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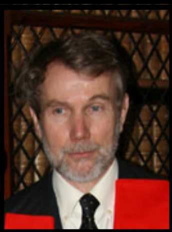

# FROM 19th CENTURY TO PRESENT: CHANGES IN HYDROGRAPHIC SURVEYING TECHNIQUES AND DETERMINATION OF SOUNDING ACCURACY

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## Abstract

Calculation of morphological change between hydrographic surveys is marred by uncertainties, in particular when methods have changed. When examining estuarine evolution, an approximation of measurement errors is needed. An overview of the changing approaches since the 19th century is given to aid error estimation and subsequent comparison with modern surveys. Changes and errors in horizontal positioning, soundings and datums need to be considered when interpreting sediment gains and losses. As a case study, the derivation of error estimates for an 1845 and modern hydrographic dataset on the south-west coast of Ireland is described.

## Résumé

Les calculs du changement morphologique entre les levés hydrographiques sont faussés par les incertitudes, en particulier, lorsque les méthodes changent. Lorsqu'on examine l'évolution des estuaires, il est nécessaire d'avoir une estimation des erreurs de mesurage. Une vue d'ensemble du changement d'approches depuis le 19ème siècle est présentée aux fins d'appuyer l'estimation des erreurs et la comparaison ultérieure avec les levés modernes. Les changements et les erreurs dans le positionnement horizontal, les sondes et les systèmes de référence doivent être pris en compte pour interpréter les gains et les pertes en sédiments. Comme étude de cas, l'évolution des estimations d'erreurs pour une série de données de 1845 et pour un ensemble de données hydrographiques modernes sur la côte sud-ouest de l'Irlande est décrite.

## Resumen

El cálculo del cambio morfológico entre los levantamientos hidrográficos está deformado por incertidumbres, en particular cuando los métodos han cambiado. Al examinar la evolución de los estuarios, se requiere una aproximación de los errores de medida. Se proporciona una visión general de los aproches cambiantes desde el siglo 19, para ayudar a efectuar la estimación de errores y la consiguiente comparación con los estudios modernos. Tienen que considerarse los cambios y errores en el posicionamiento horizontal, en las sondas y los datums, al interpretar los aumentos y las pérdidas de sedimentos. Como estudio de un caso, se describe la derivación de las estimaciones de errores para una colección de datos hidrográficos de 1845 y una colección moderna en la costa suroccidental de Irlanda.

## Introduction

Hydrographic and topographic surveys of estuarine channels and intertidal flats provide a source of data for quantifying volume changes over time. The integration of these datasets is important for a wide range of coastal applications e.g. channel maintenance, infrastructure development and restoration of habitats, as well as research into the sedimentation and erosion rates. The net movement of sediment in and out of the study area can be calculated, and longer term trends may be determined using historical datasets (Van der Waal and Pye, 2003; Byrnes *et al*., 2002). With growing evidence of climate change and the predicted effects on storminess, sea level and hydrological balances, there is an increasing need to understand the evolution of estuaries to determine past changes in order to predict future trends

This paper provides an overview of historical survey methods and the uncertainties to be considered when comparing modern and historical surveys. A case study is presented describing the determination of error in hydrographic surveys, of different time periods, from the Argideen Estuary on the south west coast of Ireland.

There have been large improvements in the accuracy and precision of soundings and positioning over time, therefore the error associated with measurements may be different between historical and modern surveys and between two modern surveys. In the 19th century soundings were acquired using a lead line, Rude-Fisher pressure tube or a graduated pole in shallow areas. The collection of elevation and depth data now includes the use of accurate GPS systems, echo sounders and remote techniques such as LIDAR. However determination of the accuracy and total error associated between two bathymetric datasets is difficult. When comparing survey data an assessment of the differences, whether real, as a result of differences in the methodology between the two surveys, and/or errors within the survey itself, should be performed.

