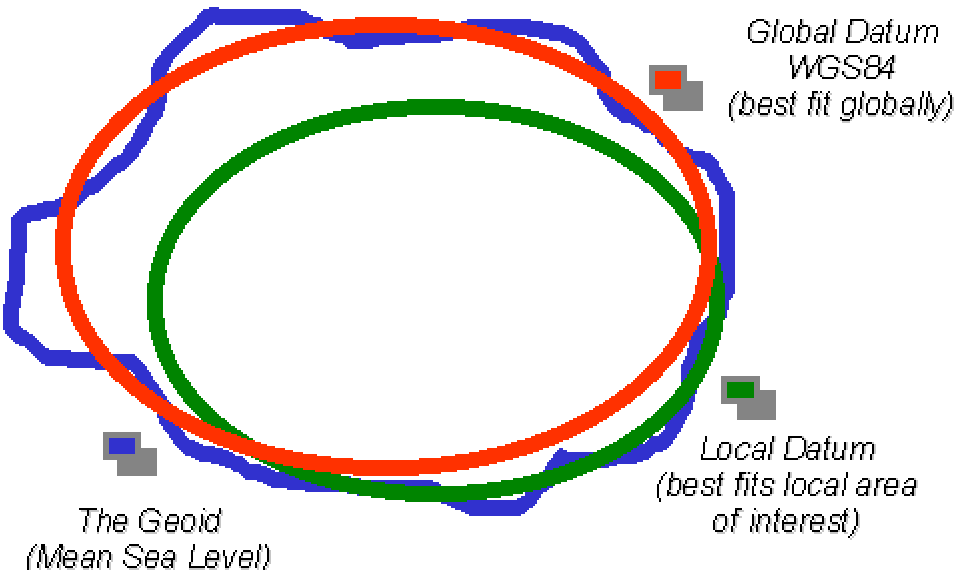
CONCLUSION

This paper has described the background to and objectives of the FIG Commission 5 Working Group 5.5 on Reference Frames in Practice. It has also covered meeting and membership details. However, the major focus of the paper has been to introduce the Technical Fact Sheets and Local Information Sheets that will become the products of Working Group 5.5. It is hoped that surveyors representing many areas of the globe and from all sectors of our industry will become involved in the development of these sheets. With such broad involvement it will be possible to develop a significant collection of such sheets dealing with a broad range of topics and countries. In so doing WG-5.5 will serve surveyors well in better understanding and working with Reference Frames in Practice.

FIG FACT SHEET 5.001 - THE WORLD GEODETIC SYSTEM OF 1984 (WGS84)

Geodetic Datum in General

The depiction of three-dimensional position requires a three dimensional surface. A convenient surface to represent the earth is the geoid. It is the equipotential surface of the earth's gravity field that on average coincides with mean sea level in the open oceans. Due to variations in gravity, the geoid undulates significantly and a regular mathematical model is required for the calculations associated with a datum. An appropriate mathematical model is an ellipsoid (or spheroid). Geodetic datum tend to use ellipsoids which best represent the geoid in the area of interest. An example of the spatial relationship between a local datum, a global datum and the geoid is represented in the following Figure.



Prior to the development of space based measurement systems, locally defined geodetic datum were sufficient. However, satellite positioning systems require a single global geodetic datum and GPS, GLONASS and other space based measurement techniques have had some fundamental influences on datum definition and use.

- Satellites move around the centre of mass of the earth and require a datum which is geocentric.
- Their global nature has meant that what has previously been considered geodetic science is having increasing importance in day to day surveying.
- Height from these systems is measured above the ellipsoid which has required better geoid models.
- There has been a trend to revise local working datum to be more compatible with measurements from systems such as GPS and GLONASS.
- Their three dimensional nature has led to a need to closely relate horizontal and vertical datum.

A global datum is based on the Conventional Terrestrial Reference System (CTRS). An important underlying concept is that reference systems definitions are purely definitions and must be realized through some defined process. Three particularly relevant realizations of the

CTRS are WGS84 as used for GPS, PZ90 as used for GLONASS and the International Terrestrial Reference Frame (ITRF - see Boucher and Altamimi, 1996). WGS84 and PZ90 are established and maintained by military organisations while the ITRF is produced by a scientific institution, the International Earth Rotation Service (IERS).

The World Geodetic System of 1984

The geodetic datum used for GPS is the World Geodetic System of 1984 (WGS84). The significance of WGS84 comes about because GPS receivers rely on WGS84. The satellites send their positions in WGS84 as part of the broadcast signal recorded by the receivers (the so-called Broadcast Ephemeris) and all calculations internal to receivers are performed in WGS84.

From a technical point of view, WGS84 is a particular realization of the CTRS. It is established by the National Imagery and Mapping Agency (NIMA) of the US Department of Defense (for original descriptions see DMA, 1991 and Kumar, 1993). The initial realization of WGS84 relied on Transit System observations and was only accurate at the one to two metre level. At the start of 1994 (start of GPS Week 730) use of a revised value of the gravitation constant (GM) along with improved coordinates for the Air Force and NIMA GPS tracking stations led to WGS84 (G730). That realization was shown to be consistent with the ITRF at the 10 centimetre level (Malys and Slater, 1994). The improved tracking station coordinates came from a combined solution using selected IGS stations (Swift 1994). Further improvements to the tracking station coordinates in 1996 led to WGS84 (G873). The G873 represent GPS Week 873 and refers to the date when the new tracking station coordinates were implemented in the NIMA precise ephemeris process. The G873 coordinates were implemented in the GPS Operational Control Segment on 29 January 1997. Tests have shown WGS84 (G873) to be coincident with the ITRF94 at a level better than 2cm (Malys et al, 1997).

It should also be noted that the ellipsoid used for WGS84 agrees with that of the Geodetic Reference System of 1980 (GRS80 - Moritz, 1980) except for a very small difference in the flattening term. GRS80 is the reference ellipsoid associated with ITRF.

Working with WGS84

It should be noted that there are only two ways to directly produce WGS84 coordinates. The first is by GPS surveying measurements relative to the US DoD’s GPS tracking stations. However, the GPS data from those DoD stations is not typically available to civilians. The second way is by point positioning using a GPS receiver. However, the accuracy of point positions performed by civilians is limited by the policy of Selective Availability to +/- 100m at 95% confidence. Only US DoD or allied military agencies can perform point positioning with centimetre to decimetre accuracy.

Civilian surveyors often require WGS84 coordinates to an accuracy better than that available from point positioning. For example, a common requirement for accurate WGS84 coordinates is to seed the processing of GPS surveying baselines (post-processed or real time). However as outlined above, civilians cannot access WGS84 directly with high accuracy and must therefore resort to indirect means to produce WGS84 compatible coordinates.
One way to obtain more accurate WGS84 compatible coordinates is to use local datum coordinates and a published transformation process. In practice, a transformation process is derived between data sets on both datum and any errors in those data sets affect the transformation process. The quasi WGS84 coordinates that result from a transformation

process can be in error in an absolute sense by as much as several metres but are usually more accurate in a relative sense. Transformation processes in common use include the three parameter Molodensky method (or block shift), seven parameter (or similarity) transformation, multiple regression equations and surface fitting approaches (see the FIG Fact Sheet on Datum Transformation).

The most rigorous way for civilian surveyors to produce WGS84 compatible coordinates is to perform GPS surveying measurements relative to control stations with published ITRF coordinates. That will produce ITRF coordinates for any new stations. As outlined above, ITRF94 (or later) coordinates can then be claimed to be within a few centimetres of their WGS84 G873 equivalents.

An important mechanism allowing the ITRF to be accessible for geodetic networks anywhere in the world is the ability to access precise ephemeris for the GPS satellites and precise station coordinates from the International GPS for Geodynamics Service (IGS). The IGS has a global network of stations with high quality receivers observing GPS continuously (Zumberger et al 1995).

Given widespread use of GPS, there is a trend for the working geodetic datum to be consistent with recent ITRF and therefore with WGS84. This trend was set with the North American Datum of 1983 as a geocentric datum using the GRS80 ellipsoid. Recent implementations have taken advantage of the continued development of the various ITRF (e.g. for European developments see Seeger, 1994). Australia is also progressing toward adoption of an ITRF based geocentric datum by the year 2000 (Manning and Harvey, 1994). In such cases where the modern geodetic datum is based on a recent ITRF it will be compatible with WGS84 at the few centimetre level.

Relevant Internet Links:

- WGS84 NIMA Publications - Includes links to a PDF file of "DMA 1991" as referenced above plus other useful WGS84 documents and software at http://164.214.2.59/geospatial/products/GandG/pubs.html
- Geodetic Reference System of 1980 (GRS80) - Moritz, 1980 - Internet Version at http://www.gfy.ku.dk/~iag/handbook/geodeti.htm
- International Terrestrial Reference Frame (ITRF) at http://lareg.ensg.ign.fr/ITRF/
- International GPS for Geodynamics Service (IGS) at http://igscb.jpl.nasa.gov/

Other Relevant FIG Fact Sheets:

FIG Fact Sheet 5.xxx - Datum Transformation

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Author: Matt Higgins, Department of Natural Resources, Queensland, Australia, Vice Chair FIG Commission 5.

Email: matt.higgins@dnr.qld.gov.au Fax: 61 7 3891 5168

This and other FIG Commission 5 Fact Sheets are available from the Commission 5 Web Pages via the FIG Home Page at http://www.ddl.org/FIGtree

FIG FACT SHEET 5.002 - GLOBAL AND LOCAL GEOID MODELS

Introduction

The computation of the complex geoid surface in order to provide geoid heights, thus enabling the direct conversion between ellipsoidal and orthometric heights, is a demanding mathematical problem. Several techniques for such computation have been developed based around the original formulation by Stokes in the 19th century. Modern computational approaches include the use of Least Squares Collocation and Fast Fourier Transformations. All such computations rely on the availability of gravity data (either directly measured or in combination with related quantities such as the deviation of the vertical, potential or geoid height), which theoretically needs to be global and continuous. These last conditions obviously restrict the ability to compute an exact geoid surface, and geoid models (both global and local) are therefore not perfect. However, recent satellite altimetry missions have considerably improved the coverage of data over the oceans, where previously data was sadly lacking, and this has significantly improved the accuracy of global geoid models.

Global Geoid Models

Until the advent of satellite geodesy it was almost impossible to collect sufficient global gravity data to compute global geoid models. However in the last 25 years or so there has been a continued development and refinement of such models as more and better data has become available. Probably the three most important models produced have been the WGS 84 Earth Gravitational Model (not to be confused with the WGS 84 Ellipsoid), the Ohio State University's OSU 91 model, and most recently the Earth Gravity Model EGM 96 (developed as a joint project of NASA/Goddard Space Flight Centre and the National Imagery and Mapping Agency (NIMA) in the USA).

These models all express the complex geoid surface as a Spherical Harmonic expansion with coefficients complete to degree and order 360 (EGM 96 and OSU 91A) or 180 (WGS 84). Despite the very large number of coefficients this requires (10^5 for degree and order 360), these models only provide a smooth, long wavelength, view of the geoid with a spatial resolution of, at best, 1° in latitude (approximately 100km) and longitude. This limits their accuracy, as geoid variations within this resolution are smoothed. However EGM 96 is claimed to have a global accuracy of between ±0.5m and ±1.0m. The accuracy of global models relies on the availability and accuracy of the input data, and EGM 96 has been computed with much better global data coverage than previous models. However there are still areas of sparse data coverage (eg central Africa) and the model's accuracy will inevitably be lower in the vicinity of such regions. The spherical harmonic coefficients and gridded worldwide geoid heights are available, for both the original WGS 84 (gridded at 30 minutes of arc) and the EGM 96 (gridded at 15 minutes) models, from the NIMA web page www.nima.mil.

Local Geoid Models

Many countries have recently realised the need for an accurate local geoid (or quasigeoid) model to enable the conversion of satellite derived ellipsoidal heights to their local Orthometric or Normal height system. There has therefore been a rapid increase in the production of local or regional models to satisfy this need. Such local computations are based on global models (such as OSU 91A or EGM 96) which provide the long wavelength information, and as such have their absolute accuracy limited by that of the global model. However, the local model is derived from local gravity data of a (usually much) better spatial resolution, eg 2km surface gravity observations, and often higher accuracy, and can thus produce relative geoid accuracy of the order of a few centimetres over distances of the order of 100km. Examples of such local/regional models are the Ordnance Survey (GB)'s OSGM 91 for Great Britain, the European (quasi)geoid EGG 97 (computed by the University of Hannover), and the conterminous US G96SSS models. The European model provides gridded geoid heights at 1minute x 1.5 minute resolution and is available from the International Association of Geodesy (see their web page www.gfy.ku.dk/~iag/), whilst the US models are available from the US National Geodetic Survey (web page www.ngs.noaa.gov).

Height Reference Surfaces

Theoretically a gravimetric geoid computation will provide the necessary reference to relate GPS ellipsoidal heights to Orthometric (or Normal) heights. However, errors in the geoid model and in both the definition and realisation of conventional height systems (eg assuming Mean Sea Level is equivalent to the geoid and levelling measurement errors), mean that in reality heights derived from GPS and a geoid model do not often fit existing levelling data. To partially overcome this problem, national/regional height reference surfaces derived by 'best fitting' a geoid to known (usually primary) levelling data have been produced. (The US GEOID96 is such a surface, see NGS web page as above.) This is a procedure which is likely to be more prevalent in the future as it provides the best pragmatic approach to utilising GPS heights with an existing vertical datum. Such an approach is preferable to users defining a multitude of their own very local, and discrete, reference surfaces by fitting their own GPS data to (often unreliable) local benchmark information.

Further Information

It is impossible to list here all the global/national/regional models available, however the IAG's International Geoid Service, based in Milan, Italy maintains a repository of a number of Local Geoid Models and several Global Models. It also gives general information about the geoid, its computation and available computational software. The Service maintains a dedicated IGeS web server which can be found at http://ipmtf14.topo.polimi.it/~iges.

This version dated: 19 April 1999
Author: Prof. Alan Dodson, Director IESSG, University of Nottingham, UK.
Email: Alan.Dodson@nottingham.ac.uk Fax: +44 (0)115 951 3881
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APPENDIX C - DRAFT AND SAMPLE ONLY

FIG REFERENCE FRAMES LOCAL INFORMATION SHEET - GREAT BRITAIN

Organisation

Great Britain includes England, Scotland and Wales. It does not include Northern Ireland or the Republic of Ireland. The national mapping agency, Ordnance Survey Great Britain, is responsible for national reference frames. Ordnance Survey operates a helpline to which all enquiries should be directed in the first instance.

Reference frames summary

Historical basis of mapping: All national mapping is based on the National Grid, which is a Transverse Mercator projection of the triangulation network OSGB36 observed 1935-1962, using the Airy 1830 ellipsoid. A different National Grid exists for Ireland. Heights are shown as orthometric heights relative to Ordnance Datum Newlyn, a single tide-gauge mean sea level datum observed 1915-1921, and realised by a primary national network of 200 Fundamental levelled bench marks.

GPS reference system: The national standard GPS reference system is ETRS89, which is obtained by a 6-parameter transformation of ITRS96 published by IERS. ETRS89 is a WGS84 variant tied to the stable part of the European plate. It current (1999) differs from ITRS96 by about 25cm, growing by 2.5cm per year.

National GPS Network: The primary reference frame for GB since 1992 has been the National GPS Network, including 750 roadside marks with ETRS89 coordinates, observed in 1991-92. In 1999 the National GPS Network is being upgraded by the addition of about 30 active GPS stations (i.e. continuously observing automatic stations), such that all points in GB will be within 100km of an active station (150km in Scottish Highlands). Also, new passive stations have been added at all Fundamental height benchmarks, bringing the total passive network to 900 stations. Passive stations are now re-observed on a 5 year cycle.

Realisation of National Grid: The National Grid is currently formally realised by the stations and archive coordinates of the triangulation network OSGB36. The National Grid Transformation OSTN97 is an interpolated grid of horizontal plane shift parameters covering GB at 1km resolution, which converts ETRS89 GPS coordinates to National Grid coordinates with an accuracy of 20cm (RMS). In 2002, an improved version of this transformation will become the definition of the National Grid, and use of the triangulation network will be discouraged.

Realisation of Ordnance Datum Newlyn: The orthometric height datum is currently formally realised by the fundamental bench mark network and archive of levelled coordinates. The National Geoid Model OSGM91 is an interpolated grid of offsets between the ETRS89 ellipsoid and a gravimetric geoid model aligned to Ordnance Datum Newlyn. The accuracy of OSGM91 as assessed by GPS/levelling is better than 10cm (95% confidence). The use of the National GPS Network and OSGM91 for establishing new orthometric height benchmarks is encouraged. Reliance on densification benchmarks for orthometric height control is not recommended.

Product availability

OSTN97 and OSGM91 are licensed to software vendors for incorporation in GPS, GIS and navigation software packages. A list of current licensed data distributors is available on the OS Website. These products are not available direct to users from OS.

National GPS network Passive station coordinates and information are avaiable from OS Technical Sales. Active station coordinates and GPS data are not yet available, but are expected to become available via an Internet server during 1999.

Traditional control information (triangulation stations and height benchmark information) is available from Ordnance Survey Technical Sales.

Special Issues

The triangulation network OSGB36 contains scale and orientation distortions causing errors in coordinates at the 5-10 metre level. No simple GPS datum transformation for the whole of GB can fit National Grid coordinates to better than 5m accuracy. For precise work, the datum transformation required can change over short distances. Therefore, Ordnance Survey discourage the use of simple datum transformations in Great Britain - the national standard transformation OSTN97, which models OSGB36 distortions at 1km resolution, should be used.

References

The 'GPS positioning and coordinate systems' page on the OS Website has links to all the OS information available about Reference Frames in Great Britain.

The address is: http://www.ordsvy.gov.uk/services/gps-co/index.htm

Papers currently available on this site include:

A Guide to Coordinate Systems in Great Britain - a 42-page booklet explaining many geodetic concepts and detailing coordinate systems and reference frames used in GB.

Information Paper 12/1998 - GPS and mapping in the 21st century - a publicity document outlining current Ordnance Survey geodetic policy.

Improving Access to the National Coordinate Systems - an article first appearing in Surveying World magazine, giving an overview of current geodetic developments in Britain to the land surveying profession.

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Author: Phil Davies, Ordnance Survey Great Britain
Email: pdavies@ordsvy.gov.uk

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