Implications of the use of GNSS and WGS84 for Marine Navigation

Terry Moore, Mark Dumville, Wu Chen

(*IESSG, University of Nottingham*)

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 GNSS within all phases of marine navigation in UK waters. The project, which was recently completed, was funded by the Engineering and Physical Sciences Research Council. The project also received financial support from a prestigious team of collaborators that included the UK Ministry of Defence Hydrographic Office, Trinity House Lighthouse Service, Northern Lighthouse Board, Commissioners for Irish Lights and the Port of London Authority. The first phase of this project was reported in the *Journal* in May 1999 (Ashkenazi *et al*., 1999); this paper presents an update of the progress of the project over the last year.

KEY WORDS

1. Marine Navigation. 2. GNSS. 3. Geodetic Datum. 4. Navaids

1. INTRODUCTION. In response to Lord Donaldson's report on the Prevention of Pollution from Merchant Shipping, the UK government has agreed that the ability of ships accurately to determine their position is vitally important for safe navigation and the protection of the marine environment. GNSS technology has the greatest potential in addressing this vital requirement. However, existing positional information used in marine navigation is based on local coordinate datums. With the implementation of GNSS for marine navigation, there is an urgent need to present all positional information (such as; aids to navigation, charts, GNSS) onto a common global reference frame. Moreover, the accuracy of traditional positional information is not compatible with GNSS. The effective integration of GNSS with aids to navigation, charts and other positioning systems remains a fundamental challenge.

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 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 also received financial support from a prestigious team of collaborators including the UK Hydrographic Office, 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 that 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 coordinating 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 paper presents the rationale, the approach and the main findings from these studies.

2. 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 IMO, IALA, 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;

(a) To carry out fundamental research into methodologies and optimal strategies that are required for the implementation of the WGS84 coordinate datum in marine navigation. This required the investigation and establishment of appropriate strategies for the transformation of existing nautical chart data and other navaid information (for example, radar sites and marine beacons) into WGS84, or re-surveying when necessary.

(b) 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.

Furthermore, to achieve a truly seamless system for all phases of navigation, the project investigated the integration of GNSS observations with ground-based LORAN-C for operational use in the medium term. The UK General Lighthouse Authorities are considering adopting LORAN-C as a terrestrial navigation system to back up and complement the use of GNSS and radiobeacon-based DGNSS systems.

(c) 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 GPS integrity for all phases of navigation, but especially for safety critical operations (port approaches, berthing and harbour navigation).

(d) 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 height of deep draught vessels in shallow clearance zones and restricted passages.

3. PILOT SURVEY OF A TYPICAL PORT. In anticipation of the future need to register port navigation facilities on to the WGS84 datum, the first phase of the project was to carry out a pilot survey of the Port of London. The survey has been used to assess the accuracy of the existing coordinate 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 initial survey focussed on the re-surveying of the Port of London's nine VTS radar sites, and was fully reported in a previous paper (Ashkenazi *et al.*, 1999). 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 coordinate information for the same radar sites. The published coordinates for the majority of the radar sites were in close agreement with the new coordinates. However, there were sizeable differences for two radar sites. Looking to the future and the introduction of Automatic Identification Systems (and DGNSS transponders), the integration of radar-derived and GNSS-derived coordinates 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.

4. GPS TRIALS AT THE PORT OF LONDON.

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 receivers and choke ring geodetic antennas were mounted on the small survey vessel (Figure 1), along with the boat's usual complement of DGPS receivers.

Figure 1. River Thames boat test.

Three consecutive days of observations were made on 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.

There were a number of objectives for the trials:

(a) To assess the use of precise height from RTK GPS for navigating in restricted waters,
(b) To collect DGPS and radar data for the integration of GPS and the VTS,
(c) To evaluate the differences between different DGPS services,
(d) To investigate the use of RTK GPS as a dynamic tide gauge measurement.

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By using two receivers on the survey boat a fixed baseline, of known length, was obtained. The coordinates of the antennas on the boat were computed using GPS carrier phase data, relative to a reference geodetic GPS receiver at the PLA headquarters in Gravesend. This process was carried out independently for each antenna on the boat. The baseline between the antennas was then computed from the coordinates, and this, when compared to the known length (of 3·588 m), was used as a simple check on the quality of the GPS carrier phase data and processing.

The RTK GPS-derived baseline length, compared against its true value, while the survey boat was cruising up and down the river, is shown in Figure 2. The results

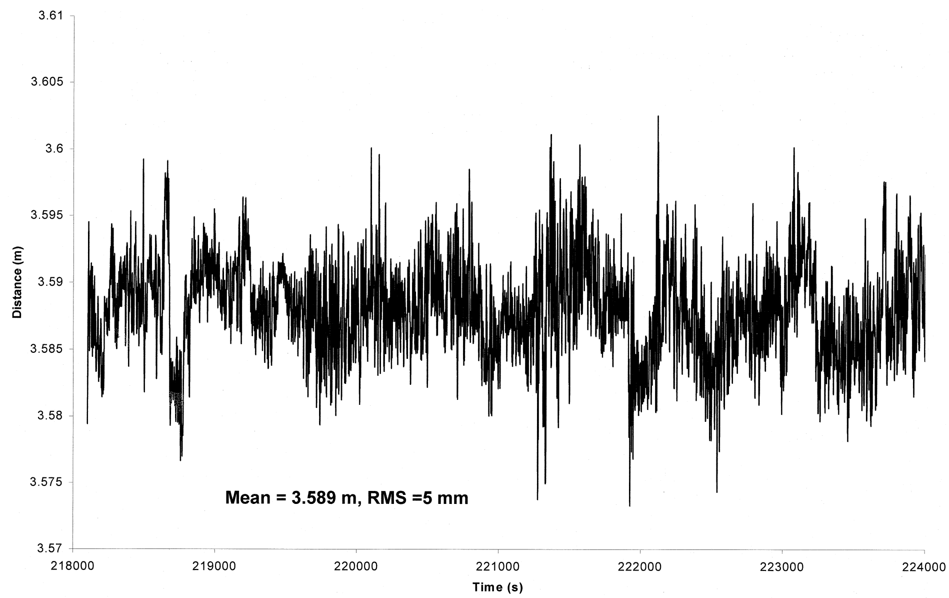

Figure 2. Differences between the GPS baseline length and the radar positions.

demonstrate the potential accuracy of the RTK GPS approach in a harsh river environment. The agreement between the GPS-determined baseline length and the known value is of the order of a few millimetres, with only a few small gaps in the data. The RTK GPS height of the survey boat may be used to compute the boat's clearance, given a knowledge of the known height of the GPS antenna over the keel, and a bathymetric survey of the river bed, referenced to WGS84. This may be compared with the clearance computed in the classical manner, from a knowledge of the chart depth, the tide and the freeboard of the vessel.

During the cruising phase of the trials, 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. 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 40 m). The aim was to 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.

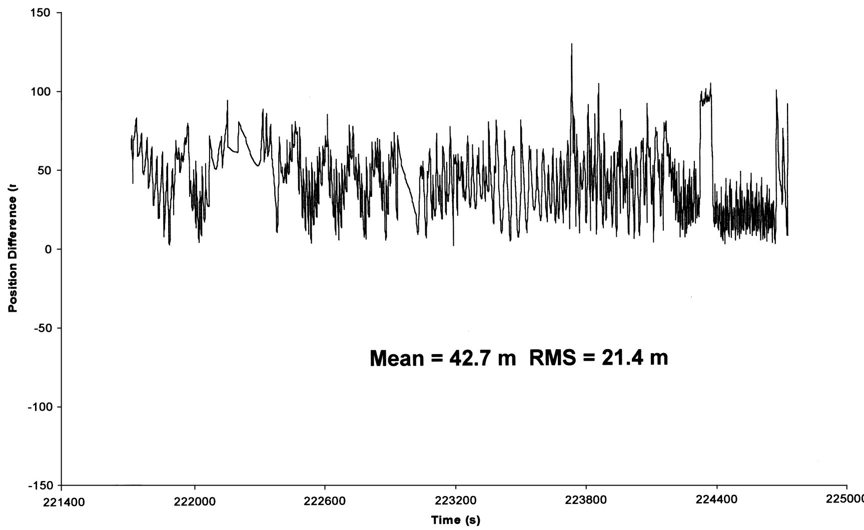

Figure 3. Differences between the DGPS track of the boat and the radar positions.

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) PLA DGPS. A local UHF-based DGPS service operated by the PLA for their own operations,
(ii) GLA DGPS. The marine beacon MF DGPS service operated around the coasts of the United Kingdom and Ireland, by the three General Lighthouse Authorities,
(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 of 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 from many outages in the DGPS corrections, and was noticeably noisier than either of the other two services. The local PLA service appears to have a small (50 cm) systematic bias in its position. The GLA DGPS service shows no systematic bias, with a RMS error of only 34 cm.

The IESSG is currently involved in a separate project to investigate the use of GPS on a buoy, to measure the heights of rivers (Moore *et al.*, 2000). Although outside the scope of this study, the overnight periods gave a opportunity to compare the RTK GPS height of the survey boat, with two tide gauges in the proximity of the mooring. Figure 5 shows the agreement between the GPS-derived baseline length and the known distance between the two antennas on the boat. Figure 6 illustrates the comparison with the tide gauge record for about twelve hours. During this trial a tidal range of about 4·5 m was experienced. The level of agreement is consistently better than 1 cm, throughout the 12-hour period of the trial.

The GPS baseline results achieve a high accuracy when compared with the fixed baseline length, but also the GPS river heights compared extremely well with the

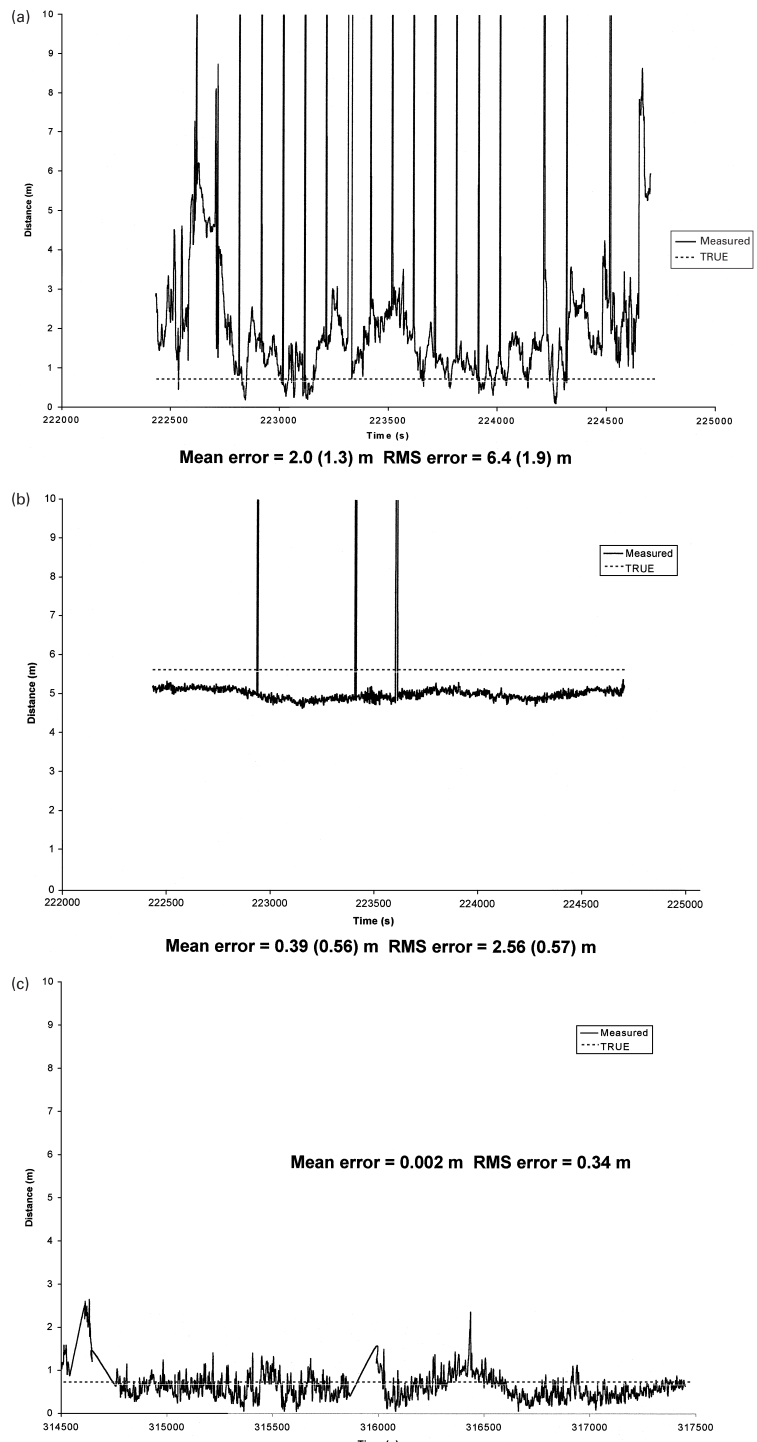

Figure 4. (a) Difference between the Focus FM DGPS positions and RTK GPS. (b) Difference between the PLA DGPS positions and RTK GPS. (c) Difference between the GLA DGPS positions and RTK GPS.

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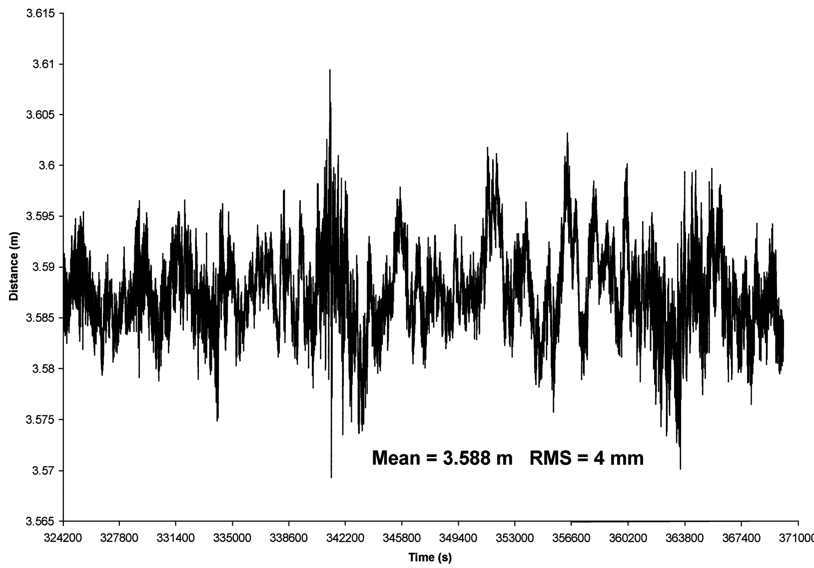

Figure 5. Difference between GPS baseline length and its true value.

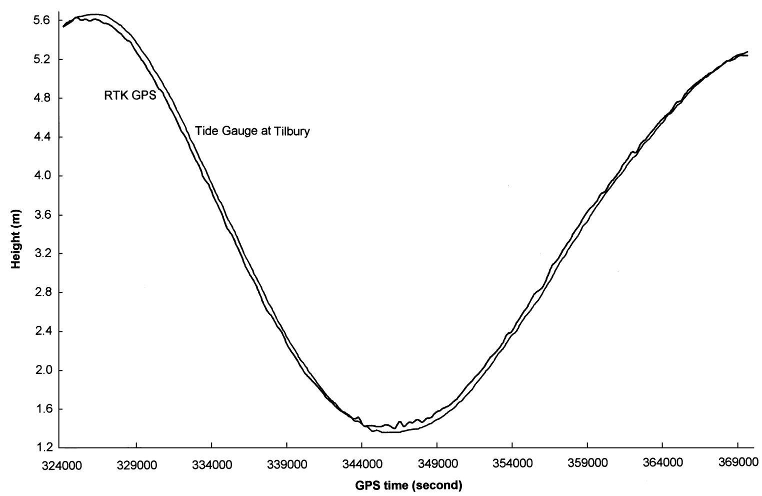

Figure 6. Comparison between GPS river height and the tide gauge measurements.

external tide gauge measurements. The overall quality of the GPS data was very high and has caused few processing problems, despite a number of obstructions surrounding the river. The data was processed using both Ashtech Office Suite (AOS) and the IESSG NOTF program, which is a component of the Nottingham GAS software package. Both software packages give comparable results, at the sub-centimetre level.

5. SURVEYING OF AIDS-TO-NAVIGATION. 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. Three test areas were selected for this purpose, including the Thames Estuary

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Table 1. The coordinate difference of UKHO survey points.

OS Mark Stn no.	Easting (m)	Northing (m)
1	−1·51	0·08
2	−1·85	0·47
3	−2·27	0·15
4	−2·50	−0·89
5	−2·28	−1·25
6	−1·56	1·34
7	−0·78	0·08
8	−1·98	0·05
9	−0·74	−0·88

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.

In the Thames Estuary, there are two Continuously Operating GPS Receivers nearby, which can be used to provide the reference stations for the experiment to tie all the surveying results to the WGS 84 frame. These receivers were part of a permanent national network operated by the University of Nottingham, for a number of government agencies. A new GPS reference station (with a 2-second update rate) was also established in Harwich for the five days of observations. During the field trials, a total of 40 points have been surveyed using GPS, to cover the whole estuary. These points include 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 techniques were used to process the GPS data. The expected accuracies for the fixed and moving aids are about a few centimetres and possibly 2–3 metres respectively. During the survey, the major problem was accessibility of the aids-to-navigation. If it was possible, the GPS antenna was located on the centre of the aid-to-navigation. Otherwise an offset measurement had to be made. For a number of fixed points in the estuary, it was not possible to mount the GPS antenna on the beacon. The GPS antenna had to be put on the survey boat, which was moving due to swell, and offset measurements of bearing and distance to the centre of the beacon had to be measured. In this case, a positioning accuracy of only a few metres was expected.

Tables 1 and 2 give the comparison of GPS survey results with coordinates 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 2 m. Table 1 shows the comparison of nine OS marks on land. The differences are within 2·5 m and this 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 10 m, with one beacon (No. 12) as large as 56 m. Clearly, this cannot be solely attributed to errors in the

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Table 2. The coordinate difference of beacons.

Beacon no.	GPS accuracy (m)	Easting (m)	Northing (m)
1	0·1	−1·33	0·15
2	0·1	1·20	−0·41
3	0·1	−0·79	−1·42
4	2–3	18·19	16·80
5	0·1	−2·07	−0·23
6	5	0·14	−3·13
7	2–3	5·09	−9·80
8	2–3	9·45	−11·56
9	2–3	1·00	−2·46
10	0·1	−2·85	0·70
11	0·1	−1·85	1·52
12	2–3	−18·19	56·28
13	0·1	3·68	−8·97

Table 3. Classification of surveyed points in Shannon Estuary.

Type of Aids	Number
Lighthouse	6
Navigational Light	6
Radar Site	1
Buoys	3
Tide Gauge	1
OSI Mark	7
Others	4
Total	28

GPS surveying or the transformation accuracy. A similar experiment has also been carried out in the Shannon Estuary, Ireland. Table 3 gives the variety of aids-to-navigation that were surveyed. The comparison between the surveyed coordinates (in WGS84) and the recorded positions are given in Table 4. The published coordinates 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*., 1998).

There are two notable points with very large coordinate differences, although one of these is an ancient ruin, and of no navigational significance. The final trial was conducted in the Sound of Mull in September 1999, and positions of six lighthouses were surveyed in WGS84 using GPS surveying techniques.

6. 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 (see Table 5). These may be converted into true financial estimates with a knowledge of daily staff rates, the costs of purchase or hire of GPS, and 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.

Table 4. Coordinate differences of points in Shannon Estuary.

Name	Northing (m)	Easting (m)
Loop Head Lt	−43·73	−4·02
Kilcreaduan Lt	−45·16	−30·06
Corlis Lt front	−46·59	−51·70
Corlis Lt rear	−39·12	−60·69
Rinealon Lt	−9·19	−14·28
Tarbert Lt	−7·12	1·12
EHB jetty sw Lt	−13·44	4·84
Tarbert Rear Lt	−20·26	−1·79
Tarbert Front Lt	−29·42	3·58
Garraunbaun Lt	−5·85	−12·96
Beeves Lt	−8·64	−13·74
Scattery Lt	14·44	−60·26
Kilbaha Quay-end Bollard	1·25	84·86
Kilcreadaun Radar	−481·97	814·35
Carrigatholt Tide Gauge	−82·85	−10·42
Moneypoint west pier	−21·22	6·54
Oil jetty-SW corner	−22·97	−14·09
Browns Castle B'Bunnion	−4734·85	4504·30

Table 5. Typical resource and financial implications of port surveys.

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

The recommended approach for the implementation of WGS84 in ports and for the fixed and floating aids to navigation may be summarised as follows.

(a) Re-position all fixed facilities,
(b) Re-position all critical floating Aids to Navigation,
(c) Transform coordinates of non-critical Aids to Navigation (provided the transformation is extensible),
(d) Verify coordinates of non-critical Aids to Navigation (preferably during routine operations).

7. 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 and shore-based) can be used in combination with GNSS to a high level of accuracy and integrity in order to satisfy the users' requirements. This includes two distinct stages;

(i) It is necessary to provide a consistent coordinate 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 coordinate information on a single coordinate system that is compatible with GNSS-derived coordinate information. The project has demonstrated many of the problems that will be encountered by the marine community in the implementation of WGS84, and has provided both financial estimates and a recommended approach.

(ii) 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. The algorithms and software tools, developed during our previous work with Eurocontrol, have been modified to cater for the requirements of the marine user. Assessments have been carried out to evaluate the use of different satellite navigation systems, for different phases of a voyage. As a result, new integrity parameters to meet the specific needs of the mariner have been proposed.

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