



Implementation of WGS84 and GPS for Marine Navigation

Terry Moore, Vidal Ashkenazi, Mark Dumville
The University of Nottingham, UK

For the last two years a large collaborative project has been taking place at the University of Nottingham to investigate novel strategies for the implementation of Global Navigation Satellite Systems (GNSS) within all phases of marine navigation in UK waters. The project, which has recently been completed, was funded by the Engineering and Physical Sciences Research Council. The project has also received financial support from a prestigious team of collaborators which include the UK Hydrographic Office (UKHO), Trinity House Lighthouse Service, Northern Lighthouse Board, Commissioners for Irish Lights and the Port of London Authority. The overall aim of the project was to develop strategies to harmonise the different positioning and display systems used in marine navigation, ashore and afloat which will ultimately lead to safe and seamless navigation at sea. The project covered a number of distinct aspects of marine navigation, including chart datum transformations, the implementation of WGS84 in a port environment, the integration of GNSS with LORAN-C, optimisation in co-ordinating aids to navigation and the provision of Receiver Autonomous Integrity Monitoring (RAIM) for marine operations. A series of specific case studies addressing different aspects of the project have been carried out in different parts of the UK. This project is now completed. Earlier papers describing progress on this project have been published in the *Journal of Navigation*. (Ashkenazi et al, 1999 and Moore et al, 2000). This paper presents the rationale, the approach and the main findings from these studies.

Project Aims and Objectives

The project's overall aim was to develop strategies to harmonise the different positioning and display systems used in marine navigation, ashore and afloat. In doing so, the project addressed the fundamental problems facing organisations such as the International Maritime Organisation (IMO), the International Association of Lighthouse Authorities (IALA), the International Hydrographic Organisation (IHO), port authorities and the vessel owners when attempting to integrate positional information from GNSS, aids to navigation and existing charting onto a common reference system. To achieve this aim, the project had the following objectives:

- (i) To carry out fundamental research into methodologies and optimal strategies which are required for the implementation of the WGS84 co-ordinate datum in marine navigation. This required the investigation and establishment of appro-

- appropriate strategies for the transformation of existing nautical chart data and other navaid information (eg radar sites and marine beacons) into WGS84, or re-surveying when necessary.
- (ii) To develop new concepts, specifications, algorithms and software for a new integrated system for Vessel Traffic Services (VTS), combining current radar positioning with modern Differential GNSS (DGNSS) telemetry technology for the navigation of vessels. Current VTS surveillance systems are radar based and operate over a local area. The integration of GNSS position information, into existing systems, will enable port authorities to monitor vessels both inside and outside their areas of jurisdiction, thus improving safety at sea and in ports.
 - (iii) To establish a methodology for assessing the integrity of GNSS for marine navigation in UK waters. This required the development of algorithms and software tools, which will help in assessing GNSS integrity for all phases of navigation, but especially for safety critical operations (port approaches, berthing and harbour navigation).
 - (iv) To investigate the combined use of Real-Time-Kinematic (RTK) GPS, tide gauge records and hydrographic survey data to provide robust and reliable techniques for accurately monitoring the under-keel clearance of deep draught vessels in shallow clearance zones and restricted passages.

To address these objectives the project was divided into six work packages, with each work package addressing a distinct fundamental problem concerning the implementation of satellite navigation for future maritime use.

Datum Transformation of Chart Data

This work package addressed the problem of transforming existing nautical chart data into WGS84. Despite the considerable benefit of GPS derived positions, it may not be possible to exploit them to their full accuracy due to the differences between the co-ordinate system used by GPS and those employed by nautical charts. GPS positions are computed in WGS84 which has been adopted internationally as the single worldwide datum for marine navigation. Historically, however, nautical charts have been produced on several different datums. Indeed the UK Hydrographic Office produces over 3300 charts in over 100 different datums (Gooding, 1992). Many existing charts, although referenced to a known datum, often contain *spatially variant scale and orientation biases*. Furthermore, there are many charts without any specified datum (45%). This problem continues to limit the full exploitation of GNSS technology. Only 10% of the Admiralty charts are currently referenced to WGS84.

The work progressed in three ways. Firstly, a GPS survey of existing aids to navigation was performed in three areas (the Thames Estuary, the Shannon Estuary, and the Sound of Mull). This allowed a direct comparison of the current tabled and chart positions with their WGS84 counterparts. This work is reported later. The second approach was to use existing transformation parameters, from the Ordnance Surveys of Great Britain, Ireland and Northern Ireland, and test how these compare with the current chart shifts published on charts. The chart shifts are simple latitude and longitude corrections, which when applied to GPS based WGS84 co-ordinates, convert them to the local datum of the map. Two tests were conducted in the Thames and Shannon regions. The agreement between both the OSGB '2m' (OSGB, 1995) and the more precise OSTN97 (Davies, 1999) transformations, and the published chart shifts was within the resolution of the chart shift parameters (0.01 minutes). In the Shannon region the same was also true, using the Ireland 7-parameter transformation (Ashkenazi et al, 1998a). Additional, parallel, tests were carried out by the UKHO, using their proprietary transformation methods, and the agreements with the OSTN97 transformation, around the entire UK coastline were better than 2m. Two conclusions can be drawn from this aspect of the study. The current methods of chart transformation, used by the UKHO, are appropriate and compare well with more precise transformations. Secondly, the new OSTN97 transformation is an appropriate method, being of sufficient precision and extensibility, to be used to transform UK coastal nautical charts. Indeed, the UKHO have recently announced that they will re-issue their charts for UK and Irish waters, on WGS84, using this method, over the next two years. This approach could also

be adopted for other regions of the World, where good transformation parameters are available. It does not address the issue of charts with no datum information, or no known transformation, or of questionable survey quality.

For the Thames region simple transformation parameters were computed, which could be implemented by the Port of London, for their survey purposes. Three and four parameter conformal transformations were computed between the GPS surveyed WGS84 co-ordinates and the published OSGB36 co-ordinates. These were compared with the OSTN97 transformation, and the RMS agreement was about 0.5m, with a maximum difference on 1.3m. This is an acceptable level of agreement for the Port of London's purposes.

The Implementation of WGS84 in Ports

In anticipation of the future need to register port navigation facilities on to the WGS84 datum, a pilot survey of the Port of London was carried out in 1998. The survey was used to assess the accuracy of the existing co-ordinate information, to identify potential problems and to estimate the effort required in "re-surveying" or "transforming" a typical European port on to the WGS84 datum. The first phase of the pilot survey focussed on re-surveying the Port of London's nine VTS radar sites.

At each radar site, one hour of GPS carrier phase observations were collected at a 30 second data interval. Each radar site was subsequently positioned independently, relative to two Continuously Operating GPS Receivers (part of the IESSG national GPS network (Dodson and Bingley, 1999)). This procedure resulted in two independent position solutions for each radar site. The difference between the two independent solutions (repeatability) gave an indication of the quality of the newly surveyed co-ordinates. The accuracy of the new WGS84 co-ordinates for the nine radar sites is estimated at better than 5 cm.

Having surveyed the nine radar sites onto the WGS84 datum in a controlled procedure, the next task was to assess the quality of the existing published co-ordinate information for the same radar sites. In this experiment the new WGS84 co-ordinates for the sites were transformed to the UK national mapping datum (OSGB36) using publicly available transformation parameters. The parameters have a quoted accuracy of 2m (OSGB, 1995). The transformed co-ordinates were then compared to the published co-ordinates for each site, to assess the quality of the existing information. The existing published co-ordinate information was supplied at a resolution of 0.01 minutes, equivalent to a resolution of 12m in Easting and 18m in Northing. Figure 1 gives the results of the co-ordinate comparisons.

It is clear from the results presented in Figure 1 that the published co-ordinates for the majority of the radar sites are in agreement with the new

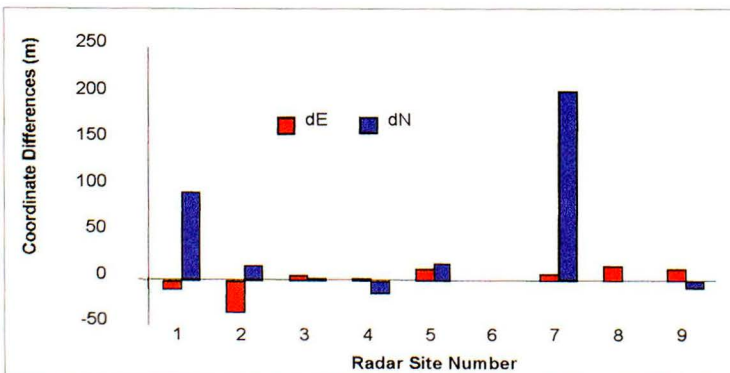


Figure 1: Comparison of "Transformed" WGS84 coordinates and the published values

Co-ordinates. However, there are sizeable differences for two radar sites (as indicated). These errors have never previously been identified. This is because the primary function of the VTS radar is one of surveillance and not navigation. Radar, although poor in terms of absolute positioning (~100m accuracy), provides a precise relative picture of vessels and obstructions which is suitable for VTS surveillance operations. For surveillance and collision avoidance applications

precise relative positioning of vessels is more important than their absolute positions. Looking to the future and the introduction of Automatic Identification Systems (and Differential GNSS transponders), the integration of radar-derived and GNSS-derived co-ordinates by VTS centres will be a complex task unless radar sites and other traditional aids to navigation (including lights, buoys, charts) are also referenced to WGS84.

The next phase of this work involved estimating the size and cost of the task in implementing WGS84 within UK and European ports. As a guideline to the magnitude of the problem, there were around 60 major airports in the United Kingdom which had to be registered on to WGS84, when civil aviation adopted that datum. In the marine community there are 96 major ports in the UK. At each airport around 50 facilities, obstructions, features had to be referenced to WGS84. The Port of London alone, has around 1000 aids to navigation which will need to be co-ordinated on to WGS84 (to varying degrees of accuracy). The estimated financial implications are discussed later.

Co-ordination of Nav aids into WGS84

One of the aims of this research project was to evaluate the accuracy of the extension of a land-based transformation into the sea and to assess the accuracy of existing information on charts. Furthermore, *in this work package the intent was to develop and test procedures for the co-ordination of coastal navigation aids onto the WGS84 datum.* These were closely related tasks and so the field work for these two work packages was combined. From land based surveys, and from GLA (General Lighthouse Authorities) vessels, the quality of the transformations and of the co-ordinates of a sample of navigation aids around the UK and Irish waters were assessed. Three test areas were selected for this purpose, including the Thames Estuary in England, the Shannon Estuary in Ireland and the Sound of Mull in Scotland. The experiments were carried out in all three areas between August and October 1999.

For the Thames Estuary trials a new GPS reference station was established in Harwich for the five days of observations, and was positioned with respect to a network of permanent GPS receivers operated by the IESSG. During the field trials, a total of 40 points were surveyed using GPS, to cover the whole estuary. These points included 17 beacons, 6 lighthouses, 6 buoys, 9 UKHO survey marks and 5 other aids-to-navigation, such as towers and radio masts.

For the fixed aids, on land and in the estuary, the GPS antenna was mounted on the top of each aid for about 30 minutes, and the positions were calculated using standard static GPS carrier phase positioning, relative to a reference station. For the moving targets, such as the buoys, approximately 5 minutes of GPS observations were taken, and either RTK GPS or DGPS (Differential GPS) techniques were used to process the GPS data. The expected accuracy was of the order of a few centimetres for the fixed aids and possibly 2-3 metres for the moving aids. For a number of the fixed points in the estuary the GPS antenna had to be left on the survey boat, which was moving due to the waves, and offset measurements of bearing and distance to the centre of the beacon were measured.

The GPS survey results were compared with the co-ordinates of the points archived in the UKHO records. Because the UKHO positions are in the local OSGB36 datum, all GPS positions were transformed to this frame, using a published Ordnance Survey (OS) transformation (OSGB, 1995), with a stated accuracy of about 2m. The co-ordinate differences for the nine UKHO marks on land are all less than 2.5m, and these differences can be mainly attributed to the accuracy of the transformation. For the beacons in the Thames Estuary, the differences are more significant. For five of the beacons the position differences are larger than 10m, with one difference as large as 56m. Clearly, this can not be solely attributed to errors in the GPS surveying or the transformation accuracy, and so is most probably due to original survey error.

A similar experiment has also been carried out in the Shannon Estuary, Ireland. A variety of aids-to-navigation which were surveyed, including 6 lighthouses, 6 navigational lights, 1 radar site, 3 buoys, 1 tide

gauge, 7 Ordnance Survey Ireland points, and 4 other features. The surveyed co-ordinates (in WGS84) were compared with the recorded positions. The published co-ordinates were recorded in the Ireland 75 datum, and these positions have been transformed to WGS84 using the Ordnance Survey of Ireland 7-parameter transformation (Ashkenazi et al, 1998a). There are two notable points which have very large co-ordinate differences (hundreds of metres), although one of these is an ancient ruin, and of no great navigational significance. The final trial was conducted in the Sound of Mull and positions of six light-houses were surveyed in WGS84 using GPS surveying techniques. In this instance three co-ordinate differences were over 10m and the largest was 32m.

WGS84 as a Vertical Reference Datum

When surveying, a hydrographer measures the depth of water and applies the tide height to produce a depth for the chart. When navigating his vessel, the mariner is thus given two pieces of information, the chart depth and the tide height. To this he then adds a third - the draught of the vessel. He then calculates the under-keel clearance available in order to determine whether it is safe to proceed. This traditional methodology for ensuring the safety of navigation of vessels in shallow waters does provide opportunities for error. In the interests of safety, the objective of this work package was to assess the feasibility of relating GPS derived heights of the vessel to the seabed, such that the under-keel clearance of selected vessels is always maintained at an agreed safe level. In this way, the requirement for complex calculations and the potential for errors is avoided.

A series of kinematic GPS trials were conducted using the survey boat of the Port of London Authority. The trials lasted for three days and took place near Gravesend on the River Thames. Multiple GPS

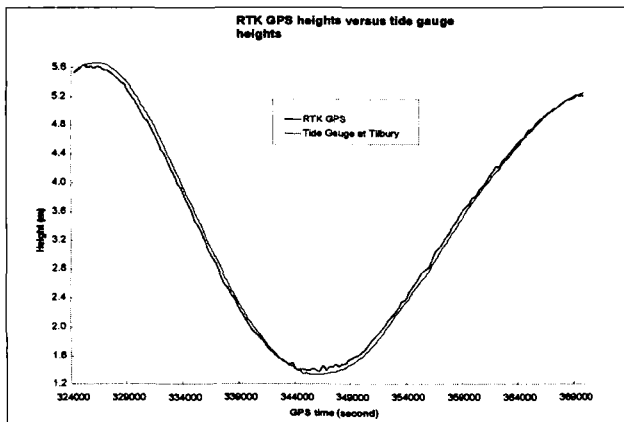


Figure 2: Comparison between GPS river height and the tide gauge measurements

receivers were mounted on the small survey vessel, along with the boat's usual complement of DGPS receivers. Observations were made over three consecutive days from 10-12 November 1998. During each day trials were conducted as the boat was surveying along the river. Overnight, as the boat was moored alongside a tide gauge site, the GPS data collection continued for at least another 12 hours per night.

Quality checks indicated that consistent millimetre level positioning was obtained, with very few breaks in the data. The RTK GPS height of the survey boat, above the WGS84 ellipsoid, was computed. In order to compute the boat's under-keel clearance further information was required. The height of the GPS antenna over the keel was known, and the tide level was measured during the trials. The sonar survey instrument on the boat was used to measure the under-keel clearance during the trials. An existing PLA bathymetric survey of the river bed could not be easily accessed and referenced to WGS84. As a result the GPS derived clearance could not be computed, and so could not be compared with the clearance computed in the classical manner

The overnight periods gave an opportunity to further investigate the ability of RTK GPS to determine the height of the survey boat. The GPS height was compared with two tide gauges in the close proximity of the mooring. Figure 2, illustrates the comparison with the tide gauge record for about twelve hours. During this trial a tidal range of about 4.5 metres was experienced. The level of agreement is consistently bet-

ter than 1 cm, throughout the duration of the trial. Comparisons with the tide tables, used by mariners, were not made.

Integration of GPS with Other Systems

During the cruising phase of the River Thames trials (see above), Radar data was also recorded from the VTS used by the PLA. Unfortunately, only the vessel track could be recorded, and not the raw Radar data. It was hoped to repeat this trial, with raw data recorded by the VTS, but this was not possible as extensive modifications would have been required to the VTS software. The agreement between the DGPS track of the boat, on the first day, and the Radar positions, is shown in Figure 3.

It is clear that there is a systematic position difference between the two tracks (of around 40m). The aim of this work package was to fully integrate DGPS data (from ship borne transponders) with the RADAR based VTS, so as to produce a seamless, and harmonised, track of the vessel on the VTS. However, without full access to the raw Radar range and bearing data from the VTS radar sites, this was not possible.

In addition to the geodetic GPS receivers, installed specifically for the trials, the survey boat also carried three different DGPS receivers.

- (i) GLA DGPS. The marine beacon DGPS service operated around the UK and Ireland, by the three GLAs
- (ii) PLA DGPS. A local UHF based DGPS service operated by the PLA for their own survey operations
- (iii) Focus FM. A commercial FM RDS based DGPS service operating in the UK

These three receivers operated continuously during the trials, and were independent from each other and from the geodetic receivers. The distances between one of the geodetic antennas and each of the other DGPS antennas are shown in Figure 4. It is clear that the Focus FM suffered

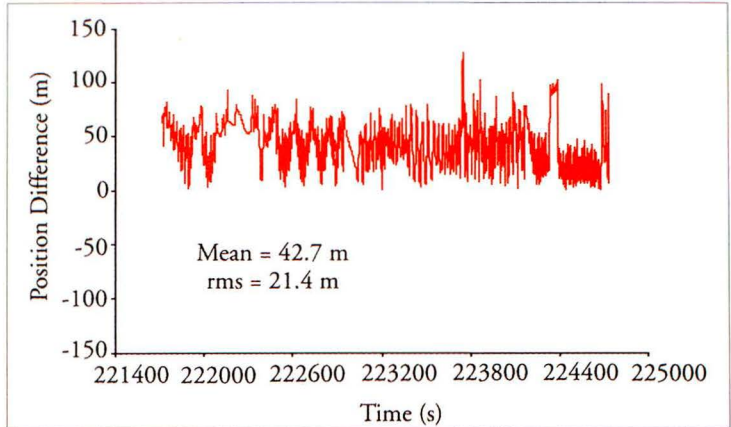


Figure 3: Difference between the DGPS and VTS tracks (total 2D)

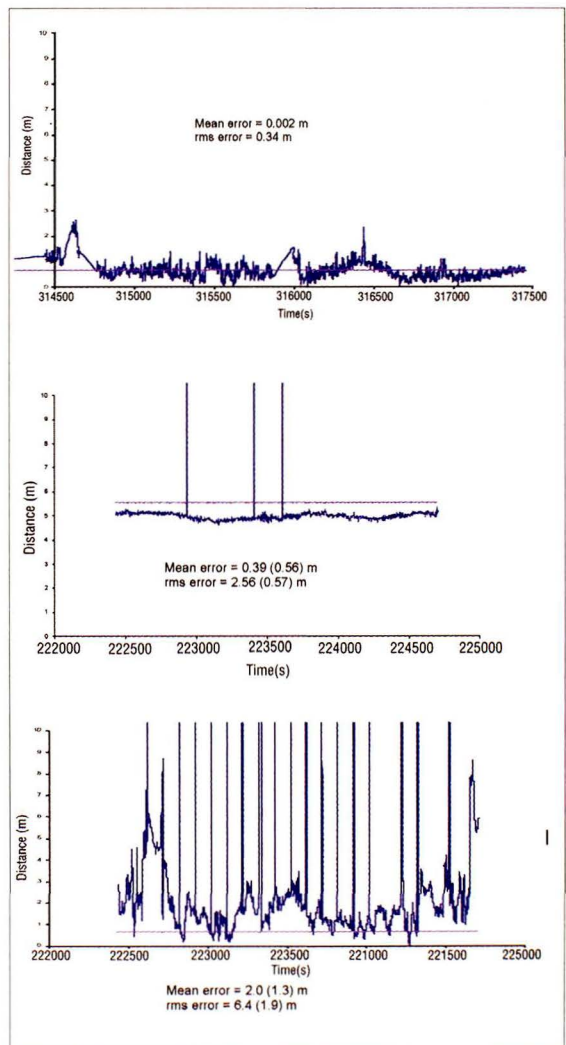


Figure 4: Difference between GLA, PLA and Focus FM DGPS positions and RTK GPS

from many outages in the DGPS corrections, and was noticeably more noisy than either of the other two services. The local PLA service appears to have a small (50cm) systematic bias in its position. The GLA DGPS service shows no systematic bias, with a RMS error of only 34cm.

Assessing GPS Integrity for Safety Critical Operations

One of the most important performance requirements for the use of GNSS in UK marine navigation is the need to monitor the GNSS system and the derived position fix, and to subsequently inform the mariner

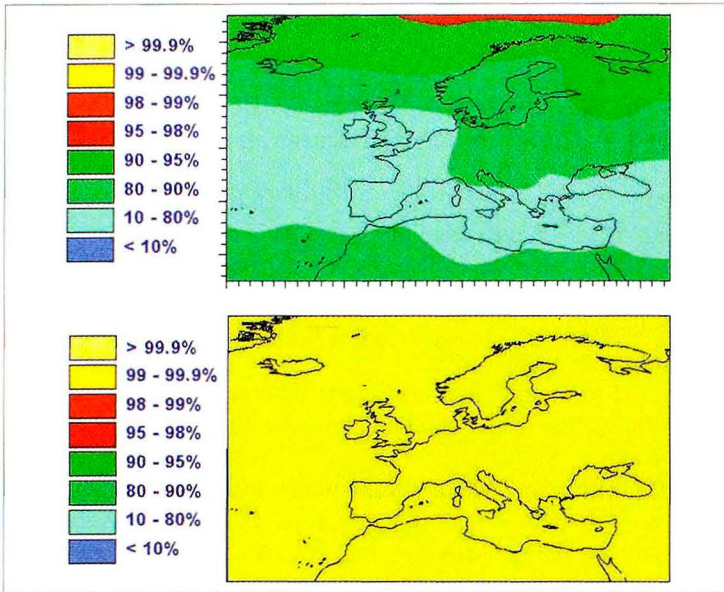


Figure 5: GPS RAIM and GPS/EGNOS RAIM for coastal phase of navigation

when the accuracy of the fix does not meet his requirements. This is the so-called integrity problem. Integrity is defined by the IMO as "... the ability to provide users with warnings within a specified time when the system should not be used for navigation" (IMO, 1997). A system is said to have 'integrity' if the system can provide timely warnings when the system is not safe to use.

The requirements of integrity differ for different applications and for different phases of navigation. The UK GLAs have yet to propose the integrity parameters for UK marine navigation, although they do appreciate the requirement for integrity during all phases of navigation (GLA, 1997). To meet the user

requirements there must be a method to detect and potentially isolate any GNSS measurements which will cause errors in the computed position fix. It was the purpose of this work package to investigate, propose and assess different integrity parameters for the different phases of voyage. This task examined the use of different GNSS constellations/configurations to satisfy the need for RAIM (Receiver Autonomous Integrity Monitoring) in marine applications.

In order to provide estimates for marine navigation the integrity parameters from the aviation counterpart were adopted and were modified as necessary. For example, parameters for the Non-Precision Approach phase of flight were modified and proposed as suitable for the Coastal phase of voyage. Figure 5 illustrates the results of RAIM availability over 24 hours for GPS and GPS/EGNOS (European Geostationary Navigation Overlay Service) in the coastal phase of navigation. This analysis was conducted using a GNSS data simulator developed at the IESSG (Ashkenazi et al, 1998b). It can be seen that although GPS alone can provide RAIM some of the time, the addition of the EGNOS overlay substantially increases the availability to greater than 99%. Other phases of navigation were also addressed and appropriate parameters were proposed.

Financial Implications and Recommendations

Based on the pilot survey of a typical port, and the survey of the aids to navigation carried out in the three regions, the following broad financial implications have been deduced. These may be converted into true financial estimates with a knowledge of daily staff rates, the costs of purchase or hire of GPS and

Fixed Aids to Navigation	
Requirement	10cm accuracy
Approach	Static GPS positioning
Production	5 points per day (average)
Resources	2+1 staff, plus equipment & mobility
Floating Aids to Navigation	
Requirement	10m accuracy
Approach	DGPS positioning
Production	10 points per day (average)
Resources	2+1 staff, plus equipment & mobility

other equipment, and the significant costs of mobility. The latter should not be underestimated, as expensive vessel or helicopter time may be required, and access to remote locations may be both difficult and time consuming.

It is recommended that in order to implement WGS84 in ports and for coastal Aids to Navigation there will be a need for extensive re-surveying, although some transformation may be possible. The recommended approach may be summarised as follows:

- Re-position all fixed facilities using GPS surveying
- Re-position all critical floating Aids to Navigation using DGPS
- Transform coordinates of non-critical Aids to Navigation (provided the transformation is extensible)
- Verify coordinates of non-critical Aids to Navigation (preferably during routine operations)

The recommendations of the study have recently been considered by the Radionavigation Committee and the Operations Committee of IALA, and will soon go to IALA Council for approval as a Recommendation or Guideline to its members. It is expected that they will be issued as a Liaison Statement or Information Paper to the International Maritime Organisation (IMO) and the International Hydrographic Organisation (IHO).

The UKHO have recently announced plans to re-issue all their charts for UK and Irish waters on WGS84. This will take place over the next two or three years. The current charts will be transformed using the Ordnance Survey Great Britain OSTN97 transformation (Davies, 1999). The findings of this project have validated the use of the Ordnance Survey transformations around UK and Irish waters.

Conclusions

The main technical challenge facing the UK marine community in the implementation of GNSS is in ensuring that all aids to navigation (visual, electronic, floating, ship-based & shore-based) can be used in combination with GNSS to a high level of accuracy and integrity in order to satisfy the users' requirements. It is necessary to provide a consistent co-ordinate information infrastructure to support the eventual introduction of GNSS. This does not relate to the provision of a new physical infrastructure. Rather, it concerns the provision of all co-ordinate information on a single co-ordinate system that is compatible with GNSS-derived co-ordinate information. The project has demonstrated many of the problems which will be encountered by the marine community in the implementation of WGS84.

It will be necessary to integrate the different "mix" of aids to navigation to meet the requirements of the UK marine community. These requirements include not only technical and operational requirements but also political and institutional. The project has investigated the technical performance requirements of GNSS, most notably in terms of system accuracy and integrity. Assessments have been carried out to

evaluate the use of different satellite navigation systems, for different phases of a voyage and new integrity parameters to meet the specific needs of the mariner have been proposed.

The recommendations of the project are now being adopted by national and international maritime agencies such as UKHO, the GLAs, the PLA, IALA, IMO and IHO.

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Biographies

Terry Moore is Professor of Satellite Navigation, and Deputy Director, of the Institute of Engineering Surveying and Space Geodesy, at the University of Nottingham. He holds a BSc degree in Civil Engineering

and a PhD in Space Geodesy, both from the University of Nottingham. He is a Fellow, and Member of Council, of the Royal Institute of Navigation and a Member of the Institute of Navigation.

Vidal Ashkenazi is Emeritus Professor at the University of Nottingham, and CEO of Nottingham Scientific Ltd. He holds a DPhil and a DSc in Physical Sciences from Oxford University. He is a Fellow of the Royal Institute of Navigation and a Member of the Institute of Navigation.

Mark Dumville is the General Manager of Nottingham Scientific Ltd. He received a BEng degree in Civil Engineering and a PhD in Space Geodesy, both from the University of Nottingham. He is a Member of the Royal Institute of Navigation.