The accuracy of soundings is dependent on many random and systematic errors in the measurement process. The amount of real versus apparent change can only be determined by quantifying the total error in the comparison of two surveys so that the apparent changes can be removed from the calculation of the overall change.

Measurement error is defined as the difference between a measured value and the true value and it can be categorized as a blatant error, systematic error or random error (e.g. Byrnes and Hiland, 1994; Kraus and Rosati, 1998; Ministry of Defence, 1987). Blatant errors (human) can be eliminated with adequate quality control procedures. Systematic errors follow a regular pattern and if identified can be measured or estimated through calibration and removed from the survey data. Random errors are typically small errors resulting from the limitation of measuring devices or from the inability to calculate and remove systematic errors exactly. They do not include the errors associated with the measurement of tides and datum (Van der Waal & Pye, 2003). These errors change rapidly with time and are governed by the laws of probability. Some authors argue that even blatant errors are difficult to detect as the bottom elevation being measured is not visible. Langeraar, (1984) claims that giving an error estimate on a value that isn't known in the first place is quite pointless. What can be measured clearly however, are the fluctuations that the depth measurements are exposed to. These include changes in sea water parameters, irregularities in machinery and fluctuations in bottom reflection processes i.e. - the systematic errors.

## Horizontal uncertainties

The accurate comparison of the position of soundings from historical and modern charts depends on the accuracy of the positioning method and knowledge of the reference datum it refers to. Horizontal datums on different charts may not be the same. A number of datums and associated spheroids have been used for charting worldwide and there are differences in geodetic latitudes and longitudes, albeit small, between different charting systems. In the past these differences had very little effect on the day to day navigation of ships, particularly because the errors inherent in astronomical observations were larger than any inconsistency in charted latitude and longitude (Ministry of Defence, 1987). See Alymer and White (1914), Ministry of Defence, (1987) and Langeraar, (1984) for more detail on geodesy, projections, grids and the creation of different coordinate systems.

The worldwide 3D reference system (WGS84) was defined in the 1960s with the advent of extremely accurate satellite techniques. It was then possible to establish the relationships between previously unconnected datums and to convert them to the world datum (Ministry of Defence, 1987). The development of satellite navigation systems has also shown discrepancies in the horizontal datums of many charts. Differences have resulted from errors in the astronomical fixes used for early surveys that were computed on local geographical datums. The reference spheroid of a local datums is a best fit for that particular area, whereas the ellipsoid used by WGS84 adjusts to the earth surface as a whole. This creates a datum shift, which can be in the order of a few hundred metres. The datum shift needed to relate older charts to current GPS datums is outlined on charts and in the "User's Handbook on Datum Transformations involving WGS84" (IHO, 2003).

In addition to datum errors, the survey data from which the chart was compiled may contain errors in geographical positions (Ministry of Defence, 1987).

These errors are the inaccuracy of the plotted soundings on charts relative to the horizontal datum. Historical surveys used transects and horizontal angles, measured against coastal features, to determine position through geometry. The precision of these positions was often affected by adverse sea conditions (Bale et al., 2007). The position error will decrease with decreasing chart scale but the affect on the soundings will depend on the slope of the seabed (Sallenger et al., 1975). See Aylmer and White, (1914) for details on historical navigation and positioning and the errors involved. In the latest IHO standards for hydrographic surveys, the horizontal position of soundings should have a 95% probability that the true position lies within a defined radius (IHO, 2008).

## Vertical uncertainties

### Changes in vertical datums

Vertical datums can be either orthometric (based on the geoid), tidal (a tidally-derived surface of high or low water), or ellipsoid (used by e.g. GPS). In the case of historical charts (early 20th century and previous), the accuracy of the vertical datums must be considered, especially when comparing depths with modern surveys. The level that was used to construct an historical survey is often unknown. It may be related to a tide gauge or mainland benchmark that is not retrievable today (Van der Waal & Pye, 2003).

The first task for surveyors on arriving in an area was to start observing the tide (Edgell, 1948). Chart datum for 19th century surveys was Mean Low Water Ordinary Springs (Aylmer and White, 1914). Now, Chart Datum is the level of the lowest possible water level (LAT). The accuracy of tidal information gathered depended on how long the surveyors were in any particular location and their focus was on tidal observations for the reduction of soundings rather than scientific investigation (Wharton, 1882). The main requirement was knowledge of low-water springs and the time of high water at full and new moon. Therefore tidal levels were usually only recorded during the duration of the survey and the results extrapolated, unlike today where tidal datums are averaged over an 18.6 year period. Despite the short nature of the tidal surveys, surveyors were cautious when carrying out the reductions. Even on a small scale chart, accuracy in reduction was regarded as being very important. If the surveyors were not in an area during the spring tide they had to note the high-water mark on the shore, measure how far it is above the high tide of the day, and subtract the same amount from the low-water mark measured on that day. This level was taken as the low water spring datum. Often a foot or two extra was subtracted to be on the safe side. A description of how tidal observations were taken and calculated in the late 19th century is outlined in Wharton, (1882).

The relative datum difference between two survey periods, especially when the period is long, could also have been influenced by decadal tidal variations, eustatic sea level rise and tectonic movement (Sallenger et al., 1975; List et al., 1997; Gibbs and Gelfenbaum, 1999).

### Modern depth measurement uncertainties

All acoustic depth readings are dependent on the sea state, water temperature and salinity, transducer beam width, bottom sediment type, surface irregularity and vessel heave-pitch-roll motions, among other things. Vessel position and elevation may be measured separately and would have uncertainties independent of those associated with the positioning and orientation systems. International Hydrographic Office standards are applicable around the world. For shallow water surveys (<40m), random errors in depth measurement should not exceed 25cm with a 95% probability, depending the survey order (IHO, 2008). There are several sources of error that need to be taken into consideration when comparing two *modern* bathymetric sets. These are:

- The errors associated with the different measurement techniques and instrumentation. The accuracy of the soundings will be affected by the precision of the equipment used and the survey conditions at the time i.e. wave height, vessel velocity and the type of sediment on the seabed.
- The errors associated with the post-processing of the data such as tidal corrections, speed of sound adjustments and vessel draft corrections, if the resolution of the corrections is not higher than the resolution of the measurements themselves.
- The potential movement of the datums to which the soundings and positions have been reduced to.
- The errors associated with the digitisation (in a GIS) of the positions and depths.
- The effect of data density on the accuracy of the interpolation between survey lines.

Measurement of depths relative to still-water level. This measurement is more difficult in small boats due to waves, course and speed changes, and variations in load distribution affecting the vertical position and the tilt of the transducer. The difference between the still water level and the mean water level in the presence of waves of just 0.5m high would hide bedforms and bars of similar or smaller amplitude. Furthermore, in estuaries the speed of sound may vary significantly during the tidal cycle and in space which may result in an error (Gibeaut et al., 1998).

### Historical depth measurement uncertainties

In addition to the errors in comparing two modern surveys, even larger errors may be associated with comparing modern and historical charts.

Undoubtedly, the random error of depth measurements from the 19th century is likely to be greater than in modern surveys. Historical surveys were undertaken manually and for navigational purposes, so they were mainly interested in recording the shallowest point (Thomas et al., 2002; Van der Waal & Pye, 2003; Aylmer and White, 1914). Sea state and equipment limitations played a major role in the accuracy of readings. No instructions explicitly defining accuracy limits were found in the historical literature for British hydrographers. Quality control requirements for depth measurements were detailed nonetheless. The hydrographic surveyors of the time went to extreme lengths to ensure the quality of the data (Shipman and Laughton, 2000; Wharton, 1882). It is assumed that each sounding was recorded as accurately as possible in the circumstances.

According to Wharton (1882), a good hydrographer should *"have a quick eye...but above all he must have a boundless capacity for taking pains in details at all times and seasons…nothing may appear that is not known to be correct*". This opinion is borne out in further descriptions given in Wharton, (1882), emphasising the importance of checking and testing all instruments to *"ascertain their errors"*. He was very much aware of all the potential errors involved in hydrographic surveying and wrote that *"no instrument, not even engine-divided protractors can be assumed to be without error…no work can be deemed satisfactory without the knowledge of how much correction should be applied…machines are more liable to error than a trained man, under most circumstances"*

At that time new instrumentation was being developed to ease the procedure of sounding, like the Massey's, Lucas's machine. The "small boat" sounding machine was used in shallower waters and the boat had to be stopped in order to allow the soundings to be taken correctly (Edgell, 1948; Cook and Carleton, 2000). Another type of sounding machine, the Kelvin Mark IV, used by the Royal Navy at the start of the 20th century, enabled soundings to be taken from the main ship while it was moving.

Lead lines were the main method of acquiring soundings until about 1935 when the echosounder came into more general use, but the lead line continued to be used for inshore work until the 1950s (Ministry of Defence, 1987; Shipman and Laughton, 2000). It was essential that the rope or wire was vertical from the surface to the seabed and that the weight was in contact with the seabed (Shipman and Laughton, 2000). Lead line measurements only cover the few centimetres actually struck by the lead and features less than a metre away from each sounding can remained undetected. Therefore, although each line of soundings may be miles in length, it only represents a few centimetres in width (Aylmer and White, 1914; Shipman and Laughton, 2000) and depending on the scale of the chart a single figure may occupy several hectares of ground (Ministry of Defence, 1987; Aylmer and White, 1914).

As with modern surveys the density of depth measurements will have an important effect on the overall interpolation of depth. The density of soundings taken in any particular area depended on how rapidly the slope of the seabed changed and whether or not there were unexpected readings. A shoal patch between lines could easily have been missed (Aylmer and White, 1982).

Potential instrumental errors would have included a stretch in the line and curvature of the line due to currents or ship movement. By the middle of the 19th century the use of wire lines greatly reduced the amount of stretch. Sounding lines for manual use were still made from rope but had a wire core. If the correct tension was maintained on the line it was assumed not to stretch more than 1-2%. Surveyors were instructed to measure the lead lines on return to the main ship and to note whether the length of the lead line didn't exceed the 1-2% tolerance (Wharton, 1882, Shipman and Laughton, 2000). Operational errors may also have occurred where the boundary between the seawater and the seabed was unclear, especially where the bottom was muddy. The point at which the bottom was thought to have been reached depended on the density of the material on the bed and on the shape and weight of the weight attached to the wire (Shipman and Laughton, 2000).

Unlike modern survey equipment that records to several decimal places, soundings using leadlines were recorded to the nearest half or quarter fathom. How much the halves and quarters were recorded depended on the scale of the chart. Therefore the accuracy of a chart is often dependent on the scale that the original survey was made on (Aylmer and White, 1914). In general, fractions were retained up to 6 fathoms and above that depth the fathoms were rounded down to the nearest even fathom. For safety, depth values are usually rounded down, especially if low water at spring tide was not measured directly.

During the metrification of charts in the 1950's, further errors might have been included as a result of conversion and subsequent rounding down (Van der Waal & Pye, 2003). A description of the range of instrumentation used in surveys from the late 1800's to the early 1900's can be found in Wharton, (1882); Aylmer and White, (1914) and Shipman and Laughton, (2000). Although accuracies increased with the initial use of echo sounders, the determination of where the seabed began and where the water column ended still caused uncertainties. The first echo sounders were subsonic and at this frequency the signal penetrated into soft mud before being reflected.

These were replaced by sounders using ultrasonic frequencies which reflected the echo from the top of the fluid mud which still may have been mostly liquid (Van der Waal & Pye, 2003).

## Determination of measurement error

A compilation of the magnitude of different error sources should be estimated to give better confidence in whether the changes calculated between two surveys are real or apparent. Estimation of error is easily obtained with modern survey equipment as the accuracy and precision capabilities of instrumentation, under optimum conditions, are clear. In addition systematic errors can be carefully monitored. The determination of RMS error provides a consistent means of combining biases and random errors for calculating the statistical error associated with depth observations (Byrnes et al., 2002). As an additional test, the relative precision of individual depth measurements can be checked by comparing measurements of survey lines that intersect.

The determination of the accuracy of historical surveys is more difficult given the nature of the measurements as outlined in the previous section. Gibbs and Gelfenbaum, (1999) used the survey accuracy standards of 1883 for United States surveys as a starting point for determining the error estimates in their comparison of historical datasets (Table 1). Although determination of RMS error is more rigorous for modern surveys, Byrnes et al., (2002) found that potential errors in water depth measurements for late 1800s and early 1900s surveys in the USA were approximately ± 1-1.3m. For mid-1900s surveys, the RMS error is about ± 0.6-1m.
No explicit standards have been found thus far in the literature associated with the surveys undertaken by the British Admiralty. It is assumed that errors in British surveys are of the same magnitude considering similar procedures would have been followed. What can be determined from the literature on British survey techniques from the 19th century is summarized as follows:

**1.** Soundings were recorded to the nearest ½ or ¼ fathom or foot;

**2.** Fractions were retained only up to 6 fathoms and for safety values were rounded down;

**3.** Further rounding down may have occurred during the metrification of charts; and

**4.** Tidal datum were only recorded over the survey period and so could have been influenced by meteorology and sea level changes. If surveyors were not present during the time of low water springs the value was estimated and a foot or two extra could have been subtracted from the depths as a precaution.

| Water Depth | Depth resolution |
|---|---|
| Deep sea soundings | Nearest fathom (~2m) |
| Outside 15 fathom curve (27m) | Nearest half fathom (0.91m) |
| Between 15 and 10 fathom curves (27-8m) | Nearest foot (0.3m) |
| Between 10 and 4 fathom curves (18-7m) | Nearest half foot (0.15m) |
| Between 24 and 12 foot curves (7-3.6m) | Nearest quarter foot (0.08m) |
| Inside 12 foot curve (<3.6m) | Nearest tenth foot (0.03m) |

***Table 1***
*Late 19th century bathymetric survey accuracy standards in the USA (Gibbs and Gelfenbaum, (1999))*

A summary of all potential errors, both vertical and horizontal, that must be considered when comparing and interpolating data from both modern and historical surveys is given in ***Table 2***.

| Modern surveys | Historical surveys | Both |
|---|---|---|
| Speed of sound adjustments | Variations in line length | Terrain irregularity |
| Transducer movement/heave | Vertical datum changes | Data density |
| Effect of waves | Accurate positioning | Effect of seabed sediment on instrumentation |
| Dynamic draught | Rounding up or down of readings | Heave of boat |
| | Readings to nearest ½ or ¼ fathom | Vessel speed |
| | | Accuracy of digitisation |
| | | Water levels, tides, transducer elevation |

***Table 2***
***A range of vertical and horizontal error considerations to be taken into account when comparing surveys of either historical or modern origin***

## Volume change calculations

Data density, the magnitude and frequency of bottom irregularities and the orientation of survey tracklines relative to bathymetric features are the most important factors influencing the calculation of volume change between two bathymetric surveys. These issues must be considered when creating a grid or contours. The presence of these uncertainties can be checked by visually comparing surface characteristics at adjacent survey lines. The closer the survey lines are or the smaller the bottom irregularities between lines, the lower the uncertainty will be (Sallenger et al., 1975; Byrnes et al., 2002). The orientation of tracklines may also cause an error in interpolation. According to Sallenger et al., (1975) surveyors were told to orient tracklines along the supposed contours until 1878 so they may have missed deep or shallow points by not surveying across that particular contour resulting in extremes in bathymetric fluctuation.

There are a number of techniques that were used for making quantitative estimates of change; contour overlay, contour overlay-data point and grid point comparisons (Sallenger et al., 1975). These were standard practice up to the 1980's (Byrnes and Hiland, 1993). Now statistical techniques and surface modelling software, such as Surfer, and GIS packages can be used to calculate volume changes between two surfaces. Two common ways of representing bathymetric surfaces from hydrographic data are TIN and interpolating the data on a grid. Creation of a TIN surface is best suited where data are sparse or unevenly distributed throughout the survey area. Furthermore all data points are used directly as they form the vertices of triangles that comprise the modelled terrain. Where data density is higher, interpolating the data on a grid (e.g. krigging) provides a good representation of surface characteristics.

According to Gibeaut et al., (1998) detailed comparisons of repeated bathymetric surveys are commonly inconclusive because the magnitudes of potential errors are equal to or greater than the actual changes of seafloor morphology. For example, in a survey covering 2,500m of shoreline across a nearshore width of 400m, a systematic elevation error of just 5cm would translate into an error in sand volume of 50,000m$^3$.

## Case Study: Argideen estuary, Ireland

The bathymetric surveying of Irish coastal waters was very limited until 1999 when the Irish National Seabed Survey (INSS) was launched by The Geological Survey of Ireland (GSI). Today it is amongst the largest marine mapping programme ever undertaken in the world, producing over 300 paper-based charts and a total of 5.5 Terabyte of digital information stored on the INSS database in GSI.

The main focus of the Irish National Seabed Survey was deep water mapping at the outer margins of Ireland's territorial seabed, moving shoreward as time went by. Now INFOMAR (INtegrated mapping FOr the sustainable development of Ireland's Marine Resource), the successor to INSS, concentrates on nearshore surveys (GSI, 2010).

In this study, the error estimates of historical sounding data (year 1845) and modern bathymetric and topographic surveys (years 1991 up to 2008), for the Argideen Estuary on the south west coast of Ireland, were estimated. These errors were used in the calculation of morphological changes that have occurred in the estuary over the last 163 years. In addition, the surveys were used as input and validation data for two numerical models of the estuary. Delft3D, a process-based model was used to simulate annual morphological change and ASMITA, a behavior orientated model, the longer-term volume changes (Cronin et al., 2007; Cronin et al., 2009). The interpolated depth profiles were compared rather than individual points, so the accuracy considerations for depth measurements were examined in more detail than position accuracies. An overview of the charts and survey data used in this analysis is given in *Table 3*.

Charts and maps in Ireland were related to the Irish Grid geodetic system. It was developed more than 200 years ago and is based on a rigorous adjustment of a carefully observed triangulation network. Since then there have been many changes and adjustments to the system. In 1994, OSI (Ordnance Survey Ireland) and OSNI (Ordnance Survey Northern Ireland) agreed to establish a new geodetic control network in Ireland based on ETRS89 (European Terrestrial Reference System 1989) and from this the IRENET95 network was developed. The IRENET95 network complies with international standards and provides high precision, distortion free control for GPS surveys. 79% of all Irish charts refer to this OSI datum. The most recent Admiralty chart of the Argideen estuary refers to this datum and has a gnomonic projection.

All depths and elevations in this analysis were referenced to the same vertical reference datum in order to be compared. In Ireland the current vertical datum is the Malin Head Vertical Datum. Earlier maps used the low water mark of the spring tide on the 8$^{th}$ of April 1837 at the Poolbeg Lighthouse, Dublin. Elevations above or below this datum were in feet. The Malin Head datum is approximately 2.7m above the Poolbeg Light house datum.

| Map/Chart/Survey | Date | Source | Horizontal Datum | Vertical Datum |
|---|---|---|---|---|
| 1845 Admiralty Soundings of Courtmacsherry Bay | 1845 | UKHO | digitised to Irish Grid | depths (in feet) at level of LWS |
| 1846 Admiralty Chart of Courtmacsherry Bay | 1846 | UKHO | digitised to Irish Grid | depths reduