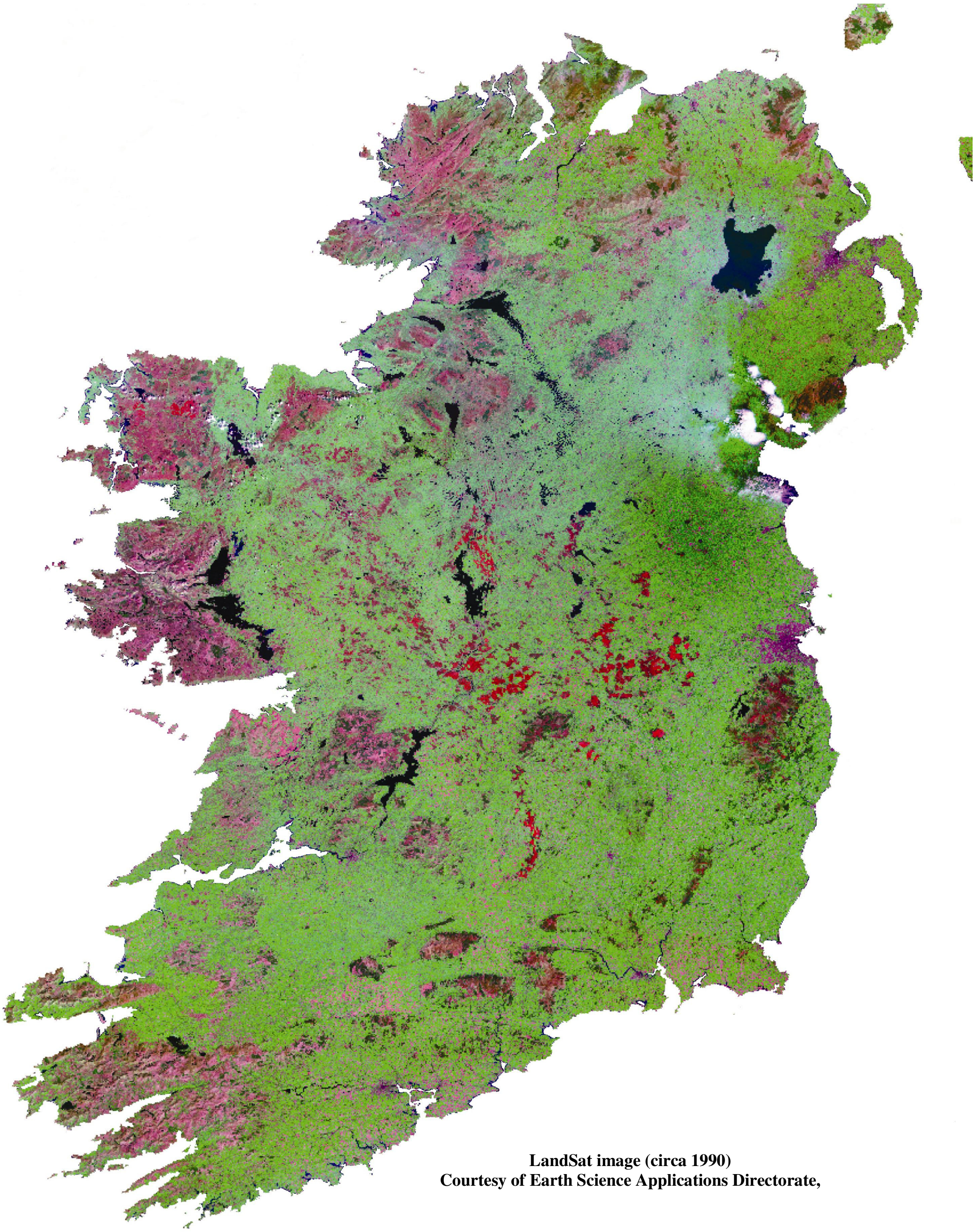
# BEST PRACTICE GUIDELINES FOR PRECISE SURVEYING IN IRELAND



LandSat image (circa 1990)
Courtesy of Earth Science Applications Directorate,

# BEST PRACTICE GUIDELINES

# FOR

# PRECISE SURVEYING

# IN IRELAND

Compiled and edited by W. P. Prendergast

Published by the Irish Institution of Surveyors, 2004

ISBN 0-9533154-2-8



Copies are available at €30 from
The Irish Institution of Surveyors, 36 Dame Street, Dublin 2, IRELAND
Tel/Fax: + 353 (0)1 677 4797
Email: iissecretary@eircom.net



Charts prepared using Microsoft Excel
Diagrams prepared in Microsoft Word
Maps prepared using ESRI Arc View 3.2

Printed in Ireland by ENPRINT
Earl's Court Industrial Estate, Beaumont Avenue, Churchtown, Dublin 14.

# TABLE OF CONTENTS

# LIST OF TABLES



## APPENDICES

# LIST OF FIGURES



## APPENDICES

# GLOSSARY OF TERMS

| | |
|---|---|
| DGPS | Differential GPS – observation procedure using two GPS receivers – often meant to imply GIS grade GPS only, to sub-metre accuracy |
| Ellipsoidal Height | Height above the reference ellipsoid (GRS80 in Ireland) |
| ETRS | European Terrestrial Reference System |
| ETRS89 | European Terrestrial Reference System 1989 |
| EUREF | Sub-Commission of Commission X of the International Association of Geodesy with responsibility for the European (Geodetic) Reference Frame |
| GPS | Global Positioning System |
| GRS80 | Geodetic Reference System of 1980 |
| IAG | International Association of Geodesy |
| IERS | International Earth Rotation and Reference Systems Service |
| IRENET95 | GPS campaign in 1995 to realise the Zero Order and Passive GPS Networks in Ireland |
| IRENET02 | GPS campaign in 2002 to realise the Active GPS Network in Ireland |
| IG | Irish Grid - co-ordinate reference system for Ireland (for late 20$^{th}$ century) |
| IG75 | 1975 realisation (mapping adjustment) of the Irish Grid co-ordinate reference system |
| IIS | The Irish Institution of Surveyors |
| ITM | Irish Transverse Mercator - new co-ordinate reference system for Ireland (for 21$^{st}$ century) |
| ITRS | International Terrestrial Reference System |
| IUGG | International Union of Geodesy and Geophysics |
| MSL | Mean Sea Level |
| Orthometric Height | Height above the national vertical height datum (mean sea level at Malin Head for Ireland)) |
| OSGB | Ordnance Survey of Great Britain |
| OSGM02 | Ordnance Survey Geoid Model 2002 |
| OSI | Ordnance Survey of Ireland |
| OSNI | Ordnance Survey of Northern Ireland |
| ppm | parts per million |
| RTK | Real Time Kinematic observation procedure for GPS using dual frequency equipment to centimetre level accuracy |
| Static | Observation procedure for GPS using dual frequency equipment to centimetre level accuracy |
| UTM | Universal Transverse Mercator |
| WGS84 | World Geodetic System of 1984 |

# ACKNOWLEDGEMENTS

The author wishes to thank Iain Greenway (OSI) and Trevor Steenson (OSNI) for their commitment to work with the IIS Task Force to resolve issues as they were identified. Thanks are also due to Colin Bray and John O'Connor (OSI) and Ken Stewart and Kieran Adams (OSNI) the Ordnance Survey representatives on the Technical Working Group on the implementation of the new Co-ordinate Reference System, Irish Transverse Mercator (ITM) for Ireland. It was fortunate that the IIS Task Force and the OSI and OSNI Technical Working Group were conducting their respective examinations at the same time, which allowed the results of the two studies to be linked. A special word of appreciation goes to Ken Stewart (OSNI) who acted as the Ordnance Survey contact with the Task Force for his many emails, explanations and helpful assistance.

The author also wishes to thank Oliver Finch (OSI) for assisting the Task Force to resolve some issues relating to the published co-ordinates and the orthometric heights of the control stations of the Passive GPS network.

The author is also indebted to Mr Frank Prendergast and Dr Eugene McGovern (Department of Geomatics, DIT) for their valuable suggestions and contributions while proofreading the report.

Finally, many thanks are also due to the members of the Task Force who gave unselfishly of their time and experience in the many discussions and debates held while preparing this publication.

Although the report is written with the co-operation of OSI and OSNI, it cannot be considered to define OSI or OSNI policy.

**TASK FORCE MEMBERS**

**Paddy Prendergast,** paddy.prendergast@dit.ie
Department of Geomatics, DIT Bolton Street, Dublin 1

**Brendan Sweeny,** bsweeny@iol.ie
Hempenstall Survey and Scientific Co. Ltd, 56 Lansdowne Road, Dublin 4

**Paddy Scully,** paddy@gps.iol.ie
GPS Surveying, Newmarket House, Newmarket, Co. Cork

**Chris Shackelton,** eas@iol.ie
Digitech 3D Ltd, Unit 11, North Main Street Business Park, Swords, Co Dublin

**Paul Corrigan,** pcageo@indigo.ie
Paul Corrigan Associates (PCA) Ltd, 65 Merrion Square, Dublin 2

# EXECUTIVE SUMMARY

1. OSI and OSNI should be congratulated on providing significantly improved all-Ireland infrastructures for surveying and mapping which the surveying sector should immediately adopt, including:
   a) The three-dimensional GPS networks.
   b) The new ITM co-ordinate reference system.
   c) The new geoid model (OSGM02).

2. The old trigonometric network of trig pillars and levelling network of benchmarks should not be used for precise surveying projects any longer because:
   a) They are no longer being maintained by OSI and OSNI.
   b) They are appreciably less rigid than the new GPS networks.
   c) OSI and OSNI have never quantified their quality or published a statement on their accuracy.

3. Ideally, precise surveys should use the new ITM co-ordinate reference system, which has been specifically designed as the Irish reference framework for the 21$^{st}$ century, is GPS compatible, and no transformation is necessary.

4. The major implications of adopting the new GPS networks in place of the trigonometric network, and the ITM co-ordinate reference system in place of the Irish Grid co-ordinate reference system include:
   a) New observation procedures and computation methodologies for which training courses are urgently required for practitioners.
   b) The need for care and transparency in computations using transformations.
   c) Only dual frequency GPS equipment should be used to establish control for precise surveying projects.
   d) The use of qualified survey professionals to minimise difficulties adapting to these new technologies and computational procedures.

5. The major implications of adopting the new GPS networks and the geoid model (OSGM02) in place of the levelling network and its associated benchmarks for computing heights above the Malin Head datum (orthometric) include:
   a) The decommissioning of the network of benchmarks to provide heights for precise surveying projects.
   b) The need to use GPS equipment to supply heights for precise surveying projects.
   c) New observation procedures and computation methodologies for which training courses are urgently required for practitioners.
   d) The need for care and transparency with respect to modelling Ocean Tide Loading (OTL) and tropospheric effects in height computations.
   e) The use of qualified survey professionals to minimise difficulties adapting to these new technologies and computational procedures.

6. Investment for surveying and mapping infrastructures for the island of Ireland should be paid from public funds to suit the needs of the engineering, construction, surveying and scientific communities on both sides of the border. The Task Force propose:
   a) The establishment of a cross border committee with responsibility for the design, implementation, quality assurance, maintenance and dissemination of information from these infrastructures.

b) The immediate consideration of the following projects by the committee:
   - Upgrading the Active GPS network to provide national coverage for absolute accuracy of < 60 mm (2σ).
   - Developing accurate models for Ocean Tide Loading (OTL) and tropospheric effects on GPS observations.
   - Supply improved information to compute a more accurate geoid model by 2010 by re-observing the geodetic levelling network to identify terrain uplift/subsidence since the 1970s and conducting gravity measurements in areas where information is scarce at present.

7. Consultants and contractors of precise surveying projects are advised to conduct check surveys to ensure the quality of the data delivered meets the specification requested.

8. Specific recommendations for surveyors are included separately in Appendix E.

# INTRODUCTION

The Irish Institution of Surveyors (IIS) established a Task Force in January 2002 to investigate a difficulty being experienced by private surveyors when using the Passive GPS network. The difficulty arose when a private survey firm carried out a survey for a client and a second survey firm subsequently conducted a check survey, which yielded a different result. Although both surveys were based on the same Passive GPS station there was a difference of approximately 0.25 m in the computed Irish Grid (1975) co-ordinates.

The two private surveying firms alleged that it was possible to calculate two different survey solutions when using the different co-ordinates (ETRS89 and Irish Grid (1975)) published for the Passive GPS stations. This is due to the fact that these two reference systems were established independently of each other, and consequently the ETRS89 and Irish Grid (1975) co-ordinates vary in terms of their absolute and relative accuracy. An accuracy statement equivalent to ± 20 mm in Latitude, Longitude and ellipsoidal height is quoted for the ETRS89 co-ordinate. However, the accuracy for the Irish Grid (1975) co-ordinates is quoted as better than ± 250 mm in easting and northing between adjacent stations and their absolute accuracy is everywhere better than 1 metre (OSI and OSNI, 1999).

Since the Passive GPS network became available in 1996, it became normal survey practice to calculate values for a local seven-parameter transformation from ETRS89 to Irish Grid (1975) for specific projects as required. Then in 1999, Ordnance Survey Ireland (OSI) and Ordnance Survey of Northern Ireland (OSNI) then published official values for a seven-parameter transformation between the ETRS89 and Irish Grid (1975). Survey practice should have changed at that stage to adopt the new official values in preference to locally calculated unofficial values, to ensure consistency in survey practice. Whereas it is impossible to precisely relate co-ordinates in one system to those in a different, unconnected system, the use of the official values for the seven-parameter transformation provides a connection between the two systems to a consistent accuracy tolerance. However, the adoption of the new official values by practitioners was not as widespread as one would have wished for, but in the specific case, which gave rise to the investigation, the official values were used.

The implementation of the Irish Grid co-ordinate reference system in Ireland during the latter half of the $20^{th}$ century and its widespread adoption by all was hugely beneficial in providing a homogeneous co-ordinate reference system for the whole island. However, difficulties have arisen since the provision of dual co-ordinates (ETRS89 and Irish Grid (1975)) for the Passive GPS stations in 1996. Complications arise when combining survey data based on different control networks, whether the survey is observed using traditional survey methods or by GPS. Consequently, the Irish Institution of Surveyors felt that action was necessary to provide information and guidance to its members to improve understanding and minimise confusion.

Although the Passive GPS network has been available since 1996, surveyors have made relatively little use of it until quite recently. The main factors that hindered the adoption and widespread use of the Passive GPS network were:

a) The initial high cost of purchase for a set of dual frequency GPS receivers;
b) The need for training and implementing new field and computation procedures for GPS observations;
c) The continued requirement in survey specifications to supply data on the Irish Grid (1975), and the need to transform co-ordinates calculated from the Passive GPS network into this co-ordinate reference system;
d) The lack of an ellipsoid/geoid separation model meant that the potential (as a three-dimensional network) of the GPS network could not be fully exploited;

e) The lack of a new co-ordinate reference system for Ireland such as ITM (Irish Transverse Mercator) based on the GPS Network, which would eliminate the need for transformations (and consequent degradation of survey data) if adopted by the user community.

The Institution recognised the potential for confusion resulting from the use of different co-ordinate reference systems and multiple transformations between them, and understood the importance of providing information and guidance for its members. The Institution hopes that this guidance will:

a) Assist surveyors to provide consistent survey data to meet their legal and contractual obligations, especially with respect to accuracy tolerances requested within contracts;
b) Assist consultants and contractors to set accuracy tolerances within survey specifications, which are relevant and achievable.

## *Objectives*

The original aims of the Task Force were:

a) To describe the difficulties being experienced;
b) To propose practical solutions for IIS members in order to improve the quality and consistency of spatial data collected in Ireland;
c) To make users of spatial data more aware of the new GPS Networks available for survey control and their associated co-ordinate reference system, ITM (Irish Transverse Mercator), which can significantly improve the quality of spatial data if used.

These aims were subsequently revised to include:

a) The provision of information on the Irish geodetic control networks to improve understanding by all using them;
b) A proposal to develop and use standard conventions for clarity in survey practice.

This report does not purport to be an authoritative source for geodetic information in Ireland. However, the Institution hopes that in gathering information from a range of sources and presenting it in a practical format suitable for surveyors, that it will assist developing an understanding of the ‘quirks’ of the traditional Irish control networks and provide much needed guidance for professionals working in the surveying and construction sectors in Ireland.

## *Task Force Methodology*

Fourteen formal meetings (and numerous informal contacts) of the Task Force (Table 1) were held to conduct the investigation and hold discussions with OSI and OSNI over a twenty-one month period. A proposal was initially circulated to OSI, OSNI and the IIS Corporate Members (~ 30 private surveying firms) in early April 2002 for comments and suggestions. At that stage the intention was to publish a ‘Practice Direction’ as an instruction to IIS members to adopt a preferred methodology for precise surveying operations.

However, two significant announcements were made in April 2002. OSI announced their intention to implement the new ITM co-ordinate reference system for Ireland. This meant that three co-ordinates (ETRS89, Irish Grid (1975) and ITM) would in future be published for the stations of the GPS Networks. Concurrently, OSI, OSNI, and Ordnance Survey of Great Britain (OSGB) also announced the imminent release of the Quest software, which was to provide a polynomial transformation as the definitive transformation solution for Ireland and also included an ellipsoid/geoid separation model (OSGM02).

**Table 1. Formal meetings held by members of the Task Force.**

| Meeting | Location | Date |
|---|---|---|
| Task Force Meeting | Dublin Airport | 18/02/2002 |
| IIS Company Owner's Forum 2002 | Kilkenny | 25/03/2002 |
| Task Force Meeting | Malahide | 20/05/2002 |
| Task Force Meeting | Malahide | 09/09/2002 |
| With OSI and OSNI (after ITM TWG meeting) | OSI Dublin | 30/09/2002 |
| With OSI and OSNI (after ITM TWG meeting) | OSI Dublin | 14/11/2002 |
| With OSI and OSNI (after ITM TWG meeting) | OSNI Belfast | 21/11/2002 |
| Task Force Meeting | Malahide | 06/12/2002 |
| Task Force Meeting | Malahide | 20/01/2003 |
| IIS Company Owner's Forum 2003 | Kilkenny | 24/03/2003 |
| Task Force Meeting | Malahide | 14/04/2003 |
| With OSI and OSNI | OSI Dublin | 15/05/2003 |
| Task Force Meeting | Malahide | 12/09/2003 |
| With OSI | OSI Dublin | 19/09/2003 |

The availability of the new polynomial transformation created further potential for confusion by providing yet another method of computation for surveyors. Although this polynomial transformation purported to improve transformation quality, it also provided a further opportunity for inconsistency if not applied in a harmonised manner. For these reasons the publication of the 'Practice Direction' was delayed to provide sufficient time for the Task Force to assess the implication of these extra issues.

The Task Force conducted a comprehensive series of tests of the Quest software applied to the co-ordinates published for the Passive GPS network during August and September 2002 (Appendix A). An Interim Report of the results of these tests and conclusions drawn was presented to OSI and OSNI in September 2002 via the ITM Technical Working Group examining the implementation of the new ITM co-ordinate reference frame in Ireland. Although it was only intended initially to examine the horizontal (2D) co-ordinates of the GPS Network, the Task Force felt that it had no option but to include the height issue once the geoid model had been released.

A questionnaire survey was also conducted during February / March 2003 of GPS use by surveying firms (Appendix B) and of accuracy tolerances being specified by consultants and contractors for major infra-structural construction projects in Ireland.

OSI agreed in May 2003 to conduct a test of the Active GPS network to:

a) Quantify absolute accuracy obtainable by post-processing multiple Active GPS stations over different radial distances to determine the coverage of absolute accuracy of < 60 mm (2σ) from this network.
b) Quantify the repeatability of absolute accuracy obtainable by post-processing multiple Active GPS stations over different radial distances.

OSI conducted a preliminary test in September 2003, which used insufficient data to determine the information required, so the Task Force completed a comprehensive test in late October 2003, which yielded much more information than initially intended (Appendix C).

Copies of an initial draft report were circulated to OSI, OSNI and members of the Task Force in May 2003 for their comments and suggestions. The final report was again circulated to OSI, OSNI and members of the Task Force in December 2003 for final comments before publication.

# REVIEW OF HISTORICAL CONTROL NETWORKS

## *Horizontal Control Networks (2D)*

### Principal Triangulation of Ireland

Ireland's first horizontal control network, the Principal Triangulation of Ireland, was observed between 1825 and 1832 (Figure 1). Network angles were observed using two large theodolites, including the famous three-foot Ramsden theodolite, observing at night to distant mountaintops and the network was connected via observations to England, Scotland, Wales and the Isle of Man, which were observed during the 1840s and 1850s. A baseline of over 12 kilometres was measured using Colby's bars (one bar still located in the National Archives in Bishop Street, Dublin) along the eastern shores of Lough Foyle to establish scale for the network in Ireland. Distance measurements were in feet, as defined by bar $O_1$ of Colby's bars (not standard imperial feet).

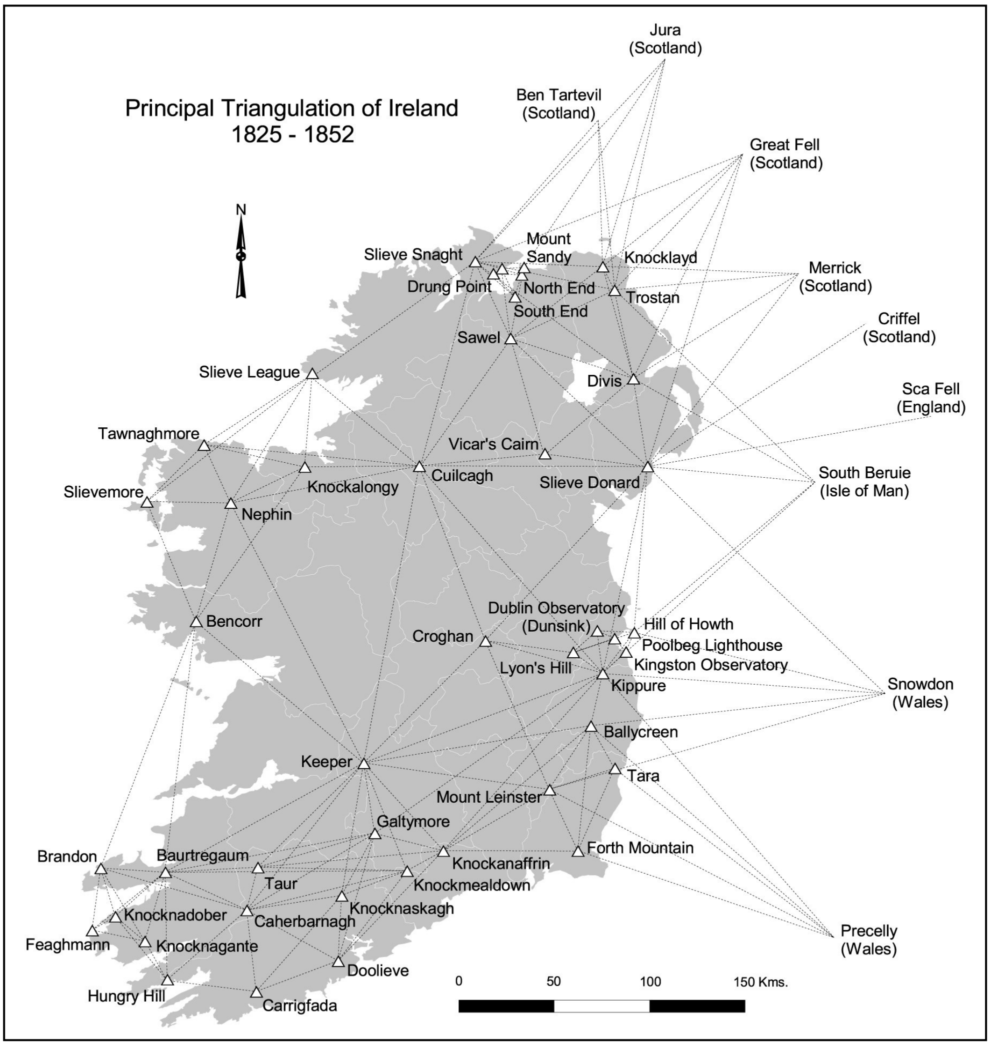



**Figure 1. Principal Triangulation of Ireland 1825 – 1852 (Cory *et al*, 2003).**

Subsequently, secondary and tertiary networks were added between 1832 and 1841 to increase the number of control points available. The tertiary network eventually contained approximately 15,000 control points, most of which were marked with terracotta tiles placed approximately two feet under the terrain surface to ensure they were not disturbed by the ploughs of the farming community. This original geodetic control network provided the framework upon which the 19$^{th}$ century large-scale Ordnance Survey mapping was based. It was not considered possible to use one national projection for large scale mapping at this time, so separate Cassini projections with individual origins were used for each county. As a result, the large scale Ordnance Survey mapping at 6 inches and 25 inches to 1 mile became known as the county series.

Although this original network was advanced for the 19th century, and was in general use until the 1960s, no overall statement of accuracy was ever published for it. The use of multiple projections also resulted in significant distortions at county boundaries making it impossible to accurately join maps of adjacent counties. This network eventually became obsolete, when it was replaced during the 1950s and 1960s with Ireland's second horizontal control network, the 're-triangulation of Ireland'.

## Re-Triangulation of Ireland

Ireland's second horizontal control network, the re-triangulation of Ireland was established to replace the ageing triangulation network, which was in many respects inadequate for modern mapping requirements, and to provide a new all island co-ordinate reference system, the Irish Grid. This system was jointly designed by OSI and OSNI to provide one common reference frame for Ireland, and it developed on the previous reference system by adopting:

a) The international metre as the unit of measurement.
b) The introduction of the Irish Grid.
c) The replacement of the Cassini and Bonne projections with the Transverse Mercator projection for all official topographic mapping.

The observation of the primary network was carried out in Northern Ireland in 1952 and in Ireland between 1962 and 1964, and the shape and size of the primary triangles in the network design were more uniform than in the principal triangulation (Figure 2). Network angles were observed using WILD T3 theodolites and scale and orientation were established by holding a number of the stations fixed for the three realisations of the Irish Grid, as described below.

The first realisation of the Irish Grid was the 1952 adjustment for Northern Ireland only. It used the Airy ellipsoid, and scale and orientation were derived from three stations (Knocklayd, Trostan, and Divis) of the original principal triangulation which were held fixed in the adjustment to provide a link to the co-ordinate frame on which the existing mapping of the province was based. It was subsequently discovered that the original principal triangulation contained a scale error of between 30 and 40ppm, so the first realisation of the Irish Grid (1952) perpetuated this 19th century scale error by holding the positions of the three primary stations fixed in the adjustment. The second and third realisations of the Irish Grid in 1965 and in 1975 maintained this scale error by holding the nine primary stations in Northern Ireland fixed to their Irish Grid (1952 and 1965) positions in both adjustments.

The second realisation of the Irish Grid was the 1965 adjustment of the primary network of the whole island, as indicated in Figure 2, which used the Airy modified ellipsoid, and changed the scale factor of the central meridian of the Transverse Mercator projection from unity to 1.000035. Scale and orientation for the second realisation were derived from the nine primary stations in Northern Ireland (Knocklayd, Trostan, Sawel, Divis, Crockkinnagoe, Cuilcagh, Carnmore, Carrigatuke and Slieve Donard) which were held fixed to their Irish Grid (1952) values to maintain a link with the new mapping produced in Northern Ireland since 1952 using the Irish Grid (1952) realisation.

The third realisation in 1975 was necessary to ensure the mapping joined correctly at the border, because OSI was using the Irish Grid (1965) realisation for their new mapping since 1965, and OSNI continued to use the Irish Grid (1952) realisation. The 1975 adjustment, known as the mapping adjustment, differed only from the 1965 adjustment in the horizontal datum used. Three primary stations in Ireland (Howth, Kippure, and Doolieve) and the same nine primary stations in Northern Ireland were held fixed to their Irish Grid (1965) values in order to maintain the link with the new mapping produced in Northern Ireland since 1952 using the Irish Grid (1952) realisation, and the new mapping in Dublin and Cork produced in Ireland since 1965 using the Irish Grid (1965) realisation. This link was considered necessary to prevent any plotable shift in those areas already mapped. Both OSI and OSNI adopted this third realisation for all new mapping since 1975.

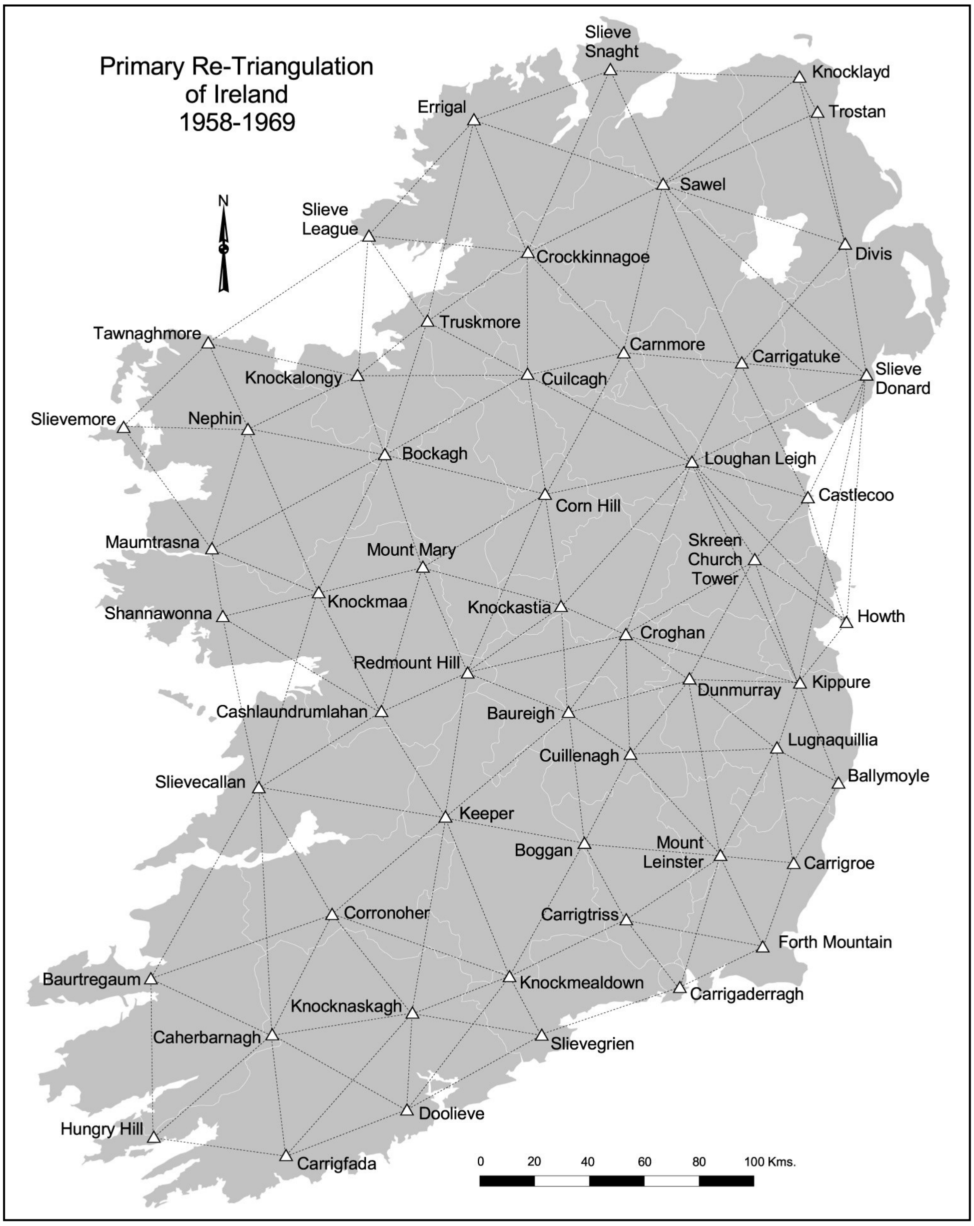



**Figure 2. Re-Triangulation of Ireland - Primary Network (Cory *et al*, 2003).**

Secondary and tertiary networks were subsequently observed up to the late 1980's to increase the number of control stations available, and were computed in blocks to provide Irish Grid (1975) values. The two tertiary blocks surrounding Dublin and Cork have retained their Irish Grid (1965) values to maintain sympathy with the mapping produced between 1965 and 1975 (Cory *et al*, 2003), and this may account for errors of up to 0.600 m encountered by private surveyors in some instances. The boundaries of these two tertiary blocks are included in Figures 3 and 4 to identify the interface between the Irish Grid (1965) and Irish Grid (1975) realisations, which still exists today.

The supply of the Irish Grid (1975) co-ordinate reference frame was hugely beneficial in providing an homogeneous system for surveyors, engineers, architects, planners and developers during the latter half of the 20th century. However, the provision of the Passive GPS network in 1996 as an alternate means of supplying control for surveying and mapping, and the decision by OSI and OSNI to discontinue the maintenance of the triangulation pillars in the early 1990s sounded the death knell for the Re-Triangulation Network.

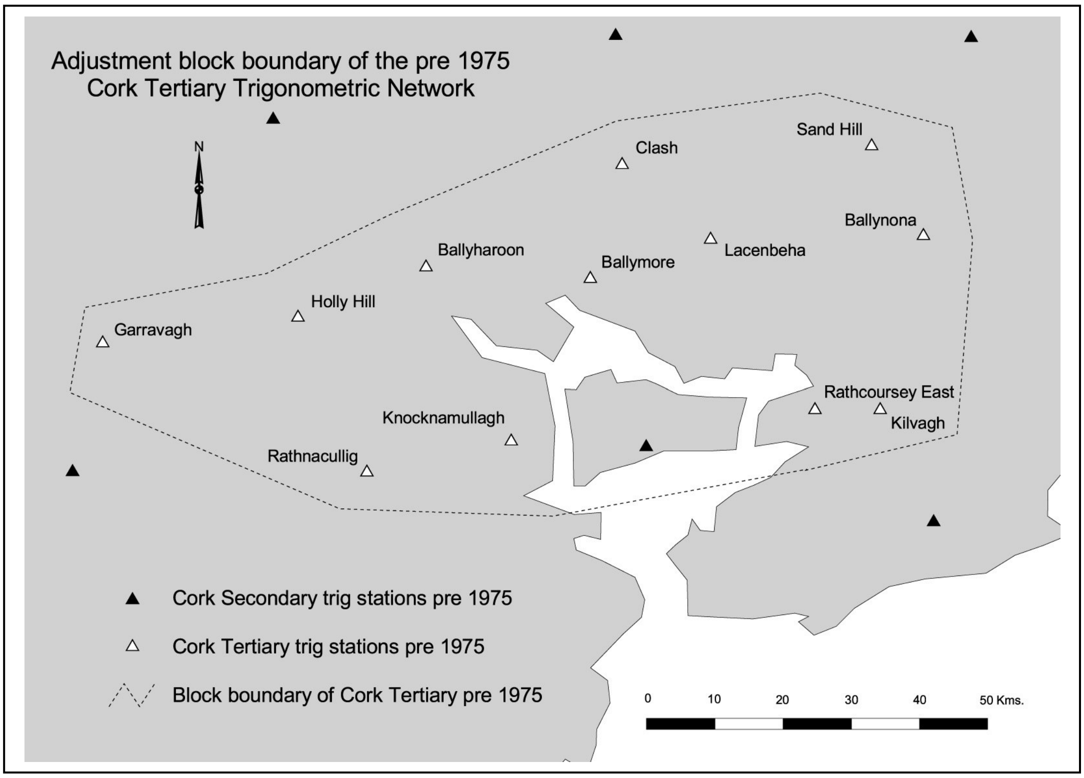



**Figure 3. Tertiary Network block in Cork with Irish Grid (1965) co-ordinates (OSI, 1980s).**

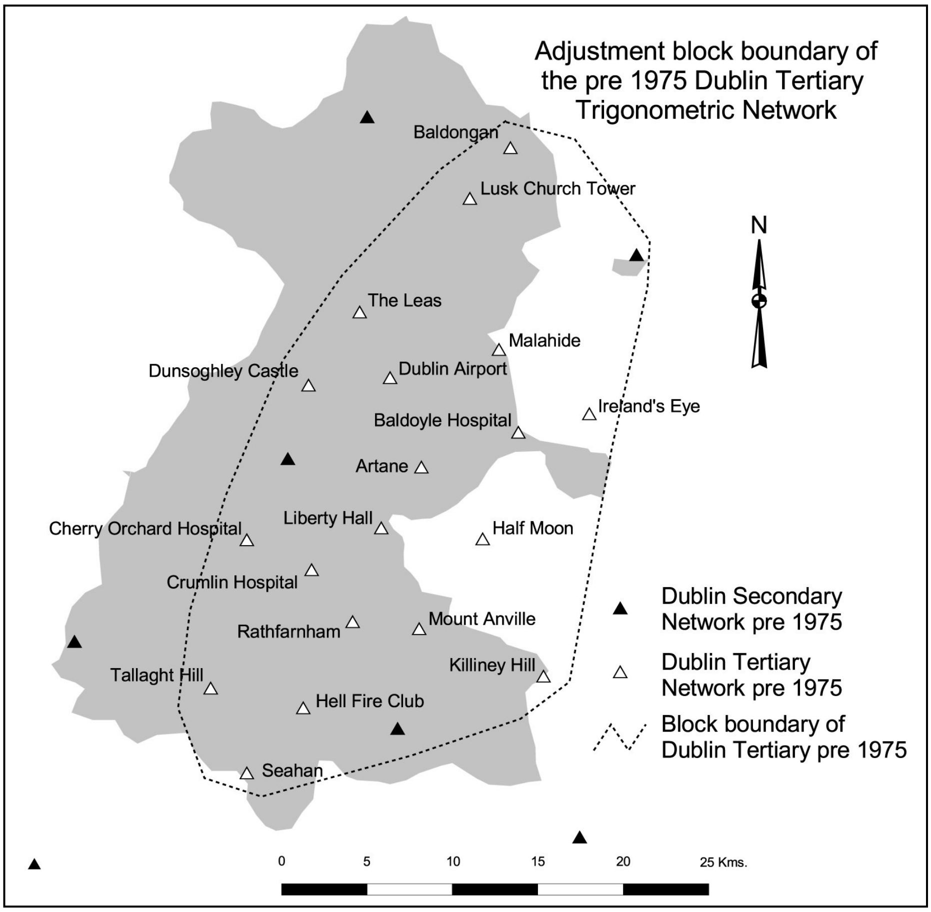



**Figure 4. Tertiary Network block in Dublin with Irish Grid (1965) co-ordinates (OSI, 1980s).**

## *Vertical Control Networks (Third dimension)*

### Principal Levelling Network

Although trigonometric heighting methods can be used to calculate height difference between control stations of the horizontal network, the method is not accurate enough to be used for a national geodetic network. Similarly, it would have been too difficult to spirit level each of the trigonometric pillars on tops of the hills, so a separate network of benchmarks in the lowlands was necessary for vertical control to relate the heights of points in the landscape to a national height datum.

The original height datum adopted for Ireland was the level of low water of spring tides observed at Poolbeg Lighthouse in Dublin Bay on 8th April 1837, and which was found to be 20.900 feet below a permanent benchmark on the lighthouse. This benchmark was then connected to other benchmarks around the country by lines of spirit levelling radiating out from Dublin (Figure 5) observed between 1839 and 1843. This original vertical control network provided the framework for all height information in feet on the 19th century Ordnance Survey mapping, and was used up to the 1970s. No overall statement of accuracy was ever published by the Ordnance Surveys for this network, and it eventually became obsolete when it was replaced by the 're-levelling network of Ireland' in Northern Ireland in the 1950s and in the rest of Ireland in the 1970s.

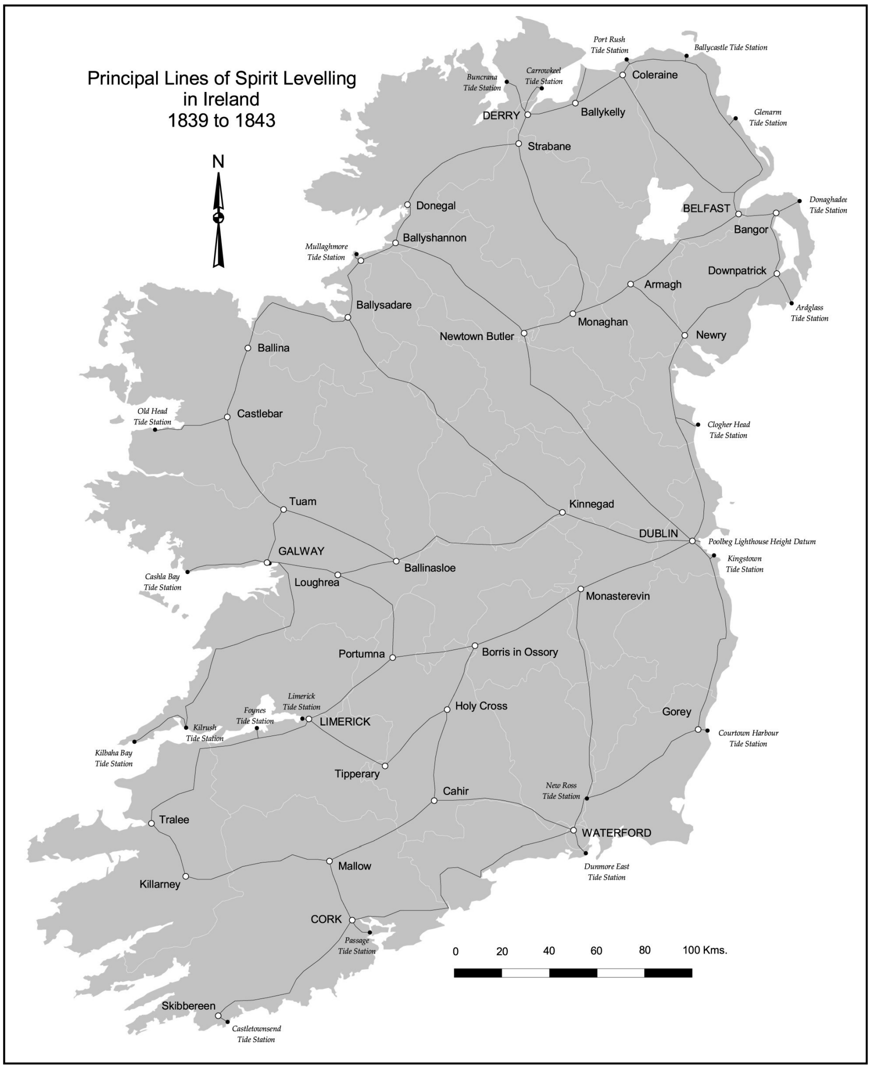



**Figure 5. Principal lines of spirit levelling 1839 to 1843 (OSI, 1991).**

## Re-Levelling Network

A new levelling network was necessary to replace the ageing existing levelling framework, which was inadequate for modern requirements. This allowed the adoption of mean sea level (MSL) and metric heights, which were becoming the norm internationally at that time for national vertical datums.

A new vertical datum was established at Malin Head, Co. Donegal by OSI and OSNI in 1957, and the height of mean sea level (MSL) was determined using 10 years of tidal measurements between January 1960 and December 1969. However, the new datum was not universally adopted. Although all OSI modern mapping (both large and small scale) and OSNI modern small-scale mapping use the Malin Head datum, OSNI large-scale mapping is related to MSL defined by a tide gauge in Belfast Lough (established during the 1950s). The Malin Head datum is on average 37 mm above the Belfast Lough datum (Cory *et al*, 2003).

Observation of the geodetic levelling network connecting the fundamental benchmarks (Figure 6) was conducted in two stages commencing in 1952 in Northern Ireland and completed in 1969 in Ireland, and the geodetic network was adjusted as one block in 1970. Secondary and tertiary networks were subsequently observed and computed in blocks between the 1950s and 1980s, which in some instances caused compatibility difficulties across adjustment block boundaries. Although OSI and OSNI do not quote accuracy data for benchmark heights, the accuracy of the levelling network is estimated by OSI and OSNI (Table D3).


**Figure 6. Geodetic Levelling Network indicating the locations of fundamental benchmarks.**

Maintenance of the levelling network was discontinued in the early 1990's, and the rate of loss of benchmarks has been quite dramatic in some areas such that many gaps are now evident in the network. The relationship between the three Ordnance Height Datums in Ireland is provided in Figure 7. However it should be noted that all conversions are subject to local anomalies mainly due to gravity anomalies causing deflections of the vertical.

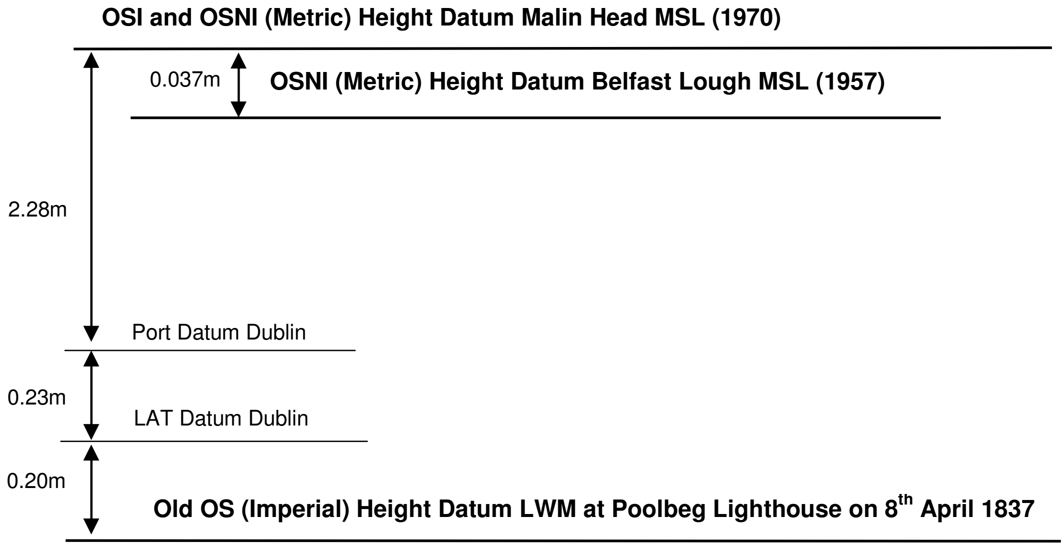



**Figure 7. Relationship between the three Ordnance Height Datums in Ireland (Dublin Port Company, 2003).**

# REVIEW OF MODERN GPS CONTROL NETWORKS (3D)

Traditionally it was necessary to have two national geodetic networks: a horizontal control network to define horizontal positions, and a vertical control network to define heights above a nominated zero datum, normally MSL. However satellite technology and improved adjustment procedures have provided the opportunity to replace the two traditional geodetic control networks with a three-dimensional GPS control network. IRENET95 was the observation campaign held during 1995 to realise the ETRS89 co-ordinate reference framework in Ireland via the Passive GPS Network, and IRENET02 complimented this by realising a higher quality ETRS89 co-ordinate reference framework for the Active GPS network in 2002.

## *Zero Order Network*

The IRENET95 campaign realised ETRS89 co-ordinates for 12 stations of the zero-order control network (8 in Ireland, 3 in Northern Ireland and 1 in the Isle of Man). Descriptions and co-ordinates for these zero-order control stations are not available for general use in order to minimise the possibility of damage to these stations and to restrict their use only for scientific purposes. This first level of stations is called a zero-order network because the accuracy of its co-ordinates is considered to be an order of magnitude (10 times) better than the accuracy of co-ordinates of previous primary horizontal control networks, and as such can expose the limitations of existing traditional control networks. This improved accuracy is mainly due to the GPS technology being used for observations and improved adjustment methods used for computations.

## *Passive GPS Network*

The second level of the 3D-control network consists of the 173 densification stations of the Passive GPS network, numbered D001 to D173 (Figure 8). Three co-ordinates (ETRS89, Irish Grid (1975) and ITM) are now published for these Passive GPS control stations. OSI and OSNI quote an accuracy the equivalent of ± 20 mm in Latitude, Longitude and ellipsoidal height for the ETRS89 co-ordinates (OSI and OSNI, 1999), and results achieved by private surveying firms to date seem to confirm this level of reliability. Since 1" of arc of latitude and longitude equates to 30 metres on the ground, ETRS89 co-ordinates in a latitude and longitude format are published to 5 decimal places of a second to provide sufficient resolution to millimetres.

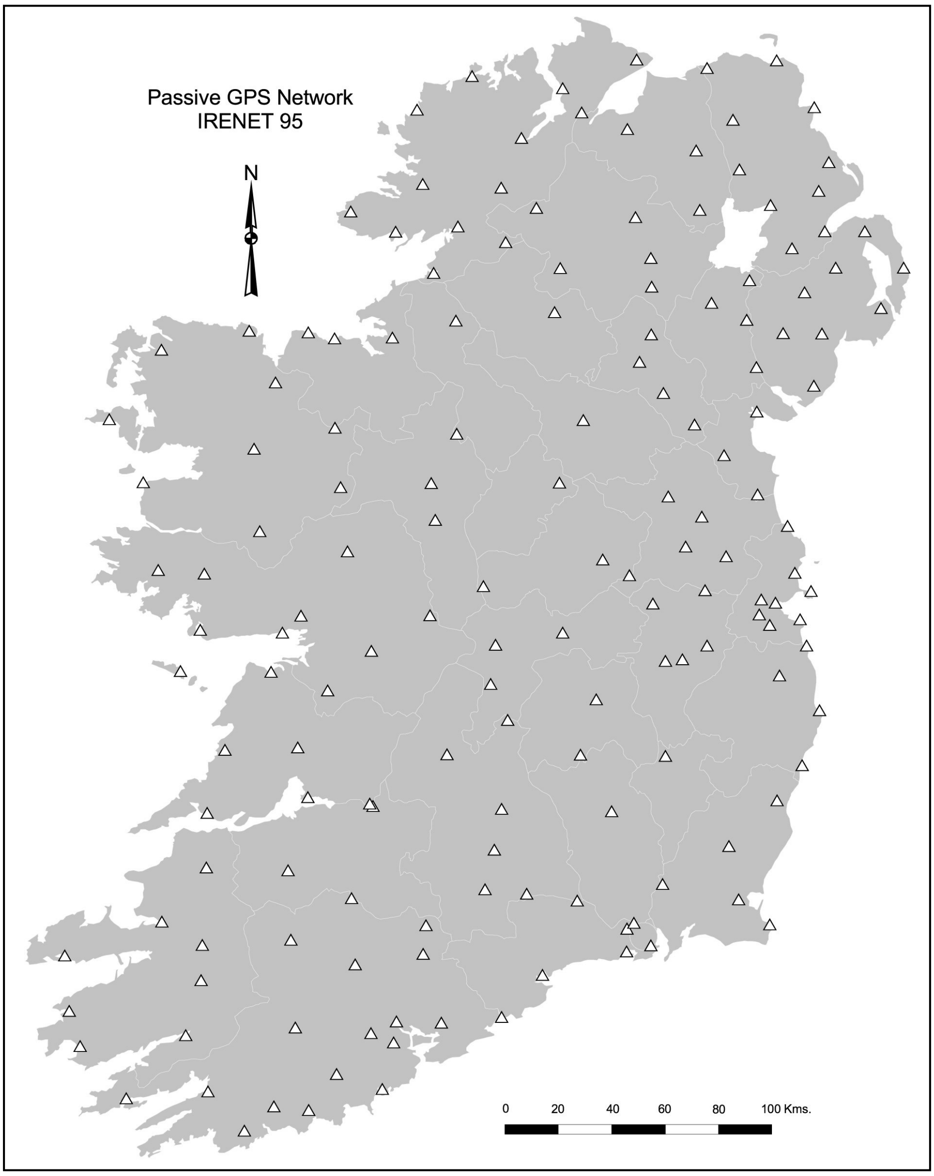



**Figure 8. Ireland's Passive GPS Network (Cory *et al*, 2004).**

The Passive GPS stations were observed using GPS, and are not necessarily inter-visible as was the case with the trigonometric pillars on the tops of mountains and hills of the Re-Triangulation Network. The Passive GPS network complies with international standards and provides a high precision, distortion-free three-dimensional control network. However, the adoption of this network by the user community to replace the Re-Triangulation Network has been slow due to:

a) The high initial cost of dual frequency GPS equipment.
b) The need for education and training in new observation and computing procedures.
c) Survey specification continuing to require Irish Grid (1975) co-ordinates, generally to a higher specification than possible through current transformations.
d) Although the network can be used to provide two-dimensional horizontal control, the lack of a geoid model precluded it from being fully exploited as a three-dimensional control network until 2002.

e) The lack of a dedicated co-ordinate reference frame (ITM) until 2002 required survey data to be degraded via a transformation to the Irish Grid (1975) co-ordinate reference frame.

However, all the components are now available to fully exploit the potential of this new 3D-control network.

OSI have also established many densification points (DP) since 1996 in some areas of the country, which were observed and computed in an *ad hoc* manner, mainly as photo control. OSI does not quote an accuracy for the co-ordinates published for these densification points, and results from private surveying firms suggest the quality of these co-ordinates is quite varied. The IIS Task Force consider the use of these densification points unsuitable for precise surveying operations, and OSI have consequently discontinued selling co-ordinates for these stations.

## *Active GPS Network*

The Active GPS network was established in 2002 by the IRENET02 observation campaign and consists of 16 stations (OSI - 10 stations, OSNI - 3 stations, and the Commissioners of Irish Lights - 3 stations). The positions of the Active GPS stations were determined to the same standards as the zero-order network. Consequently their accuracy is thought to be better than the Passive GPS stations since the network adjustment indicated a likely accuracy of ± 10 mm for latitude, longitude and ellipsoidal height for the ETRS89 co-ordinates.

This network of permanently recording GPS stations (Figure 9) will enable positioning when only using a single receiver. The intention is for the user to combine the data collected at the Active GPS station(s) nearest to the users' location with the data observed on site for post-processing off-site or for real-time processing on-site using the telecommunications network. The data collected at the Active GPS stations can be accessed in two ways:

a) The user accesses the geodetic website (http://www.osi.ie/gps/index.asp) and chooses the Active GPS station(s) and the observation period they require. This data is provided in separate RINEX files for each hour of observation and supplied over the Internet in a ZIP file to speed up download to the users' PC.
b) A Real Time Kinematic (RTK) service is provided for the four Active GPS stations located in Dublin (Belfield, Phoenix Park, Swords and Tallaght) where a differential correction is available in real-time via GSM mobile communications. OSI intend to extend this service to the other six OSI stations during 2004, to provide as much national coverage as the GSM mobile network will allow. Further extension of this national RTK service to more remote areas will follow the GSM rollout (Greenway, 2003).

OSI and OSNI are currently extending the Active GPS network by establishing additional stations in New Ross and Cavan, and since the three Commissioners of Irish Lights stations have as yet not come on-line, they might also consider establishing extra OSI stations along the western seaboard.


**Figure 9. Ireland's Active GPS Network (Cory *et al*, 2003).**

# *Further Developments*

## Network RTK (Real Time Kinematic)

Two differential techniques using a station with known co-ordinates as a reference station have been available for the last decade:

a) DGPS (Differential GPS) often meant to imply GIS grade GPS only, using single frequency observations, to sub-metre accuracy.
b) RTK (Real Time Kinematic) using dual frequency observations to centimetre level accuracy.

Both differential techniques degrade with increasing distance from the reference station due to distance dependent biases such as ionospheric refraction, tropospheric refraction, and to a lesser extent orbital errors. An additional differential technique was proposed in 1997 called network RTK, which uses a network of reference stations, rather than a single reference station used in the two existing techniques. With network RTK, the differential errors caused by the distant dependent biases are precisely estimated based on dual frequency observations of a network of reference stations. Correction model parameters are determined to allow the prediction of differential errors for the baseline between a virtual reference station close to the user's position, and the user's position (Wanninger, 2003).

The main advantage of this network RTK technique is a more accurate co-ordinate calculated for the user's position since the error resulting from the distance to the reference station is reduced. Additional advantages of this technique over the static GPS techniques are the lower fixed costs for equipment for survey teams since only one dual frequency receiver is needed, and time savings in the field since a set up on a local reference station is no longer necessary. Network RTK solutions such as GNSMART from Geo++ have been able to improve the accuracy down to ± 10 mm in position and ± 20 to 30 mm in height at ranges of 50 km by delivering a significant reduction in the error budget. With the fulfilment of some remaining technical issues, the final objective may be achievable, namely reliable 3D positioning with 1cm accuracy over long distances in real time (Snow, 2003).

OSI and Survey Instrument Services (SIS) have been testing network RTK since December 2003, and a Network RTK service is scheduled to be available to the general public in Beta test mode during spring 2004. Ultimately, this will be a chargeable service to fund the maintenance and future development of the service (Greenway, 2003).

### Glonass and Gallileo

Equipment and software to permit the combined use of the 'Glonass', the Russian GLObal, Navigation Satellite System, with the American GPS system are increasingly becoming available at present to provide for improved availability of satellites for observations and improved accuracy of computed co-ordinates. The EU Transports Committee and the European Space Agency are jointly developing the EU Global Navigation Satellite System (GNSS) called Galileo. The first EU satellite is scheduled to be transmitting by 2005 and the network of 30 satellites is scheduled to be fully operational by 2008.

## *Vertical Element of the GPS Networks*

Both the Passive and Active GPS control networks are three-dimensional in that GPS observations at a control station will yield ETRS89 co-ordinates (Latitude and Longitude and ellipsoidal height above the GRS80 ellipsoid). However, a model of the separation between the GRS80 ellipsoid and the geoid is required to convert these ellipsoid heights into orthometric heights referred to the national vertical datum at Malin Head. Since, the geoid model (OSGM02) jointly developed by OSI, OSNI and OSGB was published in 2002, it has since been possible to use these GPS networks to their fullest potential as 3D control networks.

The Quest software supplied by OSI and OSNI has this geoid model (OSGM02) embedded, so it can be used to convert ellipsoidal heights into orthometric heights as well as for co-ordinate transformations. As stated earlier, OSI and OSNI quote an accuracy of ± 20 mm for ellipsoidal heights published for the Passive GPS network (OSI and OSNI, 1999) and the accuracy of the Active GPS network is likely to be ± 10 mm from the network adjustment computations.

**Table 2. Accuracy assessment of the geoid model OSGM02 (Forsberg *et al*, 2002).**

| | Ireland | Northern Ireland |
|---|---|---|
| Maximum | 0.050 | 0.041 |
| Minimum | - 0.064 | - 0.035 |
| Mean | - 0.003 | 0.002 |
| Standard Deviation | 0.024 | 0.019 |

Although the quality of the geoid model has been initially assessed by the contractor who computed it as 0.048m in Ireland and 0.038m in Northern Ireland (Table 2) at a 95% confidence level (2σ), this assessment needs to be independently confirmed. OSI have agreed to fund a master degree by research to investigate the accuracy of the geoid model, and it is hoped that a suitable candidate can be found to commence this investigation during 2004.

# CO-ORDINATE REFERENCE SYSTEMS

Co-ordinate reference systems are theoretical, and as such are error free. However, once a system is realised to produce a set of co-ordinates for points on the ground, they incorporate observational and computational errors, and are then normally called co-ordinate reference frames to distinguish them from the error free 'systems'. The use of conventional nomenclature for co-ordinate reference systems has traditionally been somewhat loose both internationally and in Ireland, so the Task Force has attempted to use internationally accepted terms according to the International Organisation for Standardization (ISO, 2003).

## *Geodetic Co-ordinate Systems*

### International Terrestrial Reference System (ITRS)

The International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG) established the International Earth Rotation and Reference Systems Service (IERS) in 1987. One of the primary objectives of the IERS is to provide the International Terrestrial Reference System (ITRS), which is an ideal reference system, and is defined by the IUGG resolution No. 2 adopted in Vienna in 1991 (http://www.iers.org/iers/earth/resolutions/UGGI91.html). It constitutes a set of prescriptions and conventions together with the modelling required which defines its origin, scale, orientation and time evolution. The centre of mass of the earth constitutes the origin of the ITRF, the Z-axis being the mean axis of rotation of the earth, which breaks through the earth's crust at the "IERS Reference Pole" (consistent with the "Conventional International Origin" within the scope of the precision of realisation of ± 0.03"). The X-axis falls in the 0° meridian plane (Greenwich meridian).

The ITRS is realised by estimates of the co-ordinates and velocities of a set of stations observed by VLBI, (Very Long Baseline Interferometry), LLR (Lunar Laser Ranging), GPS, SLR (Satellite Laser Ranging) and DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite). The International Terrestrial Reference Frame (ITRF) is a set of points with their 3-dimensional Cartesian co-ordinates, which realise the ideal ITRS reference system. The ITRF is updated on an annual or biannual basis, and nine realisations of ITRF have been defined to date, called respectively ITRF89, ITRF90, ITRF91, ITRF92, ITRF93, ITRF94, ITRF96, ITRF97, and ITRF2000. Each is an improvement with respect to the previous ones, since more stations have been included and longer observation periods are used in order to obtain more reliable station co-ordinates and velocities.

Each realisation (ITRFyy) can be transformed into another realisation using a 7-parameter transformation model whose parameters are made available from the IERS website (http://lareg.ensg.ign.fr/ITRF/). It is also possible to have an ITRFyy propagated forward (or backward) in time using the station velocities, which reflect the effect of tectonic motion of the earth's crust. Since each realisation (ITRFyy) is produced as Earth-centred Cartesian co-ordinates (X, Y, Z) a reference ellipsoid must be used to convert to ellipsoidal co-ordinates (latitude, longitude and ellipsoidal height). The reference ellipsoid associated with recent realisations of ITRF is the Geodetic Reference System of 1980 (GRS80) ellipsoid.

## World Geodetic System 1984 (WGS84)

The US National Imagery and Mapping Agency (NIMA) and the US Department of Defence (DoD) developed WGS84 as a world geodetic reference system. The initial realisation of WGS84 was purely based on positions computed based on observations from the Transit satellite system and was only accurate at the one to two metre level. Over the years, the quality of the successive realisations of the WGS84 has improved considerably. A first step towards more consistency between the WGS84 and ITRS took place in 1993 when the complete WGS84 network was recomputed with respect to 8 GPS stations fixed to their ITRF91 position. A further improvement to the tracking station co-ordinates in 1996, led to WGS84 (G873) co-ordinates, which are consistent with the ITRF94 at a level better than 2 cm. As a consequence, for most practical applications, there is no difference between co-ordinates in the WGS84 or ITRS. The WGS84 ellipsoid is identical to the GRS80 ellipsoid (used by ETRS) at the mm level (Table 3), so for practical purposes they are assumed to be the same.

**Table 3. Minor differences between the GRS80 and WGS84 ellipsoids.**

| | **Defining Parameters of Ellipsoids** |
|---|---|
| WGS84 | a = 3 378 137.000<br>$e^2$ = 0.006 694 379 9 |
| GRS80 | a = 3 378 137.000<br>$e^2$ = 0.006 694 380 022 90 |

## European Terrestrial Reference System 1989 (ETRS89)

The main disadvantage of ITRS and WGS84 is that they are global systems, and due to plate tectonics, co-ordinates on the different continents move with respect to each other. For example, there is displacement of ETRS89 with respect to ITRF of approximately 3cm per year, and this motion with respect to time makes these co-ordinates unsuitable for practical cartographic and engineering applications of cm-precision. To remedy this problem, the IAG (International Association of Geodesy) and CERCO (Comité Européen des responsables de la Cartographie Officielle) decided, in 1987, to develop a new European Terrestrial Reference System (ETRS) based on GPS. The new system was designed to provide a modern continent-wide reference frame for multinational digital cartographic datasets, and to unify national reference systems for surveying, mapping, GIS and navigation in Europe.

The IAG and CERCO decided to base the new ETRS on the ITRS, so 37 European SLR and VLBI sites were selected whose ITRF89 co-ordinates would define the first realisation of the ETRS, called ETRS89. It was also decided to include a defined epoch (1989.0) for the ETRS in order to avoid time varying co-ordinates, which is of huge importance for practical applications, hence ETRS89 (defining the epoch at system level is unusual, since epochs are normally defined at framework level). Consequently, ETRS89 rotates together with the stable part of Europe (Figure 10), so that the station-to-station relations are kept fixed. From that date, all successive realisations of the ETRS89 have been computed by simply rotating the positions back to the place of the European plate at the epoch 1989.0. Similar to the ITRS, ETRS89 also uses the GRS80 ellipsoid, and ETRS89 provides a continental accuracy in Europe in the 10 – 20 mm range. During the last 15 years ETRS89 has become the *de facto* positioning standard within the member states of the European Union.

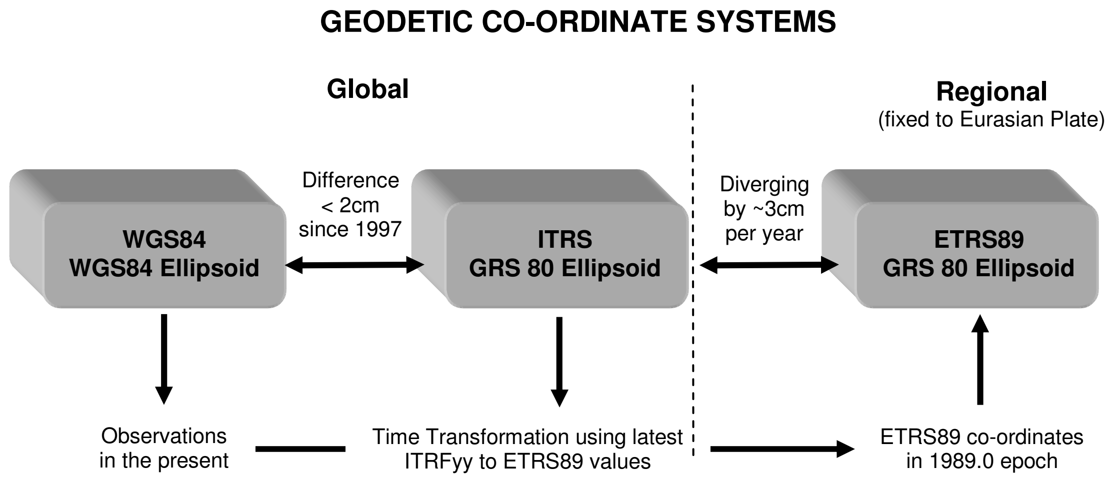



**Figure 10. Relationship between European geodetic co-ordinate system ETRS89 and the global geodetic co-ordinate systems WGS84 and ITRS.**

In practice, surveyors need not concern themselves with this transformation back in time to the 1989 epoch of the ETRS89 co-ordinate system, since connecting their survey to a station of the Active or Passive GPS Networks and using its published ETRS89 co-ordinates will have the same effect.

# *Projected Co-ordinate Systems*

## Irish Grid (IG)

The Irish Grid (IG) co-ordinate reference system (Table 4) was jointly designed by OSI and OSNI during the 1950s to provide a common reference system for the island of Ireland. Improvements to previous County based reference systems used in Ireland included:

a) Adoption of the international metre to replace non-standard imperial measurements (feet of bar $O_1$);
b) Adoption of one projection for the whole island to replace separate projections for each of the 32 counties;
c) Adoption of the conformal Transverse Mercator projection to replace the non-conformal Cassini projection;
d) Introduction of the metric Irish Grid for the whole island to replace separate imperial grids for each county.

Since equipment, observations and computation procedures can change over time, it is possible to produce different realisations of the same reference system for different epochs in time. As already stated in the section dealing with the Re-Triangulation, three realisations of the Irish Grid have been defined to date, which are:

a) The Irish Grid (1952) adjustment of Northern Ireland used by OSNI between 1952 and 1975;
b) The Irish Grid (1965) adjustment of the whole island used by OSI between 1965 and 1975;
c) The Irish Grid (1975) mapping adjustment of the whole island used by OSI and OSNI since 1975.

The Irish Grid (1975 mapping adjustment) was universally adopted by the public and private sectors as the operational co-ordinate reference frame for Ireland, and has been known colloquially as the 'Irish National Grid' for the past 30 years. Although there have been recent attempts to change the name of these co-ordinates to 'Irish Grid' by OSI and OSNI, the term 'Irish National Grid' or just 'National Grid' is still in everyday use by the surveying and construction community.

Surveyors have struggled for the past 30 years with the ambiguities of the Irish Grid (1975) co-ordinate reference frame, and there is little point in continuing to 'tweak' this system and produce more realisations of increasingly 'better' co-ordinates. The Irish Grid (1975) co-ordinate reference frame provided a coherent mapping framework for Ireland for second half of the 20$^{th}$ century. However, it has been superseded in 2002 by the ITM co-ordinate reference frame to provide a more rigorous and GPS compatible co-ordinate reference system for the 21$^{st}$ century.

## Irish Transverse Mercator (ITM)

The Irish Transverse Mercator (ITM) co-ordinate reference system (Table 4) was jointly designed by OSI and OSNI in 2000 as part of a GPS compatible co-ordinate reference system for Ireland. Improvements from the previous Irish Grid co-ordinate reference system include:

a) Adoption of GRS80 ellipsoid instead of the Airy modified ellipsoid, to ensure the system is GPS compatible.
b) Adoption of a sub unity scale factor for the central meridian of the projection to ensure projection distortions are as close to unity as possible and are symmetrical across Ireland.
c) Adoption of different false origin from the Irish Grid to ensure co-ordinates in both Irish Grid and ITM co-ordinate reference systems are easily distinguishable.

**Table 4. Defining parameters for the Irish Grid and Irish Transverse Mercator co-ordinate reference systems (OSI and OSNI, 2001).**

| | IG | ITM |
|---|---|---|
| Map Projection | Transverse Mercator | Transverse Mercator |
| True Origin | $8^0$ 00' 00" West<br>$53^0$ 30' 00" North | $8^0$ 00' 00" West<br>$53^0$ 30' 00" North |
| False Origin | 200 000 m West<br>250 000 m South | 600 000 m West<br>750 000 m South |
| Ellipsoid | Airy Modified | GRS80 |
| Scale Factor of Central Meridian | 1.000035 | 0.999820 |
| Measurement Unit | International Metre | International Metre |
| Vertical Datum | Malin Head | Malin Head |

The ITM co-ordinate reference system was first realised in 2002 when ITM co-ordinates were published on the OSI geodetic website. Consequently, the Irish Institution of Surveyors considers that ITM is an official co-ordinate reference frame, and of equal status to the Irish Grid (1975) co-ordinate reference frame since the date of publication of the ITM co-ordinates. The current use of ITM for all OSI data capture and data storage also gives credence to the fact that ITM has already been adopted as an official co-ordinate reference frame by OSI. It is anticipated that ITM will be recommended by OSI and OSNI to supersede the Irish Grid (1975) as the preferred co-ordinate reference frame for Ireland when the final report of the ITM Technical Working Group is published in the near future.

## Universal Transverse Mercator (UTM)

Universal Transverse Mercator (UTM) is a global co-ordinate reference system initially developed by the U.S. military but now also used commercially, which permits UTM co-ordinates to be defined for anywhere on the globe, except the poles (separate Universal Polar Stereographic (UPS) system is available for the poles). It divides the earth's surface into a series of zones defined by columns and rows. Columns are numbered 1 to 60 from $180^0$ West to $180^0$ East in $6^0$ intervals of longitude and rows have letters from C to X (I and O are omitted) from $80^o$ South to $84^o$ North in $8^o$ intervals of latitude (top row is $12^0$ of latitude from $72^0$N to $84^0$N). A number and a letter can uniquely reference each zone, so Ireland lies in zone 29U, within $6^0$ - $12^0$ West and $48^0$ - $56^0$ North. A small portion of County Antrim and

County Down lie east of the $6^0$ meridian, but mapping overlaps of up to 40 kilometres are permitted between zones, so it would be possible to include these areas on mapping for the UTM zone 29U.

UTM initially used a number of ellipsoids for different areas of the world, such as Clarke 1866 in the USA for example, but it is increasingly becoming common practice to use the WGS84 or the GRS80 ellipsoids. Each zone uses a Transverse Mercator projection aligned along the central meridian of the zone, which in Ireland's case is $9^0$ west. A grid is aligned along the central meridian, which is given a false easting of 500 000 mE. The origin for northings in the northern hemisphere is the intersection of the central meridian and the equator ($0^0$N and $9^0$W in Ireland's case) which is assigned a northing value of 0 mN, so grid references in Ireland would have a six digit Easting and a seven digit Northing. A scale factor of 0.9996 is applied to the central meridian in each zone.

The UTM co-ordinate reference system is used by Eurostat, the EU statistical organisation as an ideal system for combining digital mapping from many EU member States and presenting EU data on a homogeneous European co-ordinate reference system.

# ACCURACIES FOR PRECISE SURVEYING

Accuracy is defined as the difference between the '**true value**' of a measured quantity and the '**most probable value**', which has been obtained from measurement. However, since it is never possible to determine the 'true value' exactly, the assessment of survey accuracy is quoted relative to the 'most probable value' determined by precise survey methods.

## *Absolute and Relative Accuracy*

The accuracy of the 'most probable value' of any survey point can be described in two ways (Figure 11):

a) **Absolute Accuracy** is the accuracy of the position of a point relative to a national grid system. Therefore, absolute accuracy is the combined accuracy of the observations of a measurement and the datum (co-ordinate reference system to which the survey is connected).
b) **Relative Accuracy** is the accuracy of the position of a point relative to an adjacent data point, which is controlled by the precision of the observations of the measurement taken to calculate the position of the point.

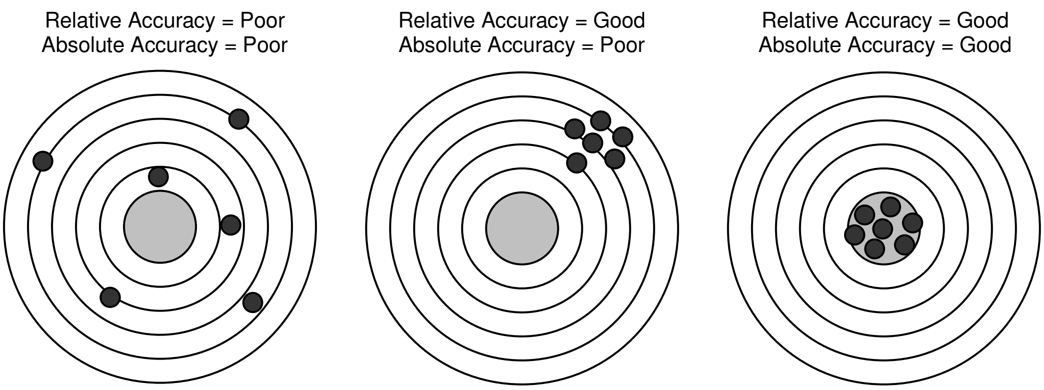



**Figure 11. Distinction between relative and absolute accuracy.**

## *Precision and Standard Error*

Precision is a measure of repeatability of observations of a survey instrument, and resolution is the smallest interval measurable by an instrument. Whereas the resolution of an instrument will dictate certain constraints on how it can be used to achieve certain accuracy, the precision of a set of observations by an instrument is expressed by the standard deviation of its observations.

Standard deviation is usually taken as a measure of the spread of a set of observations (of the same quality) of a single measurement, whereas standard error is a measure of the reliability of the mean of a set of observations. An analysis of the residuals and the standard error of a set of observations will give an estimate of the precision of the observations: a small standard error signifies high precision, and accurate determination of standard error is only possible using large numbers of observations.

Provided gross and systematic errors are absent, there is a 68.3% probability that the "most probable value" of the measurement lies within $\pm 1\sigma$ of the mean value of the series of observations. Similarly there is a 95.4% and a 99.7% probability that the "most probable value" of the measurement lies within $\pm 2\sigma$ and $\pm 3\sigma$ respectively of the mean value of the series of observations. It is normal surveying practice to adopt $2\sigma$ or a 95% confidence level for survey measurements, unless otherwise stated.

## *Accuracy Possible from the GPS Control Networks*

Manufacturers typically quote the system accuracy for dual frequency GPS equipment as ± (5 mm + 1ppm). The 1ppm is an error due to the difference in atmospherics (ionospheric and tropospheric refraction) between the two GPS stations, and the 5 mm is due to a system error resulting from the resolution of the measurement process. Consequently the resulting accuracy of GPS co-ordinates equates to ± (5 mm + 1 mm) for every kilometre between the roving station and the base station. Centring errors (2 mm) at each end of the baseline being observed are also encountered. These result from errors in setting up over the control stations (due to human error or misaligned optical plummets), errors due to misalignments of the antennae, errors due to incorrect reading of the height of the antennae above the control station, and errors in the phase centres of the antennae. If these errors are considered as standard errors, then the relative accuracy of a 20 Km baseline is given by propagation of error theory as:

$$\text{Standard error } (\sigma) = \sqrt{(2^2) + (2^2) + (5^2) + (20^2)} = 20.81 \text{ mm}$$

Where the first and second terms are centring errors and the third and fourth terms are the system errors ± (5 mm + 1ppm). If one end of the baseline is located on one of the Passive GPS control stations (which have an absolute accuracy of ± 20 mm), then the absolute accuracy for a point at the end of the same 20 Km baseline is given by propagation of errors as:

$$\text{Standard error } (\sigma) = \sqrt{(20^2) + (2^2) + (2^2) + (5^2) + (20^2)} = 28.86 \text{ mm}$$

One of the many factors, which can have a significant bearing on accuracy of GPS surveys, is the distance between the base and rover stations. With this in mind the Task Force examined the coverage provided by the Passive and Active GPS Networks in order to define the optimum accuracy achievable nation-wide. Figures 12, 13 and 14 indicate the coverage of the Passive GPS network at radial distances of 15 km (Figure 12), 20 km (Figure 13), and 25 km (Figure 14) respectively. All diagrams include the currently available 161 control stations (▲), the 6 missing passive GPS stations in Ireland (■), and the 16 active GPS stations (●) marked with the indicated symbols. Whereas a distance of 15 km provides coverage for approximately 80% of Ireland, a distance of 20 km provides coverage of approximately 95%, and a distance of 25 km increases the coverage to 98%. Consequently, coverage at a distance of 20 km is considered by the Task Force to give the widest national coverage of optimal accuracy. This means that an absolute accuracy of < 60 mm (28.86 x 2) at a 95% confidence level ($2\sigma$) would be possible from the Passive GPS network using baselines of 20 Km or less for 95% of Ireland and Northern Ireland.

However, OSI have stated that they only intend to maintain the zero order and Active GPS Networks (OSI, 2001). This means that although the Passive GPS network can provide an absolute accuracy of < 60 mm for 95% of the island of Ireland, it may not be possible if the network is not maintained. However, since the accuracy of the Active GPS network is likely to be higher at ± 10 mm and there is no centring error at the Active GPS station, the relative accuracy for a 20 km baseline from the Active GPS network is given by propagation of error theory as:

$$\text{Standard error } (\sigma) = \sqrt{(2^2) + (5^2) + (20^2)} = 20.71 \text{ mm}$$

Where the first term is the centring error for the rover station, and the second and third terms are the system errors. Similarly the absolute accuracy for a 20 Km baseline from the Active GPS network is given by the propagation of errors as:

$$\text{Standard error } (\sigma) = \sqrt{(10^2) + (2^2) + (5^2) + (20^2)} = 23.00 \text{ mm}$$

These computations suggest that longer baselines would be possible from the Active GPS network to meet the absolute accuracy standard of < 60 mm (2σ) for precise surveying operations, and it may be possible to extend these baselines further if multiple Active GPS stations are used during the post processing.

OSI agreed in May 2003 to conduct a series of tests of the Active GPS network to:

a) Quantify the absolute accuracy obtainable by post-processing multiple Active GPS stations over extended distances to determine the coverage of absolute accuracy of < 60 mm (2σ) from this network.
b) Quantify the repeatability of absolute accuracy obtainable by post-processing multiple Active GPS stations over extended distances.

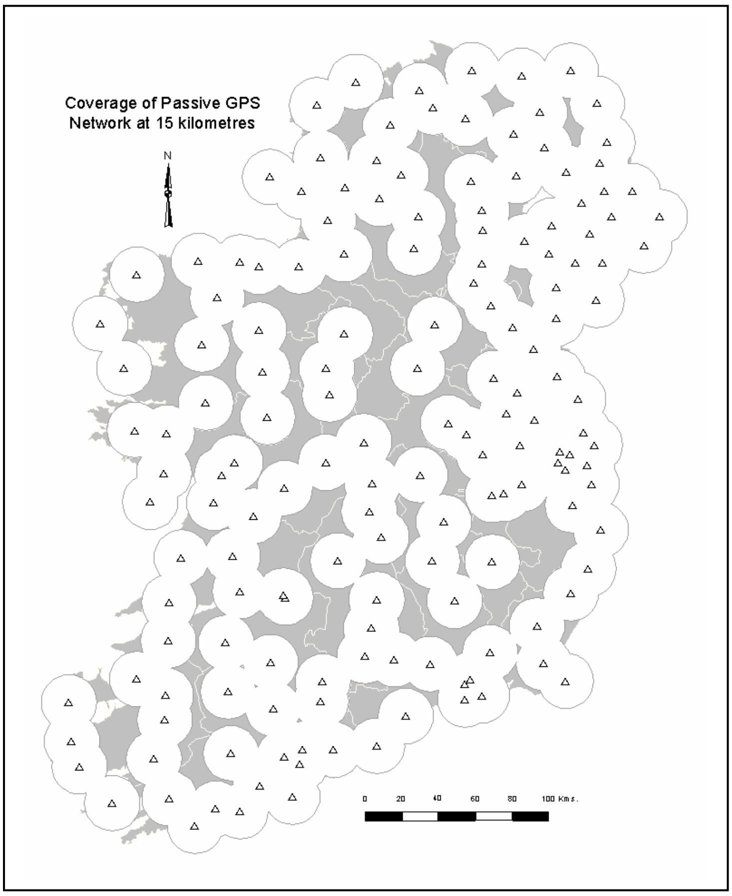



**Figure 12. Coverage of the Passive GPS Network at 15 kilometres (~ 80%).**

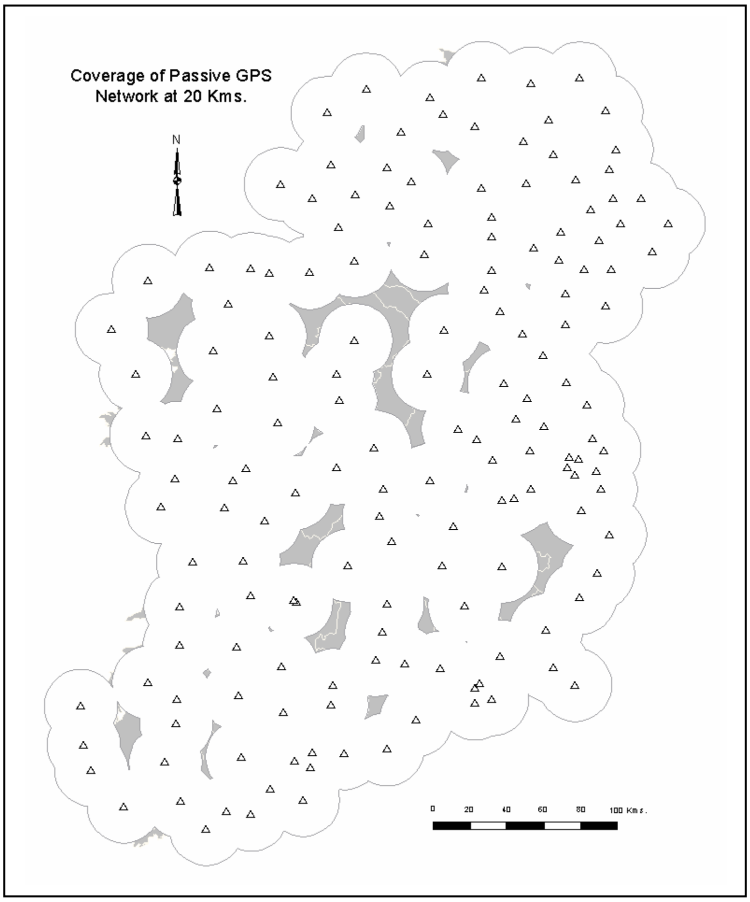



**Figure 13. Coverage of the Passive GPS Network at 20 kilometres (~ 95%).**

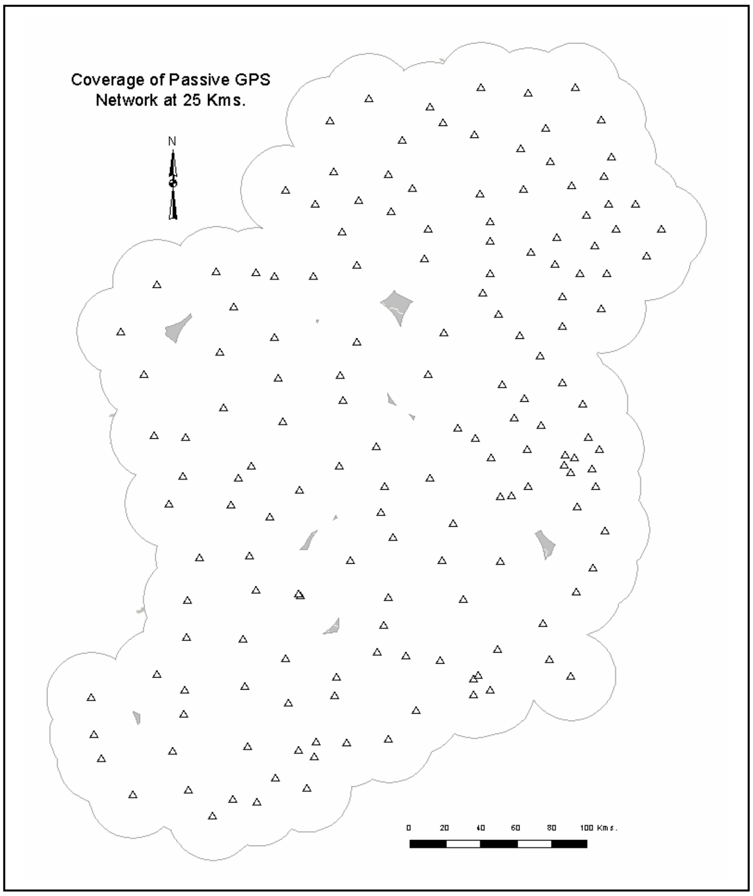



**Figure 14. Coverage of the Passive GPS Network at 25 kilometres (~ 98%).**

Preliminary indications from private surveying firms suggest that it may be possible to achieve an absolute accuracy < 60 mm (2σ) with baselines of 40 to 50 km from the Active GPS network when using at least 3 control stations in the calculation. The Active GPS network provides a national coverage of approximately 80% at radial distances of 50 km (Figure 15), once the additional Active GPS stations are established at Cavan and New Ross by OSI. However additional stations may be required along the western seaboard, even if the CIL stations eventually come on-line, to provide sufficient coverage at these radial distances.


**Figure 15. Coverage of the Active GPS Network at 50 km (CIL sites not yet operational).**

## *Accuracy Specification of Survey Contracts*

Information from private surveying firms suggests that relative accuracy tolerances specified in survey contracts for major construction projects are increasingly becoming tighter, and a survey of GPS use in surveying firms (Appendix B) confirms this situation (Table 5).

**Table 5. Most common relative accuracy (1σ) requested for precise surveying projects.**

| | Eastings | Northings | Height |
|---|---|---|---|
| Max | 0.030m | 0.030m | 0.025m |
| Min | 0.002m | 0.002m | 0.003m |
| Mean | 0.011m | 0.011m | 0.010m |

The previous section established that:

a) The relative accuracy of project control using dual frequency GPS equipment from the Passive and Active GPS Networks is 20.81 mm and 20.71 mm respectively at a distance of 20 Km from the survey site to the stations of the GPS Network.

b) The network requirements in order to ensure that an absolute accuracy of < 60 mm for project control is achievable nation-wide from the GPS Networks.

Higher relative accuracy for project control can be achieved for survey contracts by modifying observation procedures, or by operating at reduced distances between the survey site and the stations of the GPS networks. However, the location of the survey site relative to the stations of the GPS networks will dictate the size of the error resulting from distance, so modifying observation procedures may provide the only opportunity for achieving higher relative accuracy. One means of achieving higher relative accuracy is by having multiple observation sessions, and the experience of private surveying firms indicates that the following relative accuracies are possible for project control with multiple sessions using GPS in static mode:

a) ± 22 mm using one session in static mode from one GPS station.
b) ± 15 mm using two sessions in static mode from two GPS stations.
c) ± 10 mm using multiple sessions in static mode from multiple GPS stations.

The two main benefits for using multiple baselines to at least three stations of the GPS network are:

a) Residuals can be calculated for computed co-ordinates, so an analysis of the reliability of the results is possible;
b) Rogue observations can be identified and eliminated from the computation.

Since survey instruments are available in a range of different specifications, 1”, 5” and 10” theodolites for example, measurements made with them have different relative accuracy. Figure 16 graphically presents relative and absolute accuracy (2σ) at a 95% probability for ITM co-ordinates surveyed from the Passive GPS network at a range of 5 km using a selection of surveying equipment and techniques (Appendix D, Figure D1). The black circles indicate the size of the relative accuracy for each instrument, and the distance of the centre of each black circle from the bulls’ eye indicates the absolute accuracy of those measurements on the ITM co-ordinate reference frame. The smaller the black circle the better the relative accuracy and the closer to the bull’s eye the better the absolute accuracy.

The absolute accuracy of survey data is dependent on:

a) The survey instruments and observation procedures used.
b) The absolute accuracy of the geodetic control network on which the survey is based.
c) The co-ordinate reference system used to supply the survey data.

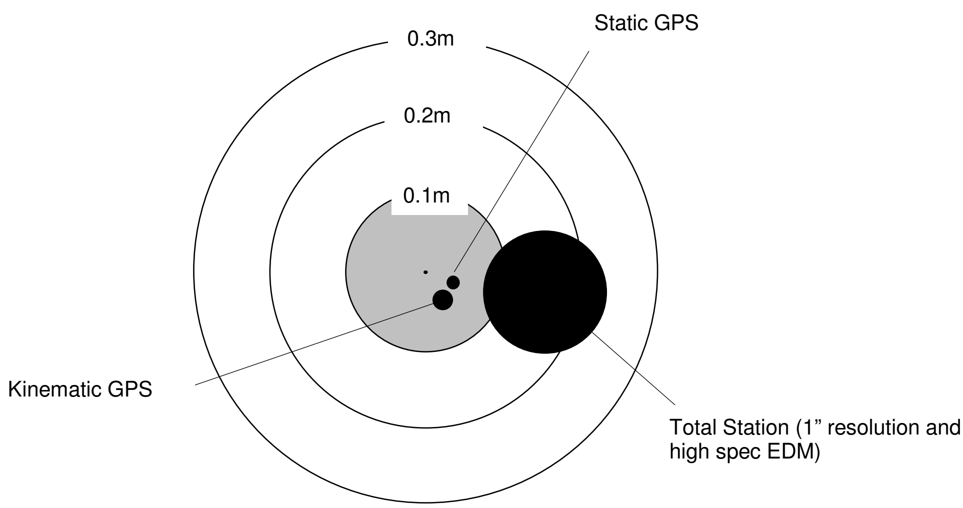



**Figure 16. Estimated absolute and relative accuracy (2σ) of ITM co-ordinates surveyed from the Passive GPS Network at a range of 5 km using various surveying instruments.**

Relative and absolute accuracy (2σ) at 95% probability for IG75 and ITM co-ordinates surveyed using GPS in static mode from the different control networks at a range of 5 km are graphically presented (Figure 17). It is obvious that the relative accuracy of each of the measurements is similar since GPS in static mode was used for each. The relative accuracy from the Active GPS network is slightly better at 14.70 mm compared to 15.23 mm from the Passive GPS network and the Trig Network because there is no centring error at the Active GPS network station. However, it is interesting to note the significant improvement in absolute accuracy by using the ITM co-ordinate reference frame instead of the IG75 co-ordinate reference frame.

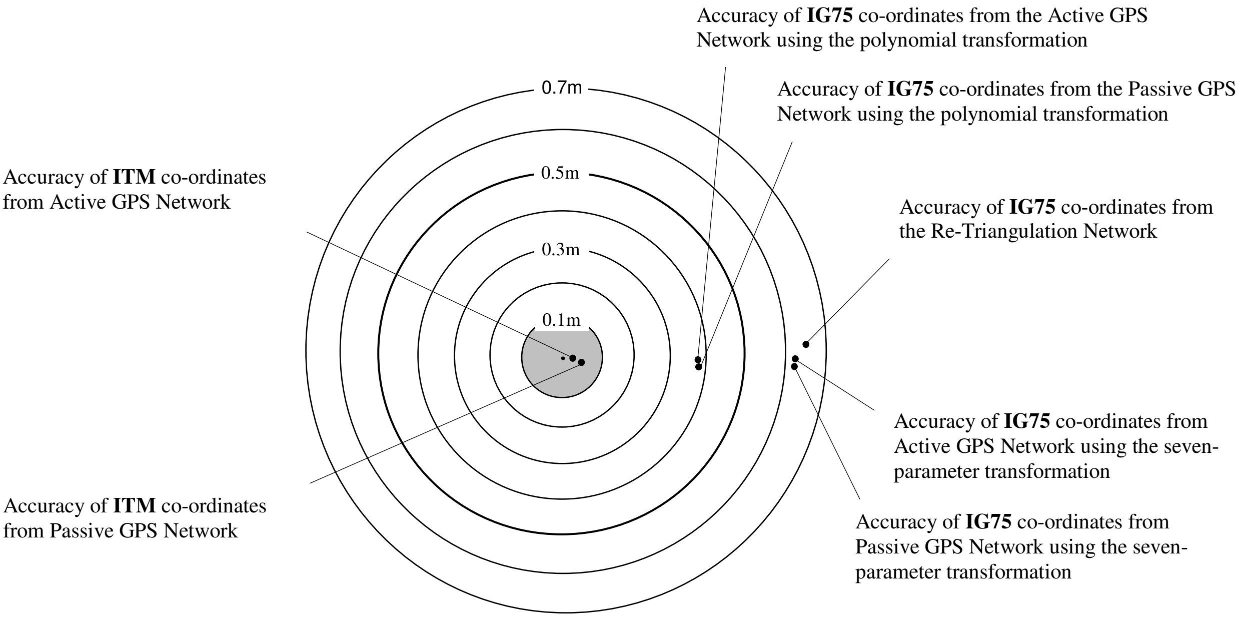



**Figure 17. Estimated absolute and relative accuracy (2σ) of IG75 and ITM co-ordinates surveyed at a range of 5 km using GPS in static mode from different control networks.**

If the ETRS89 co-ordinates of the GPS networks are adopted as the basis of co-ordinate computation for precise surveying, then it is possible to adopt the ITM co-ordinate reference system without any difficulty. However, if clients retain the IG75 co-ordinate reference system for collecting and storing survey data, using the seven-parameter or polynomial transformations to present it in the IG75 system degrades the quality of survey data collected. Therefore the ITM co-ordinate reference system should replace the IG75 co-ordinate reference system as the official reference system for Ireland as soon as possible for data capture and data storage. This will have significant implications for users with existing IG75 data, and with developing new improved specifications for survey contracts, but the benefits far outweigh the disadvantages.

The provision of project control for precise surveying will require GPS equipment in future to connect to the GPS networks in order to attain the absolute and relative accuracy proposed by these guidelines. GPS equipment is required in future because:

a) The stations Active GPS network are continually occupied, so surveys from this network are only possible with GPS equipment
b) The stations of the Passive GPS network are generally located in the lowlands and are not inter-visible, as the trigonometric pillars on the hills were. Consequently, the Passive GPS stations are not suitable for traditional surveying equipment such as total stations, which require viewing a reference object.

# DISCUSSION OF TEST RESULTS

## *Supply of Horizontal Control*

### Passive GPS Network

During the course of the investigation the Task Force noted that 11 stations of the Passive GPS network (D009, D016, D025, D030, D036, D057, D070, D095, D119, D123, and D144) were unavailable since the Network was established in 1996, and another station (D003) became unavailable in early 2003. Six of these stations are located in Ireland (D003, D070, D095, D119, D123, and D144), all of which have been destroyed, and six are located in Northern Ireland (D009, D016, D025, D030, D036, D057). Three of the stations located in Northern Ireland have been destroyed, although the Active GPS control station in Omagh has effectively replaced one of these. Another two stations (D030 and D036) are co-located with a fundamental benchmark and the Active GPS station in Belfast, and due to an anomaly in the original naming convention for the Passive GPS network station D057 never existed. This means that 8 stations have been destroyed, and three are unavailable for occupation since the system was provided in 1996 (Figure 18).

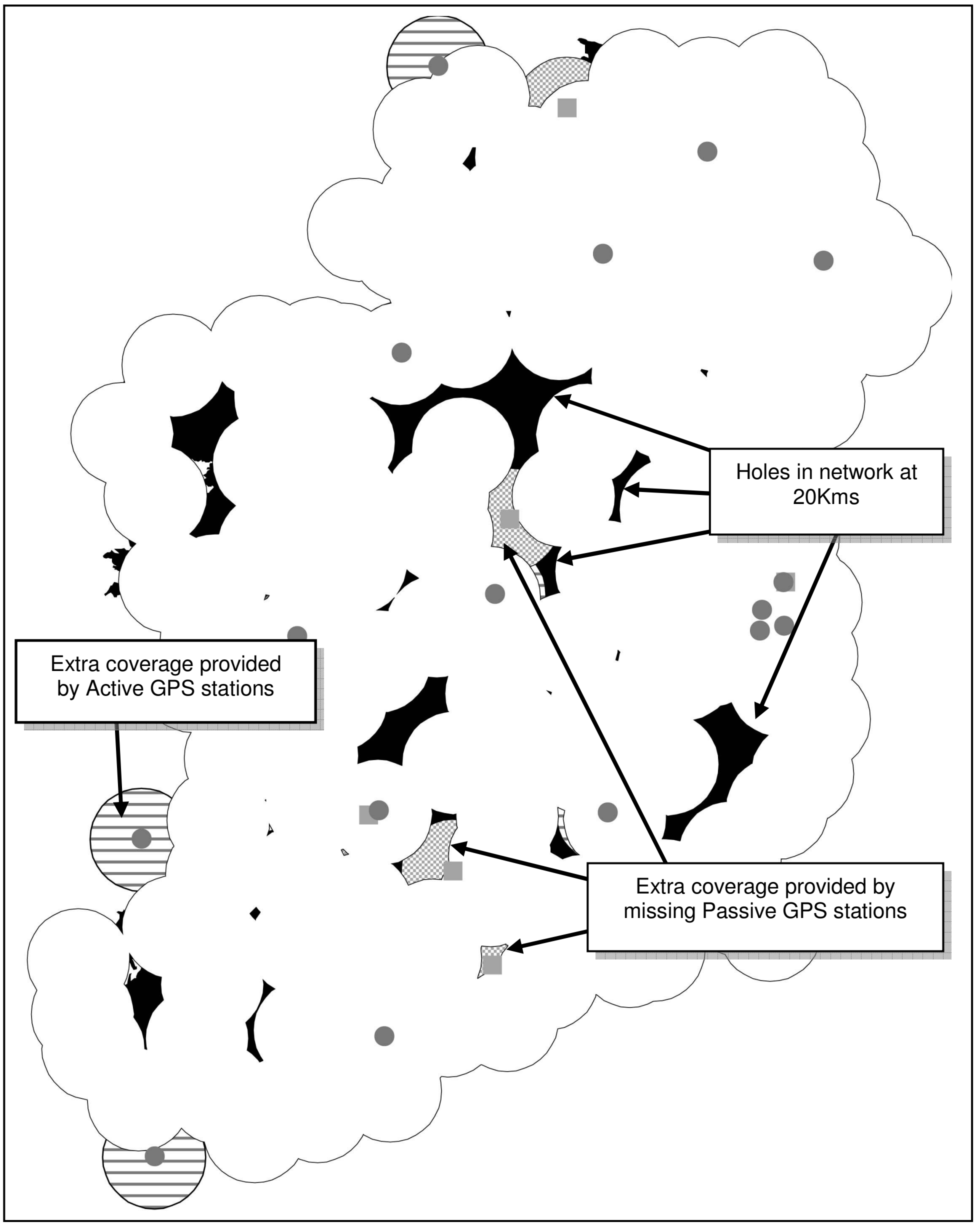



**Figure 18. Holes in the Passive GPS Network at 20 km coverage.**

This rate of loss of 6.4% (11 stations from a total of 172) is alarming and will quickly become significant if not urgently maintained. The fact that holes have already appeared in the network as a direct result of the missing stations (Figure 18) is also highly significant. Therefore, if a specification of 20 kms coverage is adopted to provide an absolute accuracy < 60 mm (2σ) for precise surveying operations then the black areas (Figure 18) represent holes in the Passive GPS network not covered at this specification. The grey areas represent holes in the network, which would have coverage if the six missing OSI Passive GPS stations were re-instated (four of these six stations are contributing to the degradation of the network). The coverage is also extended by the three Active GPS stations located at Commissioners of Irish Lights sites (although the majority of the additional coverage lies offshore, and these stations have yet to become operational) and slightly by the two Active GPS stations located at Athlone and Kilkenny. It is noteworthy that there are no significant holes in the network in Northern Ireland, even without the missing Passive GPS stations located there.

OSI announced in 2001 that they do not intend to maintain this Passive GPS Network, and that the Active GPS Network, when proven stable and reliable, will become the new standard for the realisation of ETRS89 in Ireland (OSI, 2001).

## Active GPS Network

The data available on-line for the Active GPS stations is of a very high quality and the results achieved for computing the position of D147 using medium and long baselines are extraordinarily good and bode well for the future. However, the provision of the Active GPS network is still a work in progress, and although the available stations are now stable, they are not yet reliable from the perspective of when and if the data for any individual station becomes available, and the unavailability of data for the CIL stations poses particular problems along the western seaboard.

The positional accuracy of points computed using GPS observations from the Passive GPS network is normally calculated using the formula ± (5 mm + 1ppm). If the design of the Active GPS network only provides coverage of the whole island of Ireland at radial distances of 65 km (Figure 19), then this formula predicts an accuracy at a 65 km range to be ± 70 mm (1σ), which falls short of the preferred accuracy standard (< 60 mm @ 2σ). However, the test of the Active GPS network (Appendix C) suggests that this accuracy formula of ± (5 mm + 1ppm) can be beaten, due to the improved quality of the Active GPS network, the quality of equipment used at the Active GPS stations, and by increasing observation periods and using multiple Active GPS stations in network computations.

The imminent availability of a Network RTK solution during 2004 attempts to significantly reduce the distance related error (1ppm) in this accuracy formula ± (5 mm + 1ppm) by simulating an Active GPS station adjacent to the project site. It does this by collecting Met readings at the Active GPS stations and using them to produce an atmospheric model, which is then used to predict biases due to ionospheric refraction and tropospheric refraction at the project location. It is likely that this distance related error of 1ppm will not be eliminated altogether, however results from Germany and other countries indicate that it should be significantly reduced. If this turns out to be the case perhaps the preferred accuracy standard (< 60 mm @ 2σ) might be achievable using this observation technique. However, it may be well into 2005 before the new technique has been sufficiently investigated to establish this.

The current design of the Active GPS network fails to provide sufficient coverage in the west Mayo/Galway area, even if the CIL stations eventually become operational. The establishment of an extra Active GPS station in the Newport area would rectify this failing (Figure 19).

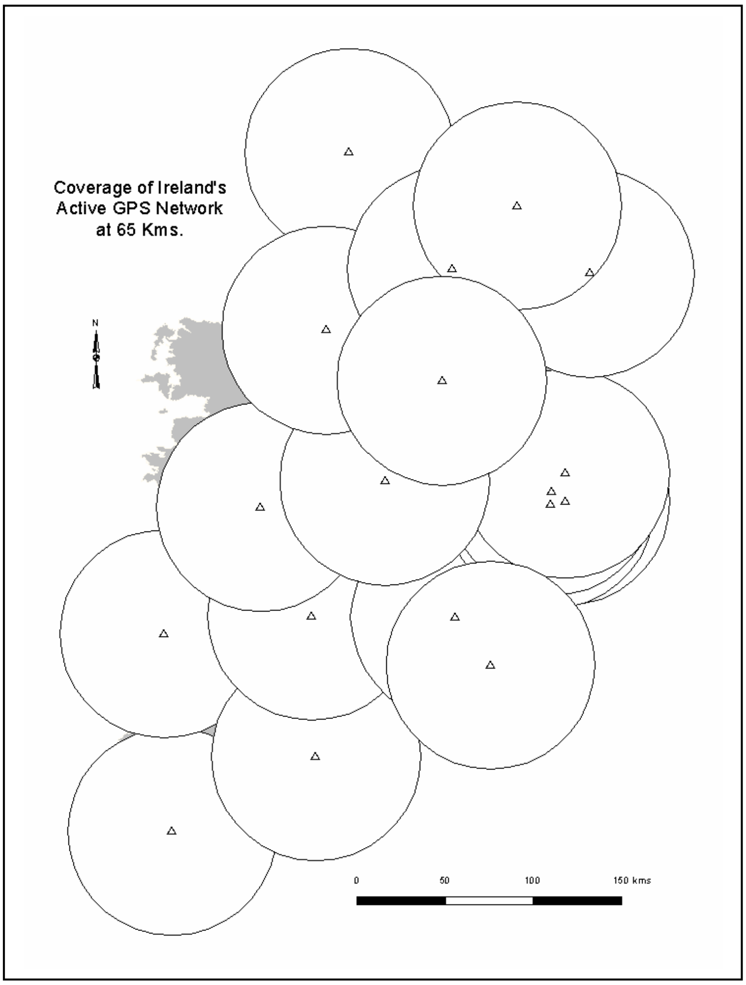



**Figure 19. Coverage of Ireland's Active GPS Network at 65 km coverage.**

## Conclusions

It is the view of the Irish Institution of Surveyors that the surveying community needs a control network that is fully operational, and provides national coverage at an absolute accuracy of < 60 mm (2σ). The Passive GPS network as currently designed supplies 95% coverage, but this has decreased due to the recent loss of stations. Similarly the Active GPS network currently only supplies 80% coverage to meet this accuracy specification (when the new stations in Cavan and New Ross come on-line). The provision of a Network RTK solution from the Active GPS network during 2004 should significantly assist in supplying co-ordinates to the necessary standard, but the network will require extension especially along the western seaboard to provide full coverage to this standard.

## *Supply of Vertical Control*

The accuracy of the geoid model is estimated to be 0.048 m in Ireland and 0.038 m in Northern Ireland at a 95% confidence level (Table 6). However, as a preliminary test of the new technique (via OSGM02) for producing orthometric heights, a hypothetical accuracy of ± 100 mm (more than twice the initial assessment of accuracy of OSGM02) was adopted for the geoid model. A basic assumption made by the Task Force before conducting these tests was that the published ETRS89 co-ordinates and ellipsoidal heights were correct, since they had been independently quality assured by EUREF to have an accuracy equivalent to ± 20 mm in latitude, longitude and ellipsoidal height.

**Table 6. Accuracy assessment of the geoid model OSGM02 (Forsberg *et al*, 2002).**

| | Ireland | Northern Ireland |
|---|---|---|
| Maximum | 0.050 | 0.041 |
| Minimum | - 0.064 | - 0.035 |
| Mean | - 0.003 | 0.002 |
| Standard Deviation | 0.024 | 0.019 |

Orthometric heights were calculated from the published ellipsoidal heights using the Quest software and compared with the published orthometric heights (Appendix A, Tests 12, 13 and 14). The residuals between the published and calculated orthometric heights were less than ± 100 mm for 103 (80%) of the 128 Passive GPS stations located in Ireland and for 38 (97%) of the 39 Passive GPS stations located in Northern Ireland (Table 7). At the time of carrying out the tests the Task Force did not appreciate the fact that they were using the same data to evaluate the quality of OSGM02 from which the geoid model was created, since very little published data was available at that time. Nevertheless, the tests yielded interesting results.

**Table 7. Residuals between published orthometric heights for the Passive GPS Network and orthometric heights calculated from the ellipsoidal heights using the geoid model in the Quest software.**

| | Residuals < ± 100 mm | | Residuals > ± 100 mm | |
|---|---|---|---|---|
| | OSI | OSNI | OSI | OSNI |
| | 103 Stations | 38 Stations | 25 Stations | 1 Station |
| Max | 0.072 | 0.081 | 3.959 | |
| Min | - 0.096 | - 0.067 | - 1.221 | - 0.141 |
| Mean | - 0.004 | 0.030 | - 0.003 | |
| St Dev | 0.030 | 0.032 | 0.411 | |

When the locations of these 26 Passive GPS stations (with residuals > ± 100 mm) were plotted, three clusters were identified in Monaghan, Cork and Galway (Appendix A, Figure A1) suggesting there might be particular difficulties with orthometric heights in these three areas, although quite a number of these 26 Passive GPS stations are located in upland areas where spirit levelling is notoriously difficult, and the cluster in Galway is located west of the area covered by the geodetic levelling network.

OSI and OSNI were supplied with the test results for these 26 Passive GPS stations (Appendix A, Table A1) in March 2003, and they stated that many of the Passive GPS stations had not been spirit levelled and consequently do not have reliable orthometric heights, since their heights may have been produced by alternative means such as trigonometric heighting, or transfer of orthometric heights by GPS. Seventeen of the 26 Passive GPS stations identified by the Task Force were omitted from the computation of the geoid model (D017, D031, D045, D048, D049, D050, D062, D067, D071, D074, D075, D078, D083, D129, D146, D156 and D173) due to the unreliability of their height data. OSI have also confirmed the unreliability of published orthometric heights for the remaining 9 Passive GPS stations (D001, D013, D072, D086, D114, D115, D117, D121 and D170), and decided to delete all orthometric heights published for the Passive GPS stations in May 2003. The definitive method now for supplying heights for these stations will be to convert the published ellipsoidal heights of the GPS stations into orthometric heights using the geoid model (OSGM02) in the Quest software.

The Task Force suggests the following reasons why the Active and Passive GPS Networks should be used for supplying orthometric heights in preference to the Levelling Network:

a) The technology used to observe and the improved adjustment methods used to compute the GPS Networks, are an order of magnitude more accurate than the older observation and adjustment methods.
b) Although the primary levelling network of fundamental benchmarks was simultaneously adjusted, the secondary and tertiary networks were adjusted in blocks, which give rise to discrepancies across adjustment block boundaries.
c) OSI and OSNI quote an accuracy for ellipsoidal heights of ± 20 mm for stations of the Passive GPS Network, and an accuracy of ± 10 mm is likely or stations of the Active GPS Network. An accuracy statement was never quoted for benchmark values of the Levelling Network, but this is estimated at ± 0.100 m (Appendix D).
d) Maintenance of the Levelling Network was discontinued in the early 1990s.

Notwithstanding this decision to adopt a new technique to supply orthometric heights, the following problems need to be examined:

a) The independent supply of heights to adjacent projects may meet relative accuracy tolerances internally, but may not be in sympathy with each other;
b) The need for networks of benchmarks within urban areas should be discussed and the responsibility for their supply and maintenance if found to be necessary.
c) The re-observation of levelling networks including gravity observations with a view to improving the quality of the geoid model in the medium term.

## *Choice of Co-ordinate Reference System*

There is some confusion on the absolute and relative accuracy of the Irish Grid (1975) co-ordinate reference frame due to the many varying estimations published to date. An OSNI calculation of the accuracy of the Re-Triangulation Networks in Northern Ireland (Table 8) suggests an absolute accuracy of 0.432 m (2σ) for the tertiary network computed using the propagation of errors theory as follows:

$$\text{Standard error } (\sigma) = \sqrt{(110^2) + (110^2) + (150^2)} = 216.1 \text{ mm}$$

However, this estimation seems slightly low in comparison with other estimations. An alternative estimation proposes that relative errors of ± 0.250 m in plan exist between adjacent stations and that the absolute accuracy of trigonometric stations is everywhere better than 1 metre (OSI and OSNI, 1999). Since absolute accuracy is always larger than relative accuracy this second estimation suggests that absolute accuracy should to be larger than 0.250 m. A third estimation provides a value of 0.648 m (2σ) for the absolute accuracy of the Irish Grid (1975) co-ordinate reference frame (Cory *et al,* 2003). Although the third estimation includes an element of error from the transformation used in the calculation it is accepted by the IIS Task Force as the most reliable estimation of the absolute accuracy of the of the Irish Grid (1975) co-ordinate reference frame.

**Table 8. Results of an analysis of the Re-Triangulation of Northern Ireland (OSNI).**

| Levels of Triangulation Network | Accuracy |
|---|---|
| Primary trig pillars | Adjustment Standard Error = 0.11 m (vector error) |
| Secondary trig pillars | Considered similar accuracy to primary trigs |
| Tertiary trig pillars | Relative accuracy between trigs of approximately ± 0.15 m |

Although the Irish Grid (1975) co-ordinate reference frame provided a coherent mapping framework for Ireland for the second half of the 20th century, it was superseded in 2002 by the ITM co-ordinate reference frame in order to provide a more rigorous GPS compatible framework for the 21st century.

The Irish Grid co-ordinate reference system uses a modified version of the Airy ellipsoid originally developed in the 1840s using 19$^{th}$ century values for the figure of the earth. The new ITM co-ordinate reference system uses the same GRS80 ellipsoid as is used in ETRS89. This ellipsoid was adopted by the International Union of Geodesy and Geophysics (IUGG) in 1979 as a more precise representation of the size, shape, and gravity field of the Earth, and the dimensions of GRS80 are less than 1 metre from the currently accepted scientific values for the shape of the earth (Table 9).

**Table 9. Ellipsoidal parameters used for the IG75 and ITM co-ordinate reference frames.**

| | Semi-major axis | Semi-minor axis |
|---|---|---|
| **Airy Modified** | 6377340.189 | 6356034.446 |
| **GRS80** | 6378137.000 | 6356752.314 |

Since the first realisation of ITM co-ordinates were projected from the ETRS89 co-ordinates it is assumed that the quality of both co-ordinates will be the same. The quoted accuracy equivalent to ± 20 mm in latitude, longitude and ellipsoidal height for the ETRS89 co-ordinates is assumed to be maintained in the published ITM co-ordinates, especially since the residuals between published and calculated ITM co-ordinates were all less than 0.5 mm (Appendix A, Tests 5, 6, 7 and 8). However, since the ITM co-ordinates are a 2D projection of the 3D ETRS89 co-ordinates, projection distortions degrade that quality marginally. This absolute accuracy of ± 0.020 m (1σ) for the ITM co-ordinates compares very favourably with the accepted estimation of absolute accuracy of ± 0.324m (1σ) for the Irish Grid (1975) co-ordinates.

The ITM co-ordinate reference system uses the GRS80 ellipsoid, which is coincident with the WGS84 ellipsoid (used by the GPS system) at the millimetre level, thus ensuring that the ITM co-ordinate reference system is GPS compatible. This means that GPS can be used for spatial data capture in ITM without the need for co-ordinate transformations. This is not the case with the Irish Grid (1975) co-ordinate reference frame, where the required co-ordinate transformation from ETRS89 co-ordinates introduces another opportunity for error in the computed Irish Grid (1975) co-ordinates. Consequently, the ITM co-ordinate reference frame is more suitable when using modern surveying equipment.

The internationally accepted norm for scale factor along the central meridian of projections is either one, or slightly less than one by retaining scale factor across the whole projection as close to unity as possible. Scale factor for the ITM co-ordinate reference system varies between 1.000150 and 0.999820 whereas scale factor for the Irish Grid co-ordinate reference system varies between 1.000380 and 1.000035 (OSI and OSNI, 2001). The range of the effect of scale factor is approximately the same at 330ppm for both systems, but the benefit with ITM is that this range is evenly distributed around unity thereby minimising its effect (Figures 20 and 21).

The Irish Grid (1975) co-ordinate reference frame was a great advance for it's time in the 20$^{th}$ century, but modern technology has now permitted OSI and OSNI to replace it with the ITM co-ordinate reference frame as defined by the Active and Passive GPS networks for the 21$^{st}$ century. The compatibility between modern surveying methods, and the new ITM co-ordinate reference frame provides surveyors with a reference system, which is significantly more rigorous than the ageing Irish Grid (1975) co-ordinate reference frame.


**Figure 20. Variation of scale factor on the ITM co-ordinate reference frame.**

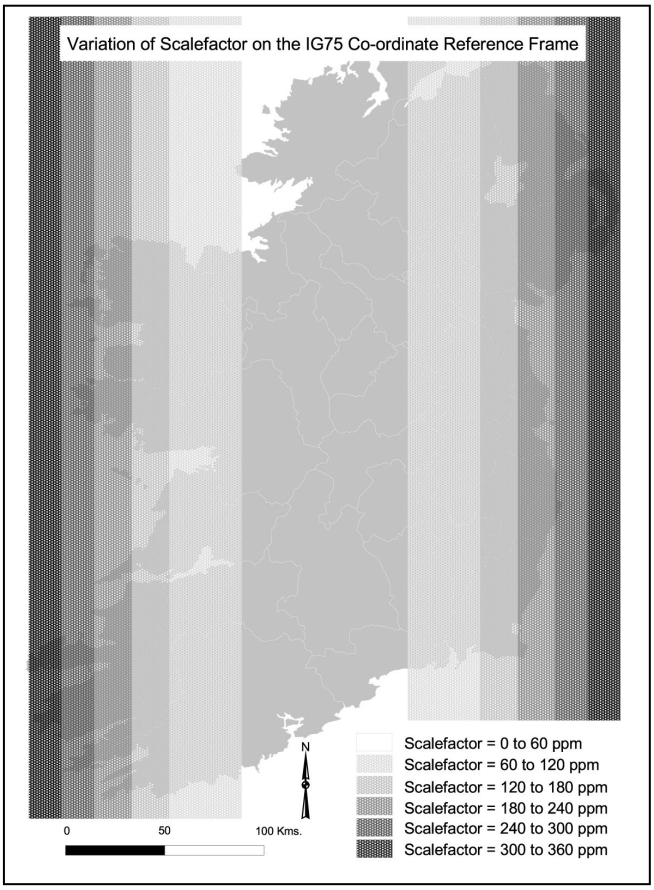



**Figure 21. Variation of scale factor on the IG75 co-ordinate reference frame.**

The publication of ITM co-ordinates in 2002 has resulted in:

a) The need to make the surveying and construction community aware of the alternative co-ordinate reference frame.
b) The need for clarity when referring to a specific co-ordinate reference system or a particular realisation of the Irish Grid co-ordinate reference system.

## Co-ordinate Transformations

Since the maintenance of the geodetic network of triangulation pillars was discontinued in the early 1990s it is no longer commercially viable to survey from this network with certainty since the availability of trigonometric pillars in the vicinity of the project location may have been damaged, or disturbed. Consequently if a client requires a survey supplied on the Irish Grid (1975) co-ordinate reference frame, it has become necessary to connect survey observations to the GPS Networks and subsequently transform ETRS89 co-ordinates to Irish Grid (1975) co-ordinates via a co-ordinate transformation process (Figure 22). It is necessary that surveyors understand the steps involved in the transformation process.

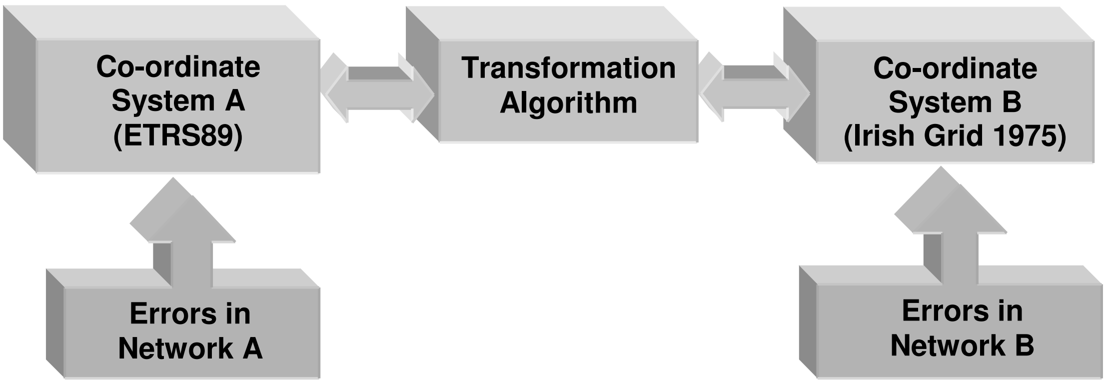



**Figure 22. Sources of errors in the co-ordinate transformation process.**

The previous section quantified the errors in the ETRS89 co-ordinate reference frame at ± 20 mm for the Passive GPS Network, and an accuracy of ± 10 mm is likely for the Active GPS Network, whereas errors in the Irish Grid (1975) co-ordinate reference frame were quantified at ± 0.324 m for the Re-Triangulation Network. Although the seven-parameter transformation is a rigorous 3D transformation, the polynomial transformation is designed as a 2D transformation, and the geoid model (OSGM02) is used to transform the 'z' co-ordinate.

The first step in the seven-parameter transformation process is to use the official OSI variables for the seven-parameter transformation to transform ETRS89 co-ordinates to the Airy Modified co-ordinates (via their Cartesian values). These Airy modified co-ordinates are then projected onto a flat 2D Transverse Mercator surface as eastings and northings in step two. The height is de-coupled in this second step. The height value provided by the seven-parameter transformation is an ellipsoidal height above the Airy modified ellipsoid. To convert this height into an orthometric height a third step is necessary. This two-step process, of transformation followed by projection, has a third step included in the Quest software. Firstly the seven-parameter transformation is replaced with a polynomial transformation, which transforms the ETRS89 co-ordinates into Airy modified co-ordinates separately for latitude and longitude. These Airy modified co-ordinates are then similarly projected onto a flat 2D Transverse Mercator surface as eastings and northings in step two. Step three in the Quest software uses the original ETRS89 ellipsoidal height value and converts it into an orthometric height above MSL (Malin Head) using the geoid model (OSGM02). Consequently, the application of the seven-parameter transformation was designed by OSI & OSNI to operate as a 2D transformation, whereas the polynomial transformation combined with the geoid model (OSGM02) was designed as a 3D transformation.

## Seven Parameter versus Polynomial

The Task Force results (Appendix A, Tests 1, 2, 3, 4, 9 and 10) indicate significantly improved results that are achieved when using a polynomial transformation rather than a seven-parameter transformation (Table 10). The polynomial transformation provides a vector accuracy of 0.375m compared to a mean vector accuracy of 0.622m for a seven-parameter transformation at a 95% confidence level (2σ).

**Table 10. Residuals between published IG75 co-ordinates and IG75 co-ordinates computed from ETRS89 co-ordinates using the polynomial and seven-parameter transformations.**

| | POLYNOMIAL | | SEVEN PARAMETER | | | |
|---|---|---|---|---|---|---|
| | | | Trimble Total Control Software | | GeoGenius Software | |
| | IG Easting | IG Northing | IG Easting | IG Northing | IG Easting | IG Northing |
| Max | 0.383 | 0.381 | 0.496 | 0.586 | 0.496 | 0.589 |
| Min | - 0.284 | - 0.350 | - 0.576 | - 0.466 | - 0.575 | - 0.463 |
| Mean | 0.014 | 0.017 | 0.064 | - 0.034 | 0.065 | - 0.031 |
| St Dev | 0.133 | 0.132 | 0.253 | 0.181 | 0.253 | 0.181 |
| Vector (2σ) | **0.375** | | **0.622** | | **0.622** | |

This means that it is now possible to calculate three official versions of Irish Grid (1975) co-ordinates, namely:

a) OSI and OSNI published Irish Grid (1975) co-ordinates for stations of the trigonometric and GPS networks.
b) Irish Grid (1975) co-ordinates transformed from the ETRS89 co-ordinates of the GPS networks using the polynomial transformation.
c) Irish Grid (1975) co-ordinates transformed from the ETRS89 co-ordinates of the GPS networks using the official seven-parameter transformation.

It has also been standard practice in the past for most survey companies to calculate a local seven-parameter transformation for particular projects. This practice produces many more versions of Irish Grid (1975) co-ordinates, which are both unofficial, and undocumented. Most survey equipment and software being currently used by the surveying sector currently incorporates the official seven-parameter transformation. OSI and OSNI have already provided the algorithms of the polynomial transformation to survey equipment and software suppliers, and even though it could be some years before it is available within equipment and software, surveyors are urged to immediately adopt the polynomial transformation as the preferred transformation solution by using the Quest software available free of cost from the OSI website (http://www.osi.ie/gps/secure/converter/download.asp). OSI and OSNI have stated that the polynomial transformation is now the definitive transformation between ETRS89 and the Irish Grid (1975) co-ordinate reference frames.

## *Clarity and Conventions*

There is an urgent need for transparency in survey graphics and documentation due to the range of alternative transformations and co-ordinate reference systems available in Ireland. Conventions are required to identify the lineage or survey practice applied to determine different co-ordinate realisations. Consequently, the abbreviation ‘IG75’ for Irish Grid (1975) co-ordinate reference frame is proposed for immediate adoption by surveyors to uniquely distinguish this reference framework from earlier realisations of the Irish Grid co-ordinate reference system.

Secondly, surveyors are recommended to use the polynomial transformation in preference to the seven-parameter transformation. This means that processing on site should be discontinued until such time as equipment suppliers can supply the polynomial transformation within software supplied with field equipment. This measure means surveyors will endure some hardship in the intervening period, but the benefit is a substantially improved transformation into IG75. Of course if surveyors could encourage their clients to accept their survey data in ITM, then this problem is eliminated.

Surveyors are also encouraged to include a statement on all survey graphics and reports, noting which transformation was used if the data is to be supplied on the IG75 co-ordinate reference frame.

## *Survey Reports*

The IIS recommends that its members, both individual and corporate, supply clients with survey reports for all projects requiring the use of precise surveying techniques. These reports should include:

a) A detailed description of the surveying and processing methodology used for project control, including computations of absolute and relative accuracy achieved.
b) A list of co-ordinates (ETRS89 and ITM) for project control.
c) A detailed description of the surveying and processing methodology used to compute orthometric heights for project control, including computations of absolute and relative accuracy achieved.
d) A list of ellipsoidal and orthometric heights for project control.
e) A detailed description of the survey methodology used for project detail, including computations of the absolute and relative accuracy achieved.
f) A description of problems encountered during the survey.

## *Check Surveys*

The Irish Institution of Surveyors recommends that consultants and contractors requiring precise surveying services include the requirements for check surveys within contract documents. These check surveys should ideally include:

a) An analysis of the survey report (as outlined above) supplied by the original survey firm.
b) An independent determination of the absolute and relative accuracy achieved for a random sample of ~ 5% to 10% of the project control.
c) An independent determination of the absolute and relative accuracy achieved for a random sample of approximately 1% of the project detail. Stable points of fine resolution (hard detail) such as gate pillars, or road junctions should be used for this determination in preference to temporary points of vague resolution (soft detail) such as wide hedgerows, or other such detail.

# METHODOLOGIES FOR PRECISE SURVEYING

When making a recommendation to adopt preferred methodologies for precise surveying, the Task Force is mindful that the methodologies should be at a level that will not limit the use of new techniques and procedures developed in the future. Similarly the methodologies are only concerned with the provision of control and do not attempt to restrict the range of surveying techniques, observation and data processing procedures, and software used by surveyors. However, survey reports should detail the specification of equipment used, observations procedures and occupation times, baseline lengths, processing strategies, etc in the computation of the accuracy of the survey data supplied to the client.

The Task Force is conscious that an absolute accuracy of ± 60 mm at a 95% confidence level (2σ) for control for precise surveying is not easy to attain, and certain principles should be adhered to, in order to ensure the specification can be consistently achieved. The intention of this report therefore is to provide best practice guidance for precise surveying in Ireland to improve the quality of survey products. The report will also help to inform survey contractors and consultants on the availability and potential of the new ITM co-ordinate reference system (ITM), the geoid model (OSGM02) and the GPS Networks for supplying survey control.

# *Horizontal Control*

## Recommendations

The following procedures should be applied to achieve an absolute accuracy of ± 60 mm (2σ) with respect to the ITM co-ordinate reference frame for precise surveying operations.

**Control Networks**

a) The old re-triangulation networks of trig pillars on tops of hills and its associated IG75 co-ordinate reference frame, and should not be used.
b) Co-ordinates for the OSI densification points (DP) should not be used.
c) The IG75 co-ordinates of the Passive GPS stations should not be used.
d) The ERTS89 co-ordinates for Passive and Active GPS stations are suitable depending on baseline length from the project area. However, since these control stations are not inter-visible, total stations can no longer be used, and GPS equipment will now be necessary to establish project control.
e) In linear projects where traverses are required off the main project route, it is good practice to include additional GPS points as reference objects to close the traverses, and these additional GPS points should be included in the network adjustment of the project control.

**Co-ordinate Reference System**

The new ITM co-ordinate reference frame should immediately replace the old IG75 co-ordinate reference frame as the preferred co-ordinate system for supply of all survey products to clients.

**Co-ordinate Transformations**

Local 'best fit' transformations are unofficial and should be not be used for the provision of control for precise surveys. The polynomial transformation is now the definitive transformation and should be used in preference to the both official and non-official versions of the seven-parameter transformation.

**Observations**

a) Multiple measurements should be made at project control stations, so kinematic techniques only using a small number of observations, or single frequency GPS equipment are not suitable to achieve an absolute accuracy of ± 60 mm for control for precise surveying.
b) It is recommended that GPS measurements should be made from at least two stations of the Passive GPS Network, or three stations of the Active GPS Network.
c) Multiple measurements of one baseline are possible for one recording period between two receivers. More measurements are possible if the survey team has access to more receivers. Multiple measurements of three and six baselines are possible for one recording period between three and four receivers respectively (Figure 20).

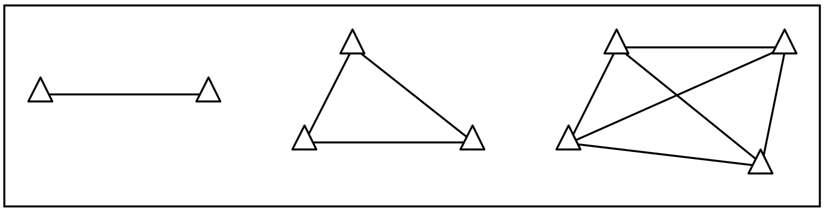


**Figure 23. Numbers of baseline measurements using 2, 3 and 4 GPS receivers.**

**Computations**

Co-ordinates for project control should be computed using network adjustment methods that identify measurements outside tolerance and use least squares techniques to achieve the required absolute accuracy of ± 60 mm. Computations of absolute and relative accuracy achieved should be supplied to the client.

**Statement**

A statement should be included within survey graphics and survey reports which outlines:

a) The type of transformation if used, and the transformation parameters employed.
b) The IIS recommended methodology used to provide survey data with improved spatial quality.

## METHODOLOGY 1 - Computing IG75 or ITM Co-ordinates

Note: The recommended methodology assumes a minimum of two dual frequency GPS receivers, for use with the Passive GPS Network, which is currently the norm.

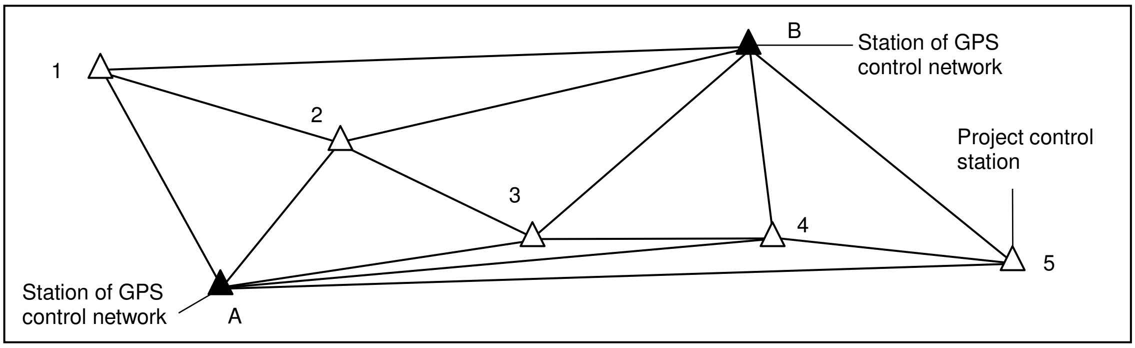



**Figure 24. Multiple measurements from multiple Passive GPS Network control stations to establish project control for precise surveying.**

**STEPS:**

1. Select two GPS network stations (points A and B in Figure 21) within 20 km of the project location, ensure their intersection geometry to the project control stations is optimum, and set the GPS receivers on points A and B to initialise them.
2. Retain GPS receiver on point A as the base station, and using the GPS receiver from point B as the rover station record measurements from project control stations 1 to 5.
3. Repeat step 2 with the base station on point B.
4. Set GPS receivers on project control stations 1 and 2 and record measurements, then move the GPS receiver from point 1 to point 3 and record measurements, and continue leapfrogging until project control station 5.
5. Use ETRS89 co-ordinates of the GPS network stations and process vectors.
6. Adjust vectors as a network by holding station A fixed.
7. Adjust vectors again as a network by holding station B fixed.
8. Test the two networks against each other to ensure all co-ordinates are within relative accuracy required. Existing experience indicates that using multiple baselines from at least three stations of the GPS network will permit residuals to be calculated for computed co-ordinates, facilitate

the identification and elimination of rogue observations and enhance the relative accuracy of results.

9. Finally, adjust network again by holding both stations A and B fixed.
10. Use Quest software to:
    a) Project the computed ETRS89 co-ordinates into
        - ITM co-ordinates.
        - Irish Grid (1975) co-ordinates using the polynomial transformation
    b) Convert ellipsoidal heights into orthometric heights using the geoid model (OSGM02).
11. The resulting co-ordinate triplet should now have the following absolute and relative accuracy (Appendix D):
    a) Absolute accuracy of ± 60 mm (2σ) for ITM Easting and Northings, and an absolute accuracy of ± 69 mm* (2σ) for orthometric heights (± 62 mm* in Northern Ireland).
    b) Relative accuracy of ± 15 mm (2σ) for ITM eastings and northings, and a relative accuracy of ± 29 mm* (2σ) for orthometric heights.
12. Include a list of the ETRS89 and ITM (or IG75) co-ordinates for all project control stations in the survey report.

* These estimations of accuracy for orthometric heights do not take account of the effects of ocean tide loading

## *Vertical Control*

## METHODOLOGY 2 – Computing Orthometric Heights

**STEPS:**

1. The Quest software is used (step 10 b in Methodology 1) to convert the ellipsoidal heights calculated during the network adjustment (using least squares) of the project control into orthometric heights.
2. Project control points should then be spirit levelled using digital levels (or equivalent) to quantify the relative height difference between the stations.
3. Final orthometric heights should be computed by holding the relative height differences (from the spirit levelling) fixed and adjusting the values up or down within the ± 20 mm tolerance of stations fixed from the GPS Network.
4. Benchmarks in the vicinity should not be included in the network.
5. All survey documents and graphics should:
    a) Include the ellipsoidal and orthometric heights for all project control stations;
    b) Include a statement identifying the surveying and computing methodology used.
6. Clients should be informed of the differences in quality of orthometric heights computed from the old Levelling Network and orthometric heights computed using the geoid model.

## *Combining IG75 and ITM data*

## METHODOLOGY 3 - Fitting legacy IG75 data to ITM data

Spatial data surveyed and presented on the ITM co-ordinate reference frame will be more rigorous than data presented on the IG75 co-ordinate reference frame (assuming the same standards of data capture are used for both). The important point here is that since the ITM data is more spatially rigorous, therefore, the IG75 data should be fitted to the ITM data, and not the reverse. The Irish Institution of Surveyors recommends the following procedures for fitting IG75 data to ITM data.

***Digital Data (Magnetic or optical media)***

**Vector Data**

Software containing algorithms to transform IG75 vector data into ITM vector data will be made available from software suppliers in the short to medium term.

a) Software using the polynomial transformation should be used in preference to software using the seven-parameter transformation to attain best results.
b) ITM data derived from IG75 data will be less spatially rigorous than primary ITM data (captured and stored on the ITM co-ordinate reference frame) because the derived ITM data will still contain some of the inherent looseness of the IG75 co-ordinate reference frame.
c) ITM data derived from IG75 data should be moved to achieve a best relative fit with primary ITM data (this will result in significant implications for large datasets).

**Raster Data**

Since data holdings of raster data are generally much smaller than data holdings of IG75 vector data, the migration to ITM raster data will probably occur by a re-issue of raster data on the ITM co-ordinate reference frame during re-negotiation of the five-year leases for OSI and OSNI digital data. Similarly, software, which contains algorithms to transform IG75 raster data into ITM raster data, may also be made available from software suppliers in the short to medium term.

***Graphic Data (Paper medium)***

During the changeover period from IG75 to ITM the Irish Institution of Surveyors recommends that OSI and OSNI should consider supplying ITM and IG75 co-ordinates on the corners of all large-scale paper products presented on the IG75 co-ordinate reference system to assist users to subsequently integrate IG75 and ITM data. The following procedure is not a rigorous method, but allows graphical data on paper from the two systems to be combined.

a) Use ITM co-ordinates on the corners of the IG75 data to get an approximate fit.
b) Move IG75 data to get best relative fit to ITM detail for final fit.

When measuring between data points represented on a map graphic it is worth noting that some distortion is likely occur due to the medium (paper shrinkage) and process used to produce the map. Scaling from paper or photocopied graphic documents is notoriously fraught with error, and dimensions measured on the ground should be used in preference to scaling.

# CONCLUSIONS

1. Three official realisations of the Irish Grid co-ordinate reference system have been computed and used to date:
    a) Irish Grid (1952) of Northern Ireland.
    b) Irish Grid (1965) of all Ireland.
    c) Irish Grid (1975) of all Ireland (referred to as the mapping adjustment).

2. The adoption of the Irish Grid (1975) co-ordinate reference system in 1975 by OSI and OSNI was hugely beneficial in providing a homogeneous system for the whole island for surveyors, engineers, architects, planners and developers during the later half of the $20^{th}$ century, so much so that it has been known colloquially as the ‘Irish National Grid’ for the last three decades.

3. The Irish Institution of Surveyors commits to assist OSI and OSNI in attempting to eradicate the use of the term ‘Irish National Grid’, which has no clear meaning among Irish professionals or map users.

4. Two tertiary triangulation blocks surrounding Dublin and Cork have retained their Irish Grid (1965) values to date in order to maintain sympathy with the mapping produced between 1965 and 1975. The can cause particular difficulties if a project spans the boundary of these blocks.

5. Maintenance of various national surveying infrastructures was discontinued by OSI and OSNI without consultation with surveyors or their professional associations, such as:
   a) Maintenance of the Re-Triangulation Network was discontinued in the early 1990s.
   b) Maintenance of the Levelling Network was discontinued in the early 1990s.
   c) Maintenance of the Passive GPS network was discontinued in the late 1990s.

6. Various national surveying infrastructures were decommissioned by removing their maintenance before replacement infrastructures were put in place, such as:
   a) Re-Triangulation Network was decommissioned in the early 1990s before the Passive GPS network was implemented in 1996.
   b) Levelling Network was decommissioned in the early 1990s before the geoid model (OSGM02) was released in 2002.
   c) Passive GPS network was decommissioned in the late 1990s before the Active GPS network was fully operational not now expected until sometime in 2004.

7. There is a urgent need to standardise public and private survey practice by adopting best international practice, such as:
   a) Eliminating the practice of using a local seven-parameter transformation between ETRS89 and IG75 in preference to official transformations, unless in exceptional circumstances which are documented.
   b) Migrating towards adopting and implementing the polynomial transformation between ETRS89 and IG75 as the definitive transformation within production flow-lines as soon as possible.
   c) Documenting within all survey products (graphics and reports), which transformation is used if the client specifically requests survey data supplied on the IG75 co-ordinate reference system.

8. The supply of project control with GPS equipment from the Active and Passive GPS Networks can significantly improve the absolute and the relative accuracy of survey data.

9. The continued use of the IG75 co-ordinate reference system introduces unnecessary errors into survey data via the transformations used, and should be replaced immediately with the ITM co-ordinate reference system as the preferred official co-ordinate reference system for Ireland. The supply of survey data on the ITM co-ordinate reference system significantly improves the absolute accuracy of survey data.

10. A three-dimensional control network is required for Ireland to provide full national coverage for precise positioning to an absolute accuracy of < 60 mm (2σ). The current Passive and Active GPS Networks have been examined against their ability to meet this accuracy standard, and suggested improvements to the networks include:
    a) Urgently re-introducing a maintenance programme for the Passive GPS network and extend it to provide total coverage for the island of Ireland (including offshore islands) at an absolute accuracy of < 60 mm (2σ).
    b) Extending the current Active GPS network where necessary to provide total coverage for the island of Ireland (including offshore islands) at an absolute accuracy of < 60 mm (2σ).
    c) Any re-instatement of existing or the establishment of new control stations should be observed and computed to EUREF standards (international accuracy standard) and should be independently quality assured and accepted by EUREF.

11. Survey data should be consistently provided at a 95% confidence level ($2\sigma$) unless specifically requested otherwise.

12. Individual and corporate members of the IIS should consistently supply clients with survey reports for all projects requiring the use of precise surveying techniques according to the outline set out in this report.

13. Consultants and contractors undertaking precise surveying projects should:
    a) Make use of this document to ensure accuracy specifications are achievable;
    b) State in tender documents that they intend to conduct a check survey to ensure contract specification has been achieved;
    c) Conduct an independent check survey according to the outline set out in this report to ensure the data supplied complies with the tender specification.

# PROGRESS TO DATE

1. ITM co-ordinates published in July 2002 for Passive GPS stations D049, D050, D078, D092, D109, D114, D121, D126, D141, and D173 were revised in November 2002. OSI has agreed to contact all 1800+ users of their geodetic website by email to inform them of these changes (yet to be done).

2. OSI have discontinued retailing co-ordinates for densification points mainly established as photo control, which the Task Force considers unsuitable for precise surveying operations because of their varying quality.

3. Orthometric heights (above MSL Malin Head) previously published for Passive GPS network stations were withdrawn in November 2002. The official method for determining orthometric heights for these stations is to convert the published ellipsoidal height using the geoid model (OSGM02) within the Quest software.

4. OSI and OSNI have agreed to finance a research project (€25,000) at master's degree level to independently determine the accuracy of the geoid model (OSGM02). The IIS and the Dept. of Geomatics in DIT will work with OSI and OSNI to find a suitable candidate to commence this research project in 2004.

5. OSI and OSNI have agreed to allow corporate members of the Irish Institution of Surveyors to distribute copies of the Quest software to clients (and the URL of the geodetic website) to encourage them to adopt ITM as the preferred co-ordinate reference system.

# RECOMMENDATIONS

1. ITM co-ordinates for a number of Passive GPS stations (D049, D050, D078, D092, D109, D114, D121, D126, D141 and D173) published on the OSI geodetic website were revised in November 2002. Persons who printed co-ordinate sheets for these stations before November 2002 should print out new sheets containing their revised co-ordinates.

2. The ITM co-ordinate reference frame should be adopted as the preferred official reference system to replace the IG75 co-ordinate reference frame as soon as possible by all sectors capturing and using spatial data. The IIS considers that the new ITM co-ordinate reference frame is an official co-ordinate reference system for Ireland since July 2002 when the ITM co-ordinates were first published. The IIS recommends that the OSI / OSNI report on ITM implementation confirms the status of the new ITM co-ordinate reference frame.

3. OSNI has not published precise co-ordinates for the Passive GPS stations located in Northern Ireland because they consider that the Passive GPS network is for OSNI mapping rather than an element of an international spatial data infrastructure for the surveying, construction and spatial planning sectors. The Task Force recommends that the IIS should open a dialogue with OSNI to ensure IIS members have access (over the internet) to precise co-ordinates for stations of the Passive GPS network located in Northern Ireland.

4. The IIS considers that both the Active and Passive GPS Networks are the primary geodetic networks for positioning in Ireland, that they are an important element of the Irish spatial data infrastructure in both jurisdictions, which supports all development on the island of Ireland, and recommends that:
   a) The GPS Networks should be maintained from public funds to facilitate all surveying operations, including precise surveying.
   b) Missing stations of the Passive GPS network should be reinstated as a matter of urgency.
   c) The GPS Networks should be extended to provide full coverage to meet an absolute accuracy < 60 mm (2σ) for precise surveying operations.
   d) Any reinstatement of missing stations or establishment of new stations should be observed and computed using EUREF standards and should be quality assured and accepted by EUREF.

5. The Irish Institution of Surveyors recommends the adoption by IIS members of the independently quality assured ETRS89 co-ordinates (3D) of the Active and Passive GPS Networks, rather than using the old planar systems (2D Re-Triangulation Network and 1D Levelling Network), for which no accuracy statements have been provided.

6. Surveyors are encouraged to migrate towards adopting and implementing the polynomial transformation between ETRS89 and IG75 as the definitive transformation within production flow-lines as soon as possible. This means that surveyors are requested to post process their data using the polynomial transformation and refrain from on-site processing using a seven-parameter transformation. The IIS can help to reduce the extra costs involved in post-processing by requesting that all survey equipment and software suppliers provide the polynomial transformation in their systems as a matter of urgency.

7. Users should calculate orthometric heights using the ellipsoidal heights of the Active or the Passive GPS Networks using the geoid model (OSGM02) rather than using the levelling network of benchmarks.

8. The Irish Institution of Surveyors recommends that a dialogue should be opened between OSI and OSNI and the professional associations of surveyors to examine the system of height determination for the island of Ireland to include issues such as:
   a) That the geodetic levelling network and the fundamental benchmarks should be maintained from public funds in both jurisdictions as the scientific method to determine orthometric heights.
   b) How to enable homogeneity of height data between projects if the methodology to produce orthometric heights outlined in 6 above is adopted.

9. IIS members are encouraged to use the facility on the OSI geodetic website, which allows users input comments on the condition of stations of the Passive GPS network and to review any comments that other users may have previously made.

# REFERENCES

## *Books and Papers:*

Cory, M., Morgan, R., Bray, C., and Greenway, I., (2001), A New Co-ordinate System for Ireland, Proceedings of the 2001 FIG Working Week, Seoul, Korea.
http://www.fig.net/figtree/pub/proceedings/korea/full-papers/session8/cory-morgan-bray-greenway.htm

Cory, M.J., Greenway, I.C., and Hill, C.J., (2003), GPS Compatible Positioning in Ireland (Part 1), Survey Review Vol. 37 No. 290, CASLE, UK, pp 294-307.

Cory, M.J., Greenway, I.C., and Hill, C.J., (2004), GPS Compatible Positioning in Ireland (Part 2), Survey Review Vol. 37 No. 291, CASLE, UK, pp 377-395.

Dublin Port Company, 2003, Tide Tables: January to December 2003 – High Water and Low Water at Dublin North Wall, Dublin Port Company, Dublin, pp 1-32.

Forsberg, R., Strykowski, G., Illife, J.C., Ziebart, M., Cross, P.A., Tscherning, C.C., Cruddace, P., Stewart, K., Bray C., and Finch, O., (2002), OSGM02: A new geoid model of the British Isles, Proceedings of the 3rd meeting of the International Gravity and Geoid Commission (ed. Tziavos, I.N.), Thessaloniki, Greece, pp. 132-137.

Greenway, I., (2003) Developing Ireland's National Mapping – *A Progress Report*, OSI Dublin, pp 1-7.

International Organisation for Standardization, 2003, Geographic Information – *Spatial Referencing by Co-ordinates*, ISO 19111, Switzerland, PP 1-43.
http://www.iso.ch/iso/en/CatalogueDetailPage.CatalogueDetail?CSNUMBER=26016

King, M., Clarke, P., and Allinson, C., (2003), The ups and downs of GPS Heighting in Britain – Part 1: Ocean Tide Loading, Engineering Surveying Showcase, October 2003, pp 20-21

Ordnance Survey Ireland, (1996), The Irish Grid - *A Description of the Co-ordinate Reference System used in Ireland*, OSI Dublin, pp 1-44.

Ordnance Survey Ireland, Ordnance Survey of Northern Ireland, (1999), Making Maps compatible with GPS - *Transformations between the Irish Grid and the GPS Co-ordinate Reference Frame WGS 84 / ETRF 89*, OSI Dublin and OSNI Belfast, pp 1-31.

Ordnance Survey Ireland, Ordnance Survey of Northern Ireland, (2001), New Map Projections for Ireland – *Consultation Paper*, OSI Dublin and OSNI Belfast, pp 1-11.

Ordnance Survey Ireland, (2001), Co-ordinate Positioning Strategy – *Information Paper*, OSI Dublin, pp 1-4.

Snow, R., 2003, GNSS Receiver Networking in the 21st Century, Geo Informatics Volume 6 – June, Emmeloord, The Netherlands, pp 14-17.

Wanninger, L., 2003, GPS on the Web: Virtual reference stations (VRS), GPS Solutions, Volume 7, Springer-Verlag, http://www.wasoft.de/lit/gpswebvrs.html.

## *Tables:*

Ordnance Survey Ireland, (1980s), Tables of Co-ordinates for the Secondary and Tertiary Trigonometric Networks, unpublished.

## *Maps:*

Ordnance Survey Ireland, Ordnance Survey of Northern Ireland, (1991), Limited edition of a selection of imprints from Irish Ordnance Survey copper plates produced to mark the Bicentenary of the establishment of the Ordnance Survey in 1791, OSI Dublin, pp 1-2.

## *Websites:*

IERS http://www.iers.org/iers/

OSI http://www.osi.ie/publications/index.shtml

# APPENDIX A - Testing Quest Software and the Passive GPS Network

## Introduction

The aims of the research were to:

a) Examine the three co-ordinates (ETRF89, IG75 and ITM) published for the Passive GPS network in order to recommend to IIS members, which was the most suitable for precise surveying.
b) Compare results from the polynomial (Quest software) and the seven-parameter transformations in order to recommend to IIS members which was more suitable, and when, for transforming precise surveys.

The initial intention was for members of the Task Force to carry out a range of independent tests on different selections of control stations from the Passive GPS network. However, OSI published the precise co-ordinates for the 128 control stations located in Ireland on their website in July 2002. Precise co-ordinates for the 34 control stations located in Northern Ireland had to be purchased from OSNI (2002 cost = £220Stg + Vat per station), which was too expensive, so reluctantly they could not be included in the tests.

During the course of the investigation the Task Force observed that 11 stations of the Passive GPS network (D009, D016, D025, D030, D036, D057, D070, D095, D119, D123, and D144) were now unavailable, and another station (D003) became unavailable in early 2003. Six of these stations are located in Ireland (D003, D070, D095, D119, D123, and D144), all of which have been destroyed, and six are located in Northern Ireland (D009, D016, D025, D030, D036, D057). Three of the stations located in Northern Ireland have been destroyed (D009, D016 and D025), although the Active GPS control station in Omagh has effectively replaced one of these. Another two stations (D030 and D036) are co-located with a Fundamental benchmark and the Active GPS station in Belfast, and due to an anomaly in the original naming convention for the network stations D057 never existed. This means that 8 stations have been destroyed, and three are unavailable for occupation since the system was provided in 1996. Consequently, it was decided to include all 128 stations located in Ireland to ensure the research was as comprehensive as possible.

Of the three co-ordinates published on the OSI website for the Passive GPS Network, OSI only quote accuracy for the ETRS89 co-ordinate (OSI and OSNI, 1999) which was independently quality assured by EUREF. On this basis the Task Force made the assumption that the ETRS89 co-ordinates published on the OSI website were correct, so the testing focussed on the IG75 and ITM co-ordinates.

Version 6.04 of the Quest software was used for the tests (PC and web versions) during August and September 2002, and version 6.06 was checked in March and April 2003 to confirm the results and ensure it had solved some of the issues identified earlier. The issues resolved by version 6.06 include:

a) The numbers of decimals provided by Quest were to be standardised.
b) Some inputs to the PC version of Quest in batch mode were requested twice.
c) Version 6.04 did not permit users to enter a second value >59" for ETRS89 longitude or latitude. This has been resolved in version 6.06.

Results of the tests are provided for download in an Excel spreadsheet from the website of the Irish Institution of Surveyors (http://www.irish-surveyors.ie/)

## Test Methodologies and Results

**Test 1:**

**Methodology:** Using the Quest software (PC version) in single point mode to transform ETRS89 co-ordinates (published on the OSI website) to IG75 co-ordinates.

**Results:** The standard deviations of residuals between the calculated co-ordinates and the published co-ordinates are in the expected range, and indicate vector accuracy for the polynomial transformation of 0.375 mm (2σ) at a 95% confidence level.

| | IG Eastings | IG Northings |
|---|---|---|
| **Max** | 0.383 | 0.381 |
| **Min** | - 0.284 | - 0.350 |
| **Mean** | 0.014 | 0.017 |
| **St Dev** | 0.133 | 0.132 |

**<u>Tests 2, 3 and 4:</u>**

**Methodology:** Using the Quest software (PC and web versions) in single point and batch mode to transform ETRS89 co-ordinates (published on the OSI website) to IG75 co-ordinates.

**Results:** The standard deviations of residuals between the calculated co-ordinates and the OSI published co-ordinates are similar to the results achieved for Test 1. There are some very minor differences (sub mm level) when using the Quest program in its different modes of operation.

**<u>Test 5:</u>**

**Methodology:** Using the Quest Software (PC version) in single point mode to transform ETRS89 co-ordinates (published on the OSI website) to ITM co-ordinates.

**Results:** The standard deviations of residuals between the calculated ITM co-ordinates and the OSI published ITM co-ordinates initially indicated some discrepancies. After investigation by OSI the ITM co-ordinates of a number of control stations (D049, D050, D078, D092, D109, D114, D121, D126, D141 and D173) were revised and republished on the OSI website in November 2002. Using the revised ITM co-ordinates the standard deviations of residuals between the calculated ITM co-ordinates and the OSI published ITM co-ordinates were zero as expected.

| | ITM Eastings | ITM Northings |
|---|---|---|
| **Max** | 0.000 | 0.000 |
| **Min** | 0.000 | 0.000 |
| **Mean** | 0.000 | 0.000 |
| **St Dev** | 0.000 | 0.000 |

**<u>Tests 6, 7 and 8:</u>**

**Methodology:** Using the Quest software (PC and web versions) in single point and batch mode to transform ETRS89 co-ordinates (published on the OSI website) to ITM co-ordinates.

**Results:** The standard deviations of residuals between the calculated ITM co-ordinates and the OSI published ITM co-ordinates initially identified the same control points identified in tests 5 (D049, D050, D078, D092, D109, D114, D121, D126, D141, and D173). These standard deviations of residuals went to zero using the revised ITM co-ordinates for these stations and the results achieved were similar to those achieved for test 5.

**<u>Test 9:</u>**

**Methodology:** Using **Geo-Genius software** (Spectra Precision Terrasat GmBH) to transform the ETRS89 co-ordinates (published on the OSI website) to IG75 co-ordinates using a seven-parameter transformation (OSI published values for the seven parameters used).

**Results:** The standard deviations of residuals between the calculated IG75 co-ordinates and the OSI published IG75 co-ordinates are larger than those achieved using the polynomial transformation in the Quest software (Tests 1 to 4), and indicate a vector accuracy for the seven-parameter

| | IG Eastings | IG Northings |
|---|---|---|
| **Max** | 0.496 | 0.589 |
| **Min** | - 0.575 | - 0.463 |
| **Mean** | 0.065 | - 0.031 |
| **St Dev** | 0.253 | 0.181 |

transformation of 0.622 mm (2σ) at a 95% confidence level.

**Test 10:**

**Methodology:** Using **Trimble total control software** (Trimble Navigation Ltd.) to transform the ETRS89 co-ordinates (published on the OSI website) to IG75 co-ordinates using a seven-parameter transformation (OSI published values for the seven parameters used).

**Results:** The standard deviations of residuals between the calculated IG75 co-ordinates and the OSI published IG75 co-ordinates are similar to the residuals achieved using the Geo-Genius software. Some minor differences were identified at the sub mm level, but the vector accuracy for the seven-parameter transformation is exactly that calculated for the Geo-Genius software at 0.622 mm (2σ) at a 95% confidence level.

| | IG Eastings | IG Northings |
|---|---|---|
| **Max** | 0.496 | 0.586 |
| **Min** | - 0.576 | - 0.466 |
| **Mean** | 0.064 | - 0.034 |
| **St Dev** | 0.253 | 0.181 |

**Test 11:**

**Methodology:** Using the Quest software (PC version) in single point mode to transform ellipsoidal heights of the ETRS89 co-ordinates (published on the OSI website) to orthometric heights (referred to the Malin Head Datum) using the new geoid model (OSGM02).

**Results:** The bulk of the residuals between the calculated orthometric heights and the OSI published orthometric heights were expected to lie at least within a ± 100 mm range, (initial hypothesis that the accuracy of the geoid model lay within this range). Although the residuals of most of the control stations lay within this ± 100 mms range, the residuals of a substantial number of control stations did not. A list of these control stations (Table A1) was supplied to OSI to investigate their reliability:

| | Residuals |
|---|---|
| **Max** | 1.221 |
| **Min** | - 3.959 |
| **Mean** | 0.003 |
| **St Dev** | 0.411 |

**Test 12:**

**Methodology:** Using the Quest software (PC version) in batch mode to transform ellipsoidal heights of the ETRS89 co-ordinates (published on the OSI website) to orthometric heights (referred to the Malin Head Datum) using the new geoid model.

**Results:** These results confirmed the results achieved in Test 11 by identifying the same 25 control stations where the residuals between the published orthometric heights and the calculated orthometric heights were greater than ± 100 mm.

However, OSI and OSNI state that many of the passive GPS stations have not been spirit levelled and consequently do not have reliable orthometric heights, since their heights may have been produced by alternative means such as trigonometric heighting, or transfer of orthometric heights by GPS. Although these unreliable stations were omitted from the alignment of the scientific geoid model to the local datums, they were published on the geodetic website without any indication of their unreliability. This difficulty arose due to the Ordnance Survey practice of publishing data without any indication of their accuracy or unreliability, and this practice needs to be addressed as a matter of urgency.

**Table A1. List of 25 OSI control stations where the residuals between calculated and published orthometric heights were greater than ± 100 mm.**

| | | PUBLISHED | | CALCULATED | | REMARKS |
|---|---|---|---|---|---|---|
| | | Ellipsoidal Height | Orthometric Height | Orthometric Height | Residuals | |
| D001 | Carrickfinn | 88.4829 | 30.9320 | 31.0830 | 0.1510 | |
| D013 | Glencolmcille | 154.4383 | 96.6440 | 96.4640 | -0.1800 | |
| D031 | Crockkinnagoe | 418.9003 | 362.2000 | 361.1700 | -1.0300 | Unreliable orthometric height |
| D045 | Doagh Mountain | 516.8118 | 459.2470 | 459.0110 | -0.2360 | Unreliable orthometric height |
| D048 | Farvrega | 270.4920 | 213.5430 | 213.3160 | -0.2270 | Unreliable orthometric height |
| D049 | Criggy | 155.1762 | 97.4690 | 98.0220 | 0.5530 | Unreliable orthometric height |
| D050 | Bannanimma | 324.5337 | 267.0110 | 267.4880 | 0.4770 | Unreliable orthometric height |
| D062 | Achill | 132.9305 | 74.8500 | 74.3950 | -0.4550 | Unreliable orthometric height |
| D067 | Louisburgh | 65.2741 | 7.1870 | 6.9170 | -0.2700 | Unreliable orthometric height |
| D071 | Granard | 233.6727 | 177.9640 | 176.7930 | -1.1710 | Unreliable orthometric height |
| D072 | Ballinrobe | 95.5678 | 37.5940 | 37.6970 | 0.1030 | |
| D074 | Clifden | 74.1131 | 16.4750 | 16.0250 | -0.4500 | Unreliable orthometric height |
| D075 | Maam Cross | 102.2015 | 44.8310 | 44.3620 | -0.4690 | Unreliable orthometric height |
| D078 | Rosaveel | 109.6959 | 52.2980 | 52.1100 | -0.1880 | Unreliable orthometric height |
| D083 | Aran Islands | 61.8738 | 0.0000 | 3.9590 | 3.9590 | Unreliable orthometric height |
| D086 | Cloghan | 145.4844 | 88.5290 | 88.7850 | 0.2560 | |
| D114 | Bandon | 150.0525 | 92.4470 | 92.5770 | 0.1300 | |
| D115 | Ballincollig | 90.3266 | 33.0260 | 33.1400 | 0.1140 | |
| D117 | Glanmire | 186.1096 | 128.9470 | 129.0670 | 0.1200 | |
| D121 | Cashel | 178.6228 | 122.0500 | 121.9270 | -0.1230 | |
| D129 | Middleton | 112.5920 | 55.8950 | 55.7760 | -0.1190 | Unreliable orthometric height |
| D146 | Howth | 59.9652 | 3.9250 | 4.0410 | 0.1160 | Unreliable orthometric height |
| D156 | Sally Gap | 543.9085 | 488.0030 | 487.5620 | -0.4410 | Unreliable orthometric height |
| D170 | Rosslare | 73.0816 | 17.3580 | 17.2350 | -0.1230 | |
| D173 | Carbury | 197.0411 | 141.8980 | 140.6770 | -1.2210 | Unreliable orthometric height |

Another station D017 (Slieve Kirk) in Northern Ireland also fails to meet this test (Test 13), and when the locations of these 26 control stations were plotted three clusters were identified in Monaghan, Cork and Galway (Figure A1) suggesting there might be particular difficulties with orthometric heights in these three areas or possibly with the geoid model. Quite a number of these control stations are located in upland areas where spirit levelling is notoriously difficult, however, this difficulty will have to be resolved for such an important infra-structure as the national geodetic network.

OSI and OSNI investigations of these 26 control stations has revealed the following:

a) The orthometric height for D031 Crockkinnagoe published on the geodetic website should read 361.200 m, not 362.200 m.
b) 16 control stations were omitted from the alignment of the scientific geoid model to the local vertical datums (Table A1). D083 Aran Islands was never connected to the levelling network.
c) 9 control stations (D001, D013, D072, D086, D114, D115, D117, D121, D170) were included in the alignment of the scientific geoid model to the local vertical datums however OSI are now not happy with the reliability of orthometric heights for these control stations also.
d) The control station situated in Northern Ireland which has a residual greater than ± 100 mm (D017 – Slieve Kirk) does not have a reliable orthometric height.

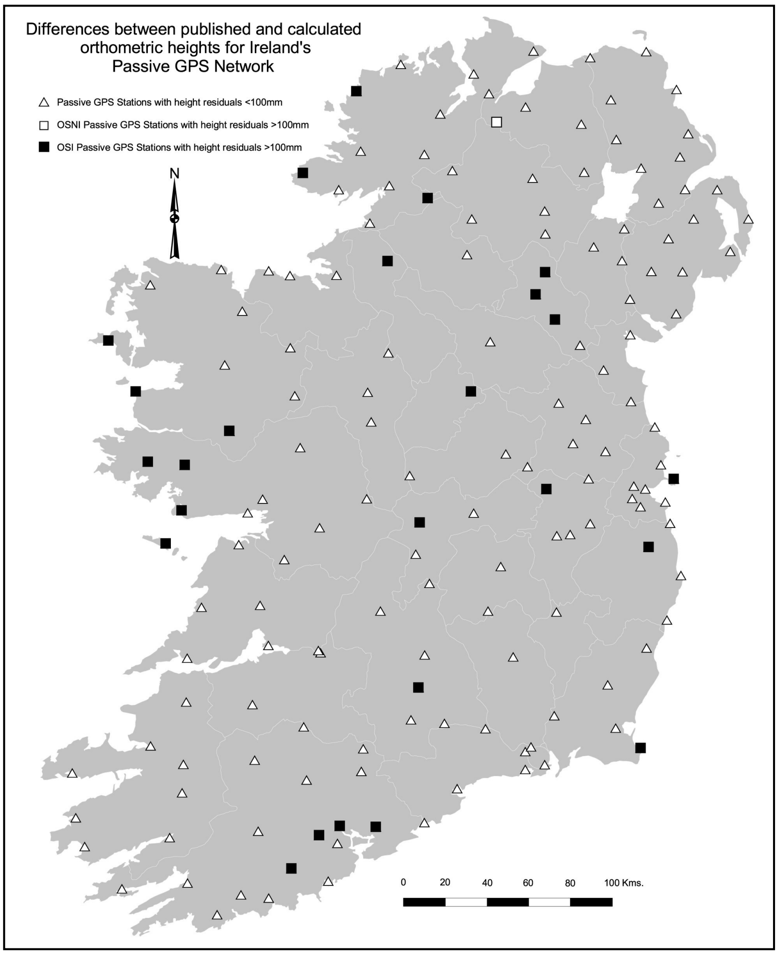



**Figure A1.** **Locations of control stations where the residuals between calculated and published orthometric heights were greater than ± 100 mm.**

**Test 13:**

**Methodology:** This test was conducted by OSNI using the Quest software (PC version in batch mode) to transform ellipsoidal heights of the ETRS89 co-ordinates (precise) for the control stations located in Northern Ireland to orthometric heights (referred to the Belfast Head Datum) using the new geoid model (OSGM02).

|  | RESIDUALS |  |
|---|---|---|
|  | OSNI | OSI |
| **Max** | 0.081 | 0.072 |
| **Min** | - 0.067 | - 0.096 |
| **Mean** | 0.030 | - 0.004 |
| **St Dev** | 0.032 | 0.030 |

**Results:** All but one (D017, Slieve Kirk) of the residuals between the calculated and precise orthometric heights for the 39 control stations located in Northern Ireland lie in a range of ± 100 mm. A reliable orthometric height for D017 (Slieve Kirk) is not available due to the impracticality of spirit levelling to this station. This means that 97% of control stations located in Northern Ireland lay in the ± 100 mm range, whereas only 80% of the control stations located in Ireland lay in the same ± 100 mm range. This suggests that more precise procedures were used in Northern Ireland to calculate orthometric heights for these control stations from the existing levelling network.

However, if the residuals greater than ± 100 mm are eliminated the results from Northern Ireland and Ireland are quite similar and the standard deviations suggest that the geoid model may be accurate to 60-65 mms at a 95% confidence level (2 standard deviations). However, it must be stressed that this test is only indicative and that much more research is required to confirm the accuracy of the geoid model (OSGM02) with confidence.

# APPENDIX B - Results of a survey of Private Surveying Firms on GPS use

## Introduction

The survey was necessary to collect information about the current use of the Passive GPS network to identify if users thought it was necessary to maintain this Network and to determine the accuracy being currently demanded in major infra-structural contracts. This information would be useful in identifying the needs of the user community. The aims of the survey were to collect information on the incidence of use of the Active GPS and the Passive GPS Networks for precise surveying in Ireland and the survey accuracy achieved when using each network, and provide information on the most common accuracy specification requested in contracts for major infra-structural projects.

## List of Survey Participants

The questionnaire was sent to 32 companies; the 31 companies that are corporate members of the Irish Institution of Surveyors, and Hempenstall Surveys and Scientific Co. Ltd. since its owner Brendan Sweeny was a member of the Task Force.

**Table B1. List of private surveying firms that participated in the survey.**

| Company Name | Location |
|---|---|
| Amicus Technology Ltd | Galway |
| Apex Surveys Ltd | Dublin |
| Arrigan Geo Surveyors Ltd | Galway |
| Aztech Land Surveys and Civil Engineering Ltd | Cork |
| Baseline Surveys Ltd | Cork |
| BPM Surveys Ltd | Celbridge |
| Coastway Ltd | Naas |
| Compass Informatics Ltd | Dublin |
| Digital Land Surveyors Ltd | Letterkenny |
| Digitech 3D / European Air Surveys Ltd. | Swords |
| DMC Surveys Ltd. | Navan |
| Euro Ortho International Ltd. | Dublin |
| Focus Surveys Ltd. | Cork |
| Geomap / Irish Engineering Surveys Ltd. | Dublin |
| GPS Surveying Ltd. | Newmarket |
| Hydrographic Surveys Ltd. | Crosshaven |
| Hempenstall Surveys and Scientific Co. Ltd. | Dublin |
| J and L Surveys Ltd. | Maynooth |
| Land Surveys Ltd. | Dublin |
| Maptech Surveys Ltd. | Naas |
| McDonald Surveys Ltd | Carlingford |
| Michael Naughton Ltd. | Furbo |
| Murphy Surveys Ltd. | Naas |
| National Land Surveys Ltd. | Longford |
| Paul Corrigan Associates (PCA) Ltd. | Dublin |
| Precise Control Ltd. | Cork |
| Precision Surveys Ltd. | Donabate |
| Premier Surveys Ltd. | Thurles |
| Sheehan Land Surveys Ltd. | Cork |
| Wasson Ltd. | Cork |

The questionnaire was circulated by email on 10/02/20003 and 30 replies (94% response) were received by 18/03/2003.

## Questionnaire

# QUESTIONNAIRE on Use of Active and Passive GPS Networks

| QUESTIONNAIRE ON USE OF ACTIVE AND PASSIVE GPS NETWORKS | | | | |
|---|---|---|---|---|
| **Questions** | | | | **Remarks** |
| 1. Does your company own GPS equipment or have you hired it for any contracts? | | | | Yes / No |
| 2. Do you use or have you ever used the Passive GPS* network to supply control for a contract? (Points numbered D001 to D173) | | | | Yes / No |
| 3. Do you use or have you ever used the Active GPS** network to supply control for a contract? (Points | | | | Yes / No |
| 4. What is the best accuracy you achieved using the Passive GPS network? | | | | In mms for x, y, and z |
| 5. What is the best accuracy you achieved using the Active GPS network? | | | | In mms for x, y, and z |
| 6. What are the most common accuracies specified within contracts for major infrastructure projects? | | | | In mms for x, y, and z |
| 7. What is the tightest accuracy tolerance ever requested of you? (please state whet type of project i.e. dam, bridge, etc) | | | | In mms for x, y, and z |
| 8. Do you think the Passive GPS network will provide the tolerances specified in question 6? | | | | Yes / No |
| 9. Do you think the Active GPS network will provide the tolerances quoted in question 6? | | | | Yes / No |

* **Passive GPS Network** was established in 1995 containing 173 stations on the island of Ireland numbered D001 to D173. Co-ordinates and station descriptions are required by surveyors to occupy these stations and use them as fixed locations from which to supply survey control.

** **Active GPS network** is a new system of 16 control stations (3 – OSNI, 3 – Irish Lights, and 10 – OSI (4 around Dublin and six around the country)) at which GPS data are collected on a 24-hour and 7 day basis for use in a differential mode.

The Task Force wishes to establish if the Active GPS network is becoming the primary positioning network for Ireland by collecting evidence on the use of both of these GPS networks by the private surveying sector. We need you all to provide your answers to the following questions to assist us in this regard.

Please complete the questionnaire and email your replies to me at paddy.prendergast@dit.ie. Please contact me at 087.7675767 if you have any queries. All Responses will be in confidence and information will only be used in aggregate form. Many thanks for your assistance.

**Figure B1. Questionnaire used for survey of private surveying firms in Ireland.**

## Results

**Table B2. Use of Active and Passive GPS networks by private surveying firms.**

| | |
|---|---|
| Have used Passive GPS network previously | 77% |
| Have used Active GPS Network previously | 33% |

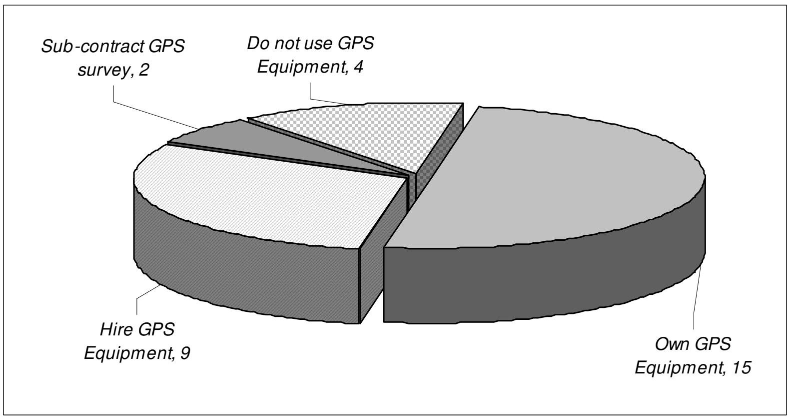



**Figure B2. Ownership and hire of GPS equipment by private surveying firms.**

**Table B3. Most common relative accuracy (mms) requested by contractors for precise surveying operations.**

| | Eastings | Northings | Height |
|---|---|---|---|
| **Maximum** | 30 | 30 | 25 |
| **Minimum** | 2 | 2 | 3 |
| **Mean** | 11 | 11 | 10 |
| **Standard Deviation** | 7 | 7 | 7 |

**Table B4. Tightest accuracy (mms) requested by contractors for specific precise surveying projects.**

| | X | Y | Z |
|---|---|---|---|
| Chemical Plant | 1 | 1 | 2 |
| ESB Turbine shaft | 1 | 1 | 0.2 |
| Tunnelling | 5 | 5 | 5 |
| Road Projects | 5 | 5 | 5 |
| Road Project | 7 | 7 | 7 |
| Road Project | 10 | 10 | 7 |
| Industrial Plant Building | 3 | 3 | 2 |
| Power Station | < 1 | < 1 | < 1 |
| Navigational Control | 5 | 5 | 20 |
| Bridge | 2 | 2 | 2 |
| Bridge | 2 | 2 | 2 |
| Road re-surface | 20 | 20 | 5 |

**Table B5. Whether private surveying firms consider if the Active or Passive GPS networks can meet the most common accuracy specifications requested of them.**

| | Yes | No | Unsure | No answer |
|---|---|---|---|---|
| Passive system to meet common specification requested | 7 | 15 | 4 | 6 |
| Active system to meet common specification requested | 3 | 14 | 8 | 7 |

# APPENDIX C – Testing the Active GPS Network

# *Indications of absolute accuracy attainable at different radial distances from the Active GPS Network*

## Introduction

This experiment was confined to using data supplied on-line for the stations of the Active GPS network and data acquired at the Passive GPS station D147 (DIT Bolton Street) on 22nd and 30th October 2003. The Task Force already had the published co-ordinates for D147 and these were used to test the accuracy of co-ordinates computed for D147 from the Active GPS Network.

**Table C1. Observation parameters for the data acquired at D147**

| | 22nd October 2003 | 30th October 2003 |
|---|---|---|
| Equipment used | Trimble 4700 | Trimble 4700 |
| Antennae Type | L1/L2 Compact without Ground Plane | L1/L2 Compact with Ground Plane |
| Antenna Height | 1.290 | 1.340 |
| Epoch | 5 second | 5 second |
| Elevation Mask | $10^0$ | $10^0$ |
| Met conditions | Localised severe electrical storm | Prolonged and some heavy showers |

Three scenarios are considered: short (< 20 km.), medium (~ 100 km) and long (~ 200 km) baselines. A comparison of the data collected on 22nd October when Dublin experienced a localised electrical storm with the data collected on 30th October when there were more even climatic conditions throughout the country is also provided. The software used for most of the computations was GeoGenius 2000 from Spectra Precision Terrasat GmBH and Trimble Geomatics Office was used where stated with data from 30th October 2003 only. ITM co-ordinates and ellipsoidal heights were used throughout in both computations.

A 'dumb' approach was taken to processing the data, where data from noisy satellites or data with significant cycle slips were not omitted. There was no attempt taken to improve individual vectors following default processing within the software packages. This approach was deliberate, although not the way processing is undertaken on a daily basis, and the results provided would normally be expected to be improved by at least 10 – 20% with normal intervention at processing stage. Whereas all the 60-minute baselines computed using the Trimble Geomatics Office software are independent, the 180-minute baselines computed using GeoGenius software had two hour overlaps with adjacent baselines. A spreadsheet containing all the results of this test is available for download from the IIS website at http://www.irish-surveyors.ie.

The reason for processing raw data was to allow a discernment of the quality of raw data. It facilitates checking by others, but more importantly it allows the reader to extrapolate from the results what they are likely to achieve in other non-static data collection modes. When using the Active GPS network kinematically or perhaps with the network RTK approach, judgements can be based on some of the values presented here.

## Short Baselines

Basic evaluation of the results of the 81 baselines computed from OSI (row 1 in table C2) provides standard deviations of 16, 28 and 19 mms for eastings, northings and elevation. This however masks two rogue values, the first of which can be explained by the high PDOP that peaked just before this incident. The second rogue value cannot be accounted for, but it could be one of the following four incidents:

a) A bird landed on the antennae;
b) A person checked the instrument during this interval and masked various satellites by mistake;
c) The readings were affected by lightening which was prevalent on the day in question;
d) This is one of the random errors that occur from time to time and is undetectable to the user on the day.

**Table C2. Short baseline results of computation of co-ordinates for D147**

| No | Station | Day | Observation Period | Number of Baselines | dE | dN | dH | Distance (Kms) | dVector | ± (5mm + 1ppm |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | IA08 | 22/10/03 | 10 minutes | 81 | 0.016 | 0.028 | 0.019 | 5.5 | 0.032 | 0.011 |
| 2 | IA08 | 22/10/03 | 10 minutes | 79 | 0.005 | 0.006 | 0.011 | 5.5 | 0.008 | 0.011 |
| 3 | IA10 | 22/10/03 | 10 minutes | 81 | 0.005 | 0.008 | 0.010 | 5.9 | 0.009 | 0.011 |
| 4 | IA08 | 30/10/03 | 10 minutes | 64 | 0.003 | 0.006 | 0.013 | 5.5 | 0.007 | 0.011 |
| 5 | IA07 | 30/10/03 | 60 minutes * | 7 | 0.001 | 0.003 | 0.005 | 12.4 | 0.003 | 0.017 |
| 6 | IA08 | 30/10/03 | 60 minutes * | 11 | 0.001 | 0.002 | 0.005 | 5.5 | 0.002 | 0.011 |
| 7 | IA10 | 30/10/03 | 60 minutes * | 11 | 0.003 | 0.005 | 0.008 | 5.9 | 0.006 | 0.011 |

* = Computed using Trimble Geomatics Office software.

It should be noted that these two rogue values did not arise in the computation from UCD (row 3 in table C2) where there is a slight period offset, but otherwise identical data processed from another Active GPS station. Applying a network solution using multiple Active GPS stations rather than individual vectors reduces greatly the probability of such an occurrence. Excluding these two rogue values from the computations reduces the standard deviations to 5, 6 and 11 mm (row 2 in table C2). The computations from UCD (row 3 in table C2) indicate similar standard deviations of 5, 8 and 10 mm, and slightly improved standard deviations of 3, 6 and 13 mm are achieved with the computations from OSI on 30$^{th}$ October (row 4 in table C2) when the climatic conditions were more favourable. Significantly better results are achieved when the observation period is increased from 10 to 60 minutes (rows 5, 6 and 7 in table C2). It should also be noted that all of these computations are well within the manufacturer tolerance of ± (5 mm + 1ppm), except the one including the two rogue values.

With good field practice, monitoring the PDOP on site would have eliminated the first rogue value. The operator should have added at least 5 minutes extra observations if it were a normal data collection process. The second incident may have been detected by monitoring the signal to noise ratio for the satellites, assuming the tools to do this were available. Notwithstanding this, one rogue value out of 161 computations is impressive. Part of the solution to eliminating rogue values is to process using multiple reference stations. This has not been done for the short baselines, because these single vector results are so impressive. Another solution to eliminate rogue values is to set up more than once at separated time intervals on each site.

## Medium Baselines

This category of medium distances (~ 100 km.) would be relevant to most of the landmass of Ireland. Even if one Active GPS station is unavailable, it should be possible to find three stations with data within this distance range in most instances to perform a network computation. In considering this option data from three Active GPS stations IA06 (Athlone), IA03 (Colby) and IA12 (Kilkenny) were processed.

The poor results of the 30-minute single vector solution (row 1 in table C3) and the 30-minute network solution (row 3 in table C3) was probably influenced by atmospheric differences between Dublin and other parts of the country on this day. The main lesson here is that the time-distance formula for the period of observation of 5 minutes + 1 minute for every kilometre from the network station cannot be easily cheated and performing a network solution rather than relying on a single vector is no absolute guarantee of a statistically safe solution. When processing, the default atmospheric model with a single RH (relative humidity) and BP (barometric pressure) for each site was adopted. Good site practice would insist that 'met readings' would be recorded for each site and incorporated into the processing for improved atmospheric modelling.

**Table C3. Medium baseline results of computation of co-ordinates for D147**

| No | Station | Day | Observation Period | Number of Baselines | dE | dN | dH | Distance (Kms) | dVector | ± (5mm + 1ppm) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | IA06 | 22/10/03 | 30 minutes | 27 | 0.069 | 0.037 | 0.084 | 109.4 | 0.078 | 0.114 |
| 2 | IA06 | 30/10/03 | 180 minutes | 11 | 0.021 | 0.029 | 0.079 | 109.4 | 0.036 | 0.114 |
| 3 | IA03, 06 and 12 | 22/10/03 | 30 minutes | 27 | 0.095 | 0.038 | 0.058 | 116.3 * | 0.102 | 0.121 |
| 4 | IA03, 06 and 12 | 30/10/03 | 180 minutes | 11 | 0.014 | 0.012 | 0.033 | 116.3 * | 0.018 | 0.121 |
| 5 | IA03 | 30/10/03 | 60 minutes # | 12 | 0.134 | 0.072 | 0.067 | 138.2 | 0.152 | 0.143 |
| 6 | IA06 | 30/10/03 | 60 minutes # | 12 | 0.055 | 0.063 | 0.070 | 109.4 | 0.084 | 0.114 |
| 7 | IA12 | 30/10/03 | 60 minutes # | 12 | 0.022 | 0.016 | 0.054 | 101.4 | 0.027 | 0.106 |

* = Average distance used for network solution
\# = Computed using Trimble Geomatics Office software.

Much better results were achieved with the 180-minute single vector solution (row 2 in table C3) and the 180-minute network solution (row 4 in table C3) for the data collected on 30$^{th}$ October when the atmospheric conditions were more consistent. The delta vector results (36 and 18 mms) indicate that the expected accuracy of 114 mms and 121 mms can be beaten. It is evident that an acceptable solution is possible even with well spread reference stations, when using sufficiently long observation periods and a network solution.

The results achieved using 60-minute observation periods for a single vector solution indicate varying levels of accuracy achieved (152, 84 and 27 mms), one of which (27 mm) significantly beats the expected accuracy of 106 mm.

## Long Baselines

The final consideration examines long baselines (~ 200 km.) where data from IA06 (Galway) 186.2 km, IA03 (Kilrea) 181.0 km and IA12 (Cork) 223.9 km were processed.

Initially the data collected in poor climatic conditions on 22$^{nd}$ October were computed. The first computation (row 1 in table C4) considers 30-minute data, which yields standard deviations of 516, 141 and 144 mms. As expected this is insufficient data for a reliable solution. The distance-time formula yields 5 + 186 = 191 minutes, so 180 minutes was subsequently used for this computation. A marked improvement is achieved for the standard deviations when computing 180-minute baselines separately for the three reference stations (rows 2, 3 and 4 in table C4) and all easily beat their expected accuracy tolerances of ± (5mm + 1ppm). A network solution using all three-reference stations (row 8 in table C4) provides standard deviations of 22, 14 and 20 mm, which are exceptionally good results for long baselines.

**Table C4. Long baseline results of computation of co-ordinates for D147.**

| No | Station | Day | Observation Period | Number of Baselines | dE | dN | dH | Distance (Kms) | dVector | ± (5mm + 1ppm) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | IA11 | 22/10/03 | 30 minutes | 27 | 0.516 | 0.141 | 0.144 | 186.2 | 0.535 | 0.191 |
| 2 | IA11 | 22/10/03 | 180 minutes | 11 | 0.056 | 0.013 | 0.031 | 186.2 | 0.057 | 0.191 |
| 3 | IA02 | 22/10/03 | 180 minutes | 11 | 0.035 | 0.047 | 0.034 | 181.0 | 0.059 | 0.186 |
| 4 | IA15 | 22/10/03 | 180 minutes | 11 | 0.067 | 0.047 | 0.112 | 223.9 | 0.082 | 0.229 |
| 5 | IA02 | 30/10/03 | 180 minutes | 11 | 0.028 | 0.014 | 0.034 | 181.0 | 0.031 | 0.186 |
| 6 | IA11 | 30/10/03 | 180 minutes | 11 | 0.027 | 0.034 | 0.047 | 186.2 | 0.043 | 0.191 |
| 7 | IA15 | 30/10/03 | 60 minutes | 7 | 0.081 | 0.114 | 0.040 | 223.9 | 0.140 | 0.229 |
| 8 | IA11, 02 and 15 | 22/10/03 | 180 minutes | 11 | 0.022 | 0.014 | 0.020 | 197.0 * | 0.026 | 0.202 |
| 9 | IA11, 02 and 15 | 30/10/03 | 180 minutes | 7 | 0.028 | 0.018 | 0.053 | 197.0 * | 0.033 | 0.202 |
| 10 | IA02 | 30/10/03 | 60 minutes # | 12 | 0.157 | 0.091 | 0.088 | 181.0 | 0.181 | 0.186 |
| 11 | IA11 | 30/10/03 | 60 minutes # | 12 | 0.101 | 0.088 | 0.076 | 186.2 | 0.134 | 0.191 |
| 12 | IA15 | 30/10/03 | 60 minutes # | 8 | 0.348 | 0.211 | 0.193 | 223.9 | 0.407 | 0.229 |

* = Average distance used for network solution

# = Computed using Trimble Geomatics Office software.

Similar computations carried out using the more stable data from 30th October achieved even better results for the computations using individual reference stations (rows 5 and 6 in table C4). However, the network solution on the day with the calmer weather is not as good as the results using the data from the 22nd October. The main reason for this is that the data collected at D147 on the 30th October has large amounts of cycle slip for the final 1.5 hours of collection. The Task Force cannot be sure what caused this, but speculates that a bird might have found itself a new perch that evening.

A set of 60-minute baselines was also computed for these individual reference stations (rows 7, 10, 11 and 12 in table C4) and all except the final computation (row 12) beat the expected accuracy tolerance of ± (5mm + 1ppm). One baseline, between 13.00 and 14.00 hours, within the final computation (row 12) was exceptionally weak giving standard deviations of 1021, 567 and 122 mms, which if excluded this computation then also beats the expected accuracy tolerance of ± (5mm + 1ppm).

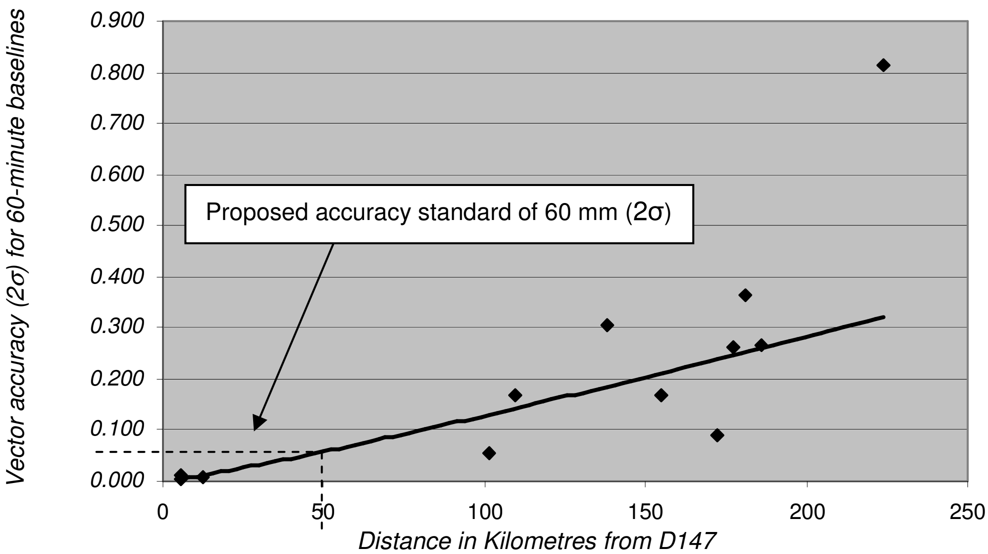



**Figure C1. Vector accuracy (2σ) of 60-minute baselines from the Active GPS Network**

Finally the vector accuracy (2σ) for all the computations of 60-minute baselines from individual reference stations were plotted against the distance of the reference stations to D147 (Figure C1). The resulting chart suggests that 60-minute baselines at distances of 50 km from the Active GPS network will provide a similar absolute accuracy (< 60 mm @ 2σ) to 25-minute baselines at distances of 20 km from the Passive GPS Network. Longer observing periods will yield better quality results, so the time-distance formula of 5 minutes + 1 minute for every km from a Passive GPS station will have to modified to produce a similar formula for the Active GPS Network.

## *Indications of repeatability from the Active GPS Network*

These results are derived exclusively from computations carried out using Trimble Geomatics Office software and in all cases the observation period for the baselines was 60 minutes.

### Short Baselines

Eleven single vector baselines each from OSI (5.5 km from D147) and UCD (5.9 km from D147) were plotted to provide an indication of the repeatability of results achieved from the Active GPS network over short distances (< 20 km). All but one of the results falls within 0.010 m of the published position for D147.

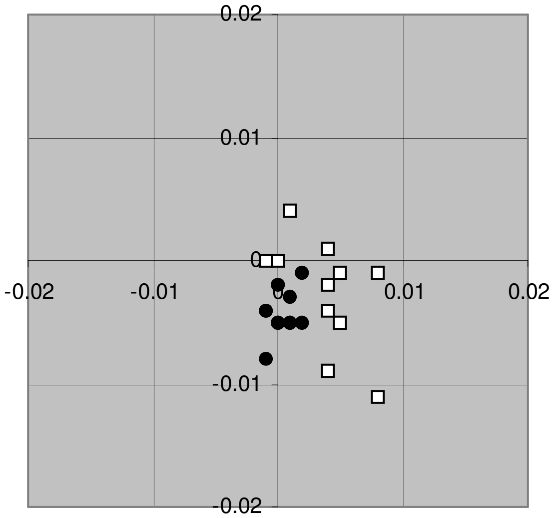



**Figure C2 Repeatability of results using short baselines (5.5 and 5.9 km).**

### Medium Baselines

Twelve single vector baselines each from Kilkenny (101.4 km from D147) and Athlone (109.4 km from D147) were plotted to provide an indication of the repeatability of results achieved from the Active GPS network over medium distances (~ 100 km). Please note that scale in the chart has changed from centimetres to decimetres. All but four of the results fall within 0.100 m of the published position for D147.

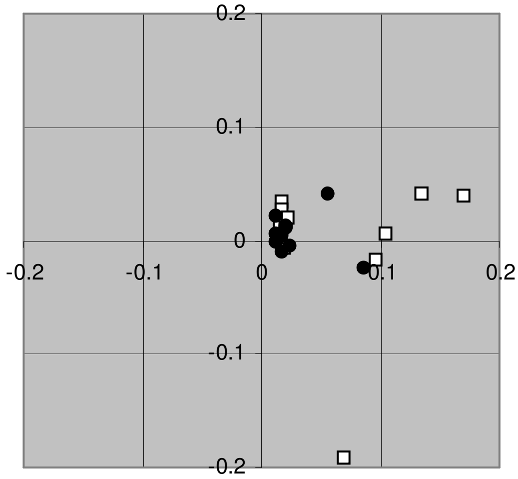



**Figure C3. Repeatability of results using medium baselines (101.4 and 109.4 km).**

## Long Baselines

Twelve single vector baselines each from Kilrea (181.0 km from D147) and Galway (186.2 km from D147) were plotted to provide an indication of the repeatability of results achieved from the Active GPS network over long distances (~ 200 km). Please note that scale in the chart has changed from decimetres to quarter metres. All but two of the results fall within 0.250 m of the published position for D147.

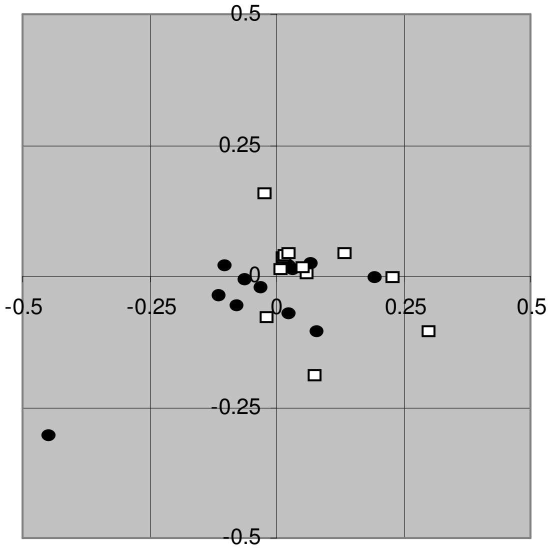



**Figure C4. Repeatability of results using long baselines (181.0 km and 186.2 km).**

## *Indications of accuracy of heights from the Active GPS Network*

These results are derived exclusively from computations carried out using Trimble Geomatics Office software and in all cases the observation period for the baselines was 60 minutes.

## Short Baselines

Eleven single vector baselines each from OSI (5.5 km from D147) and UCD (5.9 km from D147) were computed to provide an indication of the accuracy and repeatability of ellipsoidal heights derived from the Active GPS network over short distances (< 20 km). All but three of the results from OSI and two of the results from UCD fall within 0.010 m of the published ellipsoidal height for D147.

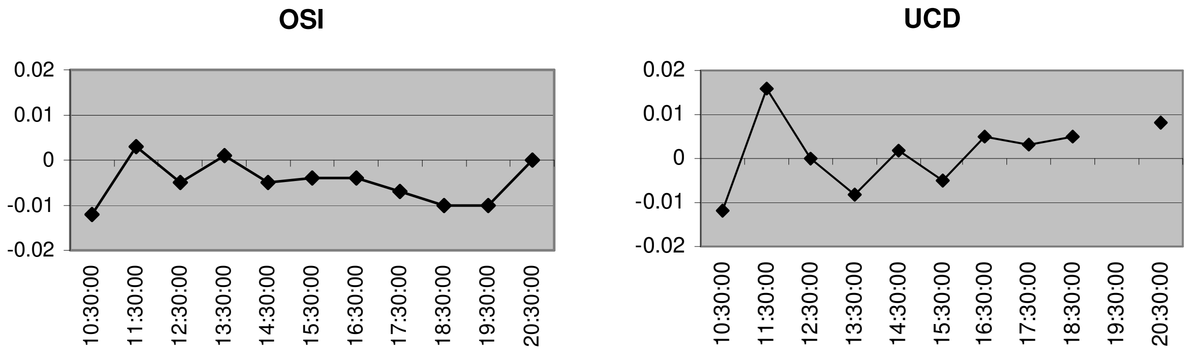



**Figure C5. Accuracy and repeatability of ellipsoidal heights computed for D147 from OSI and UCD using short baselines (5.5 km and 5.9 km) of 60-minute duration.**

## Medium Baselines

Twelve single vector baselines each from Kilkenny (101.4 km from D147) and Athlone (109.4 km from D147) were computed to provide an indication of the accuracy and repeatability of ellipsoidal heights derived from the Active GPS network over medium distances (~ 100 km). Please note that the vertical scale in the charts has changed from centimetres to decimetres. All but four of the results fall within 0.200 m of the published ellipsoidal height for D147.

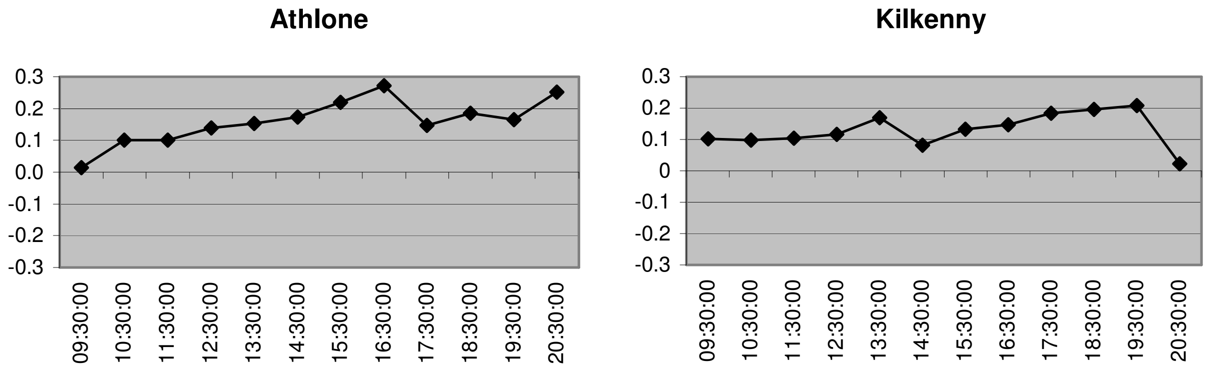



**Figure C6. Accuracy and repeatability of ellipsoidal heights computed for D147 from Athlone and Kilkenny using medium baselines (109.4 km and 101.4 km) of 60-minute duration.**

## Long Baselines

Twelve single vector baselines each from Kilrea (181.0 km from D147) and Galway (186.2 km from D147) were computed to provide an indication of the accuracy and repeatability of ellipsoidal heights derived from the Active GPS network over long distances (~ 200 km). Please note that scale in the charts has changed from decimetres to quarter metres. Whereas only 4 of the 12 computations from Galway fall outside 0.250 m of the published ellipsoidal height for D147, 9 of the 12 computations from Kilrea fall outside the same margin of 0.250 m.

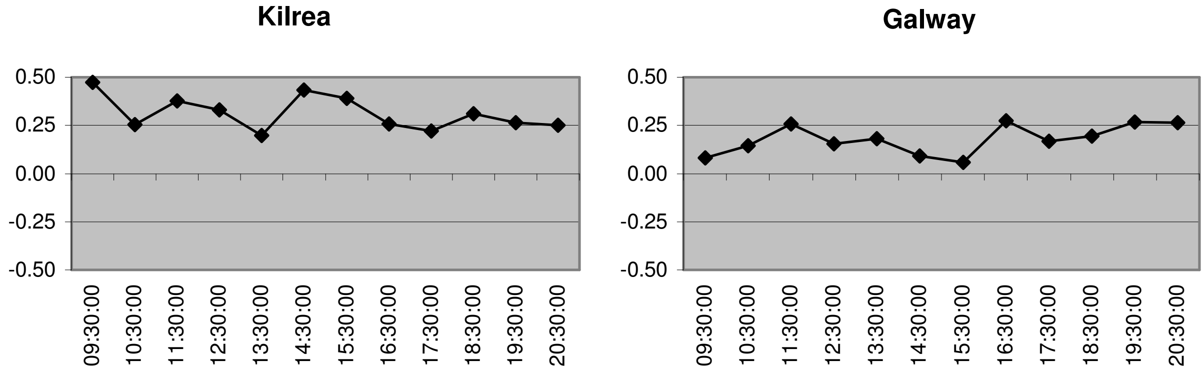



**Figure C7. Accuracy and repeatability of ellipsoidal heights computed for D147 from Kilrea and Galway using long baselines (181.0 km and 186.2 km) of 60-minute duration.**

The results achieved using medium and long baselines indicate that 60-minute observation periods are insufficient to attain an accuracy of < 60 mm (2σ) for ellipsoidal heights. The residuals would be increased further if these ellipsoidal heights were converted to orthometric heights using the geoid model (OSGM02). Consequently, the supply of heights from the Active GPS network using medium baselines to an accuracy of < 60 mm (2σ) may not be possible without network RTK methods. Further investigation is required to identify optimum observation periods and computational procedures from these distances.

## *Conclusions*

The data available on-line for the Active GPS stations is of a very high quality. This is possible because they use the highest quality antennae and the stations themselves are fixed to zero order standards. However, care must be applied at all times, for instance at the time of data collection for this test, the Galway station was re-located, but the default co-ordinate in the rinex file was not yet updated. Blind acceptance of the system can lead to errors.

**Table C5. Comparison of mean accuracy achieved for position and ellipsoidal height computed for D147 using multiple short, medium and long baselines of 60-minute duration.**

| | dE | dN | dVector | dH |
|---|---|---|---|---|
| **OSI** | 0.000 | -0.004 | 0.004 | -0.005 |
| **UCD** | 0.004 | -0.003 | 0.005 | 0.001 |
| **Athlone** | 0.058 | -0.001 | 0.058 | 0.160 |
| **Kilkenny** | 0.026 | 0.007 | 0.027 | 0.130 |
| **Kilrea** | -0.035 | -0.045 | 0.057 | 0.314 |
| **Galway** | 0.073 | -0.003 | 0.073 | 0.178 |

The accuracy of ellipsoidal heights computed for D147 were significantly of lesser quality than the plan positions computed using the same baselines. The quality of GPS plan positions has traditionally been assumed to be twice that of GPS heights, but the results achieved would suggest that a factor of 2 might be understating the situation. However, as yet these results are only indicative and further investigation is necessary to provide reliable information on the operation of the Active GPS Network.

The implementation of the Active GPS network is still a work in progress, but what a great addition to Ireland's surveying infrastructure it should eventually be. At the time of writing the system is not as reliable as it might be from the perspective of when and if the data from any individual station becomes available. Notwithstanding this, the Task Force believes it is well worth the wait, and would prefer for OSI and OSNI to get it right rather than rush its implementation.

# APPENDIX D - Accuracy Calculations

## Comparison of accuracy of surveying techniques at range of 5 km

Since survey instruments are available in a range of different specifications (1”, 5” and 10” theodolites for example), measurements made with them have different relative accuracy. Table D1 provides sample calculations of accuracy @ 95% probability of ITM co-ordinates surveyed from the Passive GPS network at a 5 km range. These estimations of accuracy are presented graphically in Figure D1. The black circles indicate the size of the relative accuracy for each instrument/observation procedure, and the distance of the centre of the black circles from the bulls’ eye indicates the absolute accuracy of the measurements relative to the ITM co-ordinate reference frame. The smaller the black circle the better the relative accuracy and the closer to the bull’s eye the better the absolute accuracy.

**Table D1. Estimated accuracy (2σ) of ITM co-ordinates surveyed from the Passive GPS Network at 5 km using a range of surveying instruments.**

| Survey Instrument | Control Network | Absolute accuracy of Network | Centring Error at Pt A | Centring Error at Pt B | GPS system error | GPS distance error 1ppm @ 5Km | Pointing Error ± 3” | EDM Error ± 3mm | EDM Error ± 3ppm | Absolute Accuracy (2σ) in mms | Relative Accuracy (2σ) in mms |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GPS (static) | Passive GPS | ± 20mm | 2mm | 2mm | 5mm | 5mm | | | | 42.80 | 15.23 |
| GPS (Kinematic) | Passive GPS | ± 20mm | 2mm | 2mm | 10mm | 5mm | | | | 46.17 | 23.07 |
| Total Station | Passive GPS | ± 20mm | 2mm | 2mm | | | ± 75mm | ± 3mm | ± 15mm | 158.33 | 153.19 |

Notes:

1. All calculations in Table D1 are from the Passive GPS network at a 5 km range to compute ITM co-ordinates for which a transformation is not required.
2. The estimations of absolute and relative accuracy are computed using the formula “square root of the sum of the squares” where the absolute accuracy uses all the values listed in each row, and the relative accuracy uses all but the ± 20 mm for the absolute accuracy of the Network.
3. A value of 2 mm was used for the centring error at each station, which should be possible to achieve if the equipment is properly calibrated and correct survey procedures are used.
4. A value of 10 mm was used for the GPS system error for kinematic GPS where an initialisation of the GPS equipment would be required and a small number of epochs of data would be observed to compute the position of a point.
5. The theodolite of the total station has a resolution of 1” and a precision of 3”.

The absolute accuracy of survey data is dependent on:

a) The survey instruments and observation procedures used.
b) The absolute accuracy of the geodetic control network on which the survey is based.
c) The co-ordinate reference system used to supply the survey data.

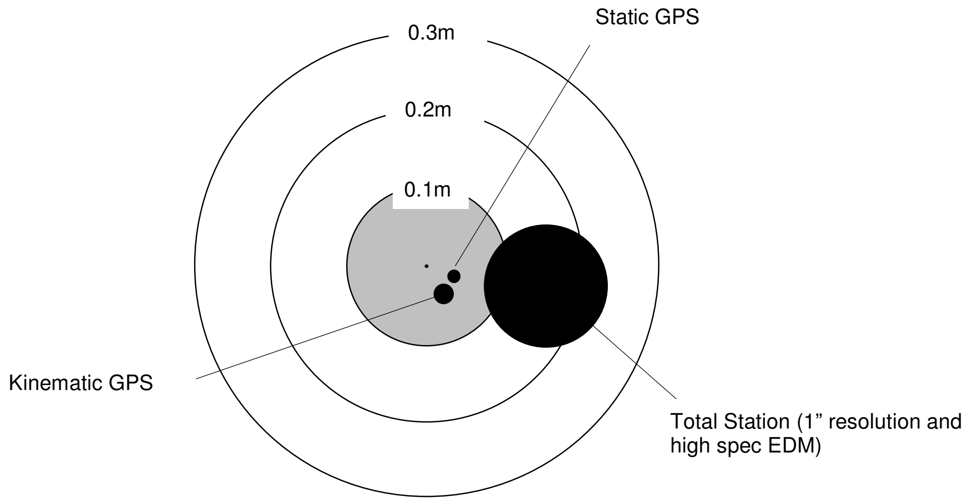



**Figure D1. Estimated accuracy (2σ) of ITM co-ordinates surveyed from the Passive GPS Network at 5 km using a range of surveying instruments.**

## *Accuracy comparison using different co-ordinate reference frames*

Table D2 provides estimations of accuracy (2σ) at 95% probability of IG75 and ITM co-ordinates surveyed using GPS in static mode from three different control networks at a range of 5 km. These estimations of accuracy are presented graphically in Figure D2. It is obvious that the relative accuracy of each of the measurements is similar since GPS in static mode was used for each. The exceptions are from the Active GPS Network, which has a slightly better relative accuracy because there is no centring error at the Active GPS network station. However, it is interesting to note the significant improvement in absolute accuracy by using the ITM co-ordinate reference system instead of the IG75 co-ordinate reference system.

**Table D2. Estimated absolute and relative accuracy (2σ) of IG75 and ITM co-ordinates surveyed at a range of 5 km using GPS in static mode from different control networks.**

| Control Network | Co-ordinates Produced | Absolute accuracy of Network | Centring Error at Pt A | Centring Error at Pt B | GPS system error | GPS distance error 1ppm @ 5Km | Transformation Error | Absolute Accuracy (2σ) in mms | Relative Accuracy (2σ) in mms |
|---|---|---|---|---|---|---|---|---|---|
| Active GPS | ITM | ± 10mm | | 2mm | 5mm | 5mm | 0.0 | 24.82 | 14.70 |
| Passive GPS | ITM | ± 20mm | 2mm | 2mm | 5mm | 5mm | 0.0 | 42.80 | 15.23 |
| Active GPS | IG75 | ± 10mm | | 2mm | 5mm | 5mm | 187.4mm (poly) | 375.62 | 14.70 |
| Passive GPS | IG75 | ± 20mm | 2mm | 2mm | 5mm | 5mm | 187.4mm (poly) | 377.24 | 15.23 |
| Active GPS | IG75 | ± 10mm | | 2mm | 5mm | 5mm | 311.1mm (7 par) | 622.69 | 14.70 |
| Passive GPS | IG75 | ± 20mm | 2mm | 2mm | 5mm | 5mm | 311.1mm (7 par) | 623.67 | 15.23 |
| Trig Network | IG75 | ± 324mm | 2mm | 2mm | 5mm | 5mm | 0.0 | 648.18 | 15.23 |

Notes:

1. All calculations in Table D2 are from either the Active GPS Network, the Passive GPS Network, or the Re-Triangulation Network at a range of 5 km to compute IG75, or ITM co-ordinates.
2. The estimations of absolute and relative accuracy are computed using the formula "square root of the sum of the squares" where the absolute accuracy uses all the values listed in each row. The relative accuracy uses all but the values for the absolute accuracy of the Network (± 10 mm, ± 20 mm and ± 324 mm) and the values for transformation error (187.4 mm and 311.1 mm).
3. A value of 2 mm was used for the centring error at each station, which should be possible to achieve if the equipment is properly calibrated and correct survey procedures are used. No

centring error was used for Point A from the Active GPS network since the base station is fixed within the absolute accuracy of the network.

4. Transformation errors of 187.4 mm and 311.1 mm (Table 8) are used for the polynomial and seven-parameter transformations respectively.

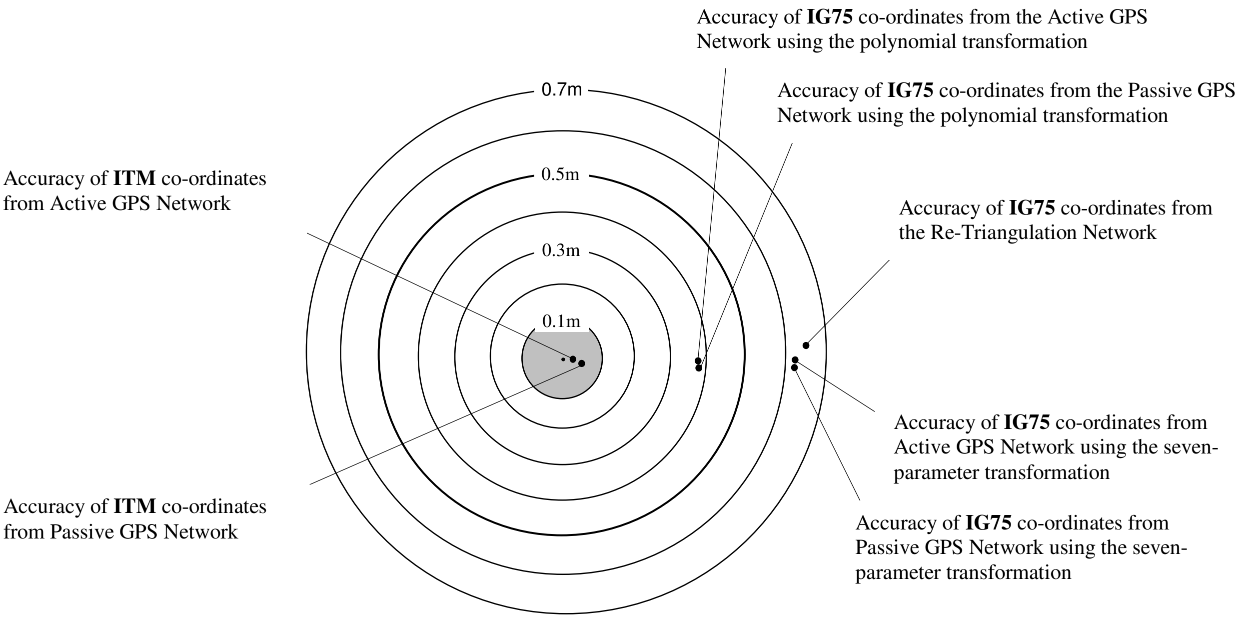



**Figure D2. Estimated absolute and relative accuracy (2σ) of IG75 and ITM co-ordinates surveyed at a range of 5 km using GPS in static mode from different control networks.**

## *Accuracy comparison of heights from GPS and Levelling Networks*

OSI and OSNI estimate the accuracy of Ireland's levelling networks (Table D3). However, based on anecdotal evidence, the Task Force considers that the relative accuracy of the Tertiary levelling network might be overstated at ± 5 mm, so a more realistic value of ± 10 mm was used in the computation for this network. Therefore, the absolute accuracy of the tertiary benchmarks was estimated using propagation of error formula as:

$$\text{Standard error } (\sigma) = \sqrt{(100^2) + (5^2) + (5^2) + (10^2)} = 100.75 \text{ mm}$$

**Table D3. Estimated accuracy of Ireland's Levelling Networks (OSI and OSNI).**

| Levelling Networks | Accuracy | Accuracy derived from |
|---|---|---|
| Fundamental Benchmarks | Absolute accuracy = 0.10 m (1σ) to MSL | Statistical results of 1970 adjustment |
| Geodetic levelling network | Relative accuracy of ± 5 mm | Statistical results of 1970 adjustment |
| Secondary levelling network | Relative accuracy of ± 5 mm | Consideration of closing tolerances |
| Tertiary levelling network | Relative accuracy of ± 5 mm | Consideration of closing tolerances |

The accuracy of the geoid model OSGM02 (Table D4) was assessed as 0.024 m for Ireland and 0.019 m for Northern Ireland (Forsberg *et al*, 2002).

**Table D4. Accuracy assessment of the geoid model OSGM02 (Forsberg *et al*, 2002).**

| | Ireland | Northern Ireland |
|---|---|---|
| **Maximum** | 0.050 | 0.041 |
| **Minimum** | - 0.064 | - 0.035 |
| **Mean** | - 0.003 | 0.002 |
| **Standard Deviation** | 0.024 | 0.019 |

**Table D5. Estimated absolute and relative accuracy of ellipsoidal and orthometric heights computed from the GPS and Levelling Networks.**

| | Control Network | Heights Calculated | Absolute accuracy of Network | Setup Error Point A | Setup Error Point B | GPS system error for height | GPS distance error 2ppm for height | Geoidal Model Error | Digital Level error 3ppm @ 5 km | Absolute Accuracy (2σ) | Relative Accuracy (2σ) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Active | Ellipsoidal | ± 10 mm | | 2 mm | 10 mm | 10 mm | 0.0 | | 34.87 mm | 28.57 mm |
| 2 | Passive | Ellipsoidal | ± 20 mm | 2 mm | 2 mm | 10 mm | 10 mm | 0.0 | | 49.32 mm | 28.84 mm |
| 3 | Active | Orthometric | ± 10 mm | | 2 mm | 10 mm | 10 mm | 24 mm | | 59.33 mm | 28.57 mm |
| 4 | Passive | Orthometric | ± 20 mm | 2 mm | 2 mm | 10 mm | 10 mm | 24 mm | | 68.82 mm | 28.84 mm |
| 5 | Active | Orthometric | ± 10 mm | | 2 mm | 10 mm | 10 mm | 19 mm * | | 51.58 mm | 28.57 mm |
| 6 | Passive | Orthometric | ± 20 mm | 2 mm | 2 mm | 10 mm | 10 mm | 19 mm * | | 62.26 mm | 28.84 mm |
| 7 | Levelling | Orthometric | ± 100.75 mm | 2 mm | 2 mm | | | | 15 mm | 203.80 mm | 30.53 mm |

* = Separate computation for Northern Ireland to take account of slightly better accuracy of geoid model (OSGM02)

Notes:

1. All calculations in Table D5 are from the Active GPS Network, the Passive GPS Network, or the Levelling Network at a range of 5 km to compute ellipsoidal and orthometric heights.
2. All observations from the Active and Passive GPS Networks were surveyed using GPS in static mode (using an observation period of 5 minutes + 1 minute for every 1 Km from GPS Network station).
3. Rows 1, 3 and 5 are surveyed from the Active GPS Network, which has an absolute accuracy of ± 10 mm, and for which there are no centring errors at the base station.
4. Rows 2, 4 and 6 are surveyed from the Passive GPS Network, which has an absolute accuracy of ± 20 mm, and centring errors were used for the base stations.
5. Height values computed from GPS observations are considered to be less reliable than horizontal co-ordinates by a factor of 2. Consequently, the GPS error of ± (5 mm + 1ppm) was doubled to ± (10 mm + 2ppm) respectively to simulate this unreliability in the estimation of accuracy for height.
6. Rows 3 and 4 estimate the accuracy of orthometric heights in Ireland using the geoid model, whereas Rows 5 and 6 estimate the accuracy of orthometric heights in Northern Ireland using the geoid model. The absolute accuracy achieved for orthometric heights in Northern Ireland are 6 to 7 mm better than those calculated in the rest of Ireland, since the accuracy of the geoid model in Northern Ireland is slightly better (possibly due to better quality levelling and gravity data used in its computation).
7. Observations from the levelling Network were surveyed using a digital level (or equivalent) where a conservative but achievable 3ppm was used for the precision of measurement.
8. 2 mm has been used exclusively so far to estimate normal centring errors on survey stations. Consequently, a value of 2 mm has also been used to estimate normal set-up errors at benchmarks. Although, some surveyors might consider 2 mm too conservative, it was used for consistency and it was considered a fair estimation of error for levelling since:
   - It is quite easy to loose a few mms taking a height from a ‘crow’s foot’ benchmark.

- It is quite easy to loose a few mms taking a height from the top of the new benchmark bolts, rather than screwing in the proper dome headed bolt to which the height value relates.

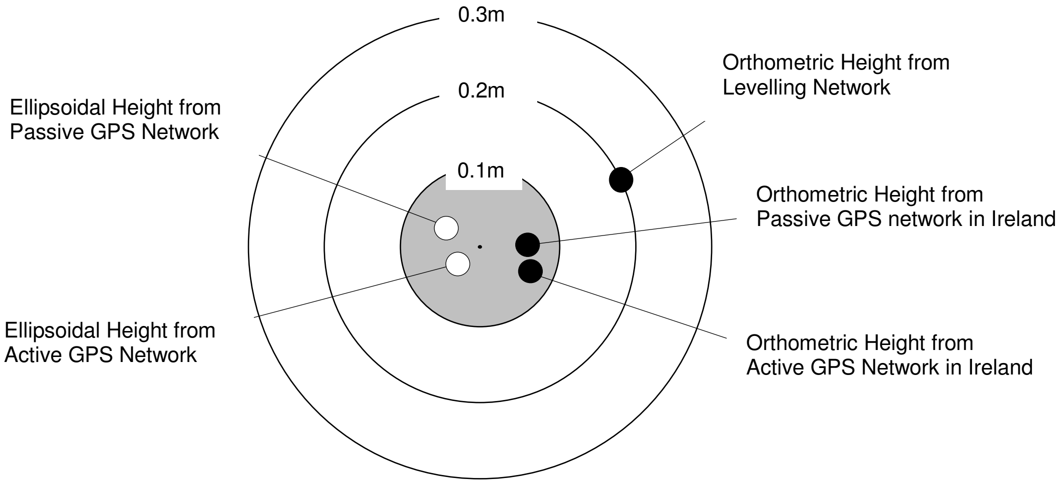



**Figure D3. Estimations of absolute and relative accuracy of ellipsoidal and orthometric heights calculated from the GPS and Levelling Networks.**

It is obvious from Figure D3 that orthometric heights surveyed from the GPS Networks have substantially better absolute accuracy than orthometric heights surveyed from the Levelling Network (51.58 mm to 68.82 mm compared to 203.80 mm). It is also interesting to note that the relative accuracy achieved (28.57 to 30.53 mms) with these two heighting techniques are similar at a range of 5 km. However, the relative accuracy of the digital level over shorter distances is superior at 6.40 mm for levelling compared to 20.49 mm from the Active GPS network and 20.88 mm from the Passive GPS network at a range of 500 m).

This accuracy estimation of height determinations does not take account of Ocean Tide Loading (OTL) in the methods described, which use GPS. Although the promise of GPS heighting is millimetre-level accuracy over hundreds of kilometres, the reality is often more like centimetre-level accuracy over tens of kilometres. For most locations in the world, baselines need to be perhaps several hundred kilometres long before relative GPS heights are affected at the 10 mm level, but in the British Isles relative OTL may exceed 10 mm over baselines as short as 75 km, and 50 mm over baselines as long as 150-200 km. (King *et al*, 2003). Current research suggests that medium length baselines may not provide the accuracy requirements of the industry for heights, which suggests that existing GPS Networks may have to be re-designed to cater for higher accuracy requirements.

# APPENDIX E – Recommendations for Surveyors

# Recommendations for Surveyors

## *Horizontal Control*

The following procedures should be applied to achieve an absolute accuracy of ± 60 mm (2σ) with respect to the ITM co-ordinate reference frame for precise surveying operations.

**Control Networks**

a) The old re-triangulation networks of trig pillars on tops of hills and its associated IG75 co-ordinate reference frame, and should not be used.
b) Co-ordinates for the OSI densification points (DP) should not be used.
c) The IG75 co-ordinates of the Passive GPS stations should not be used.
d) The ERTS89 co-ordinates for Passive and Active GPS stations are suitable depending on baseline length from the project area. However, since these control stations are not inter-visible, total stations can no longer be used, and GPS equipment will now be necessary to establish project control.
e) In linear projects where traverses are required off the main project route, it is good practice to include additional GPS points as reference objects to close the traverses, and these additional GPS points should be included in the network adjustment of the project control.

**Co-ordinate Reference System**

The new ITM co-ordinate reference frame should immediately replace the old IG75 co-ordinate reference frame as the preferred co-ordinate system for supply of all survey products to clients.

**Co-ordinate Transformations**

Local 'best fit' transformations are unofficial and should be not be used. The polynomial transformation is the definitive transformation and should be used in preference to the both official and non-official versions of the seven-parameter transformation.

**Observations**

a) Multiple measurements should be made at project control stations, so kinematic techniques only using a small number of observations, or single frequency GPS equipment are not suitable to achieve an absolute accuracy of ± 60 mm for control for precise surveying.
b) It is recommended that GPS measurements should be made from at least two stations of the Passive GPS Network, or three stations of the Active GPS Network.

**Computations**

Co-ordinates for project control should be computed using network adjustment methods that identify measurements outside tolerance and use least squares techniques to achieve the required absolute accuracy of ± 60 mm. Computations of absolute and relative accuracy achieved should be supplied to the client.

**Statement**

A statement should be included within survey graphics and survey reports which outlines:

a) The type of transformation if used, and the transformation parameters employed.
b) The IIS recommended methodology used to provide survey data with improved spatial quality.

## METHODOLOGY 1 - Computing IG75 or ITM Co-ordinates

**STEPS:**

1. Select two GPS network stations (points A and B in Figure 21) within 20 km of the project location, ensure their intersection geometry to the project control stations is optimum, and set the GPS receivers on points A and B to initialise them.
2. Retain GPS receiver on point A as the base station, and using the GPS receiver from point B as the rover station record measurements from project control stations 1 to 5.
3. Repeat step 2 with the base station on point B.
4. Set GPS receivers on project control stations 1 and 2 and record measurements, then move the GPS receiver from point 1 to point 3 and record measurements, and continue leapfrogging until project control station 5.
5. Use ETRS89 co-ordinates of the GPS network stations and process vectors.
6. Adjust vectors as a network by holding station A fixed.
7. Adjust vectors again as a network by holding station B fixed.
8. Test the two networks against each other to ensure all co-ordinates are within relative accuracy required. Existing experience indicates that using multiple baselines from at least three stations of the GPS network will permit residuals to be calculated for computed co-ordinates, facilitate the identification and elimination of rogue observations and enhance the relative accuracy of results.
9. Finally, adjust network again by holding both stations A and B fixed.
10. Use Quest software to:
    a) Project the computed ETRS89 co-ordinates into
        - ITM co-ordinates.
        - Irish Grid (1975) co-ordinates using the polynomial transformation
    b) Convert ellipsoidal heights into orthometric heights using the geoid model (OSGM02).
11. The resulting co-ordinate triplet should now have the following absolute and relative accuracy (Appendix D):
    a) Absolute accuracy of ± 60 mm (2σ) for ITM Easting and Northings, and an absolute accuracy of ± 69 mm* (2σ) for orthometric heights (± 62 mm* in Northern Ireland).
    b) Relative accuracy of ± 15 mm (2σ) for ITM eastings and northings, and a relative accuracy of ± 29 mm* (2σ) for orthometric heights.
12. Include a list of the ETRS89 and ITM (or IG75) co-ordinates for all project control stations in the survey report.

* These estimations of accuracy for orthometric heights do not take account of the effects of ocean tide loading

## *Vertical Control*

## METHODOLOGY 2 – Computing Orthometric Heights

**STEPS:**

1. The Quest software is used (step 10 b in Methodology 1) to convert the ellipsoidal heights calculated during the network adjustment (using least squares) of the project control into orthometric heights.
2. Project control points should then be spirit levelled using digital levels (or equivalent) to quantify the relative height difference between the stations.

3. Final orthometric heights should be computed by holding the relative height differences (from the spirit levelling) fixed and adjusting the values up or down within the ± 20 mm tolerance of stations fixed from the GPS Network.
4. Benchmarks in the vicinity should not be included in the network.
5. All survey documents and graphics should:
    a) Include the ellipsoidal and orthometric heights for all project control stations;
    b) Include a statement identifying the surveying and computing methodology used.
6. Clients should be informed of the differences in quality of orthometric heights computed from the old Levelling Network and orthometric heights computed using the geoid model.

## *Clarity*

1. Surveyors should adopt the abbreviation 'IG75' for the Irish Grid (1975) co-ordinate reference frame to distinguish it from earlier realisations of the Irish Grid co-ordinate reference system.

2. Surveyors should include a statement on all survey graphics and reports' noting which transformation was used if the data is to be supplied on the IG75 co-ordinate reference frame.

3. Surveyors should adopt 2σ (95% confidence level) as normal surveying practice for survey measurements, unless otherwise stated.

## *Survey Reports*

Clients should be supplied with survey reports for precise surveying projects, which include:

a) A detailed description of the surveying and processing methodology used for project control, including computations of absolute and relative accuracies achieved.
b) A list of co-ordinates (ETRS89 and ITM) for project control.
c) A detailed description of the surveying and processing methodology used to compute orthometric heights for project control, including computations of absolute and relative accuracies achieved.
d) A list of orthometric heights for project control (including new orthometric heights assigned to OS bench marks if requested).
e) A detailed description of the survey methodology used for project detail, including computations of the absolute and relative accuracies achieved.
f) A description of problems encountered during the survey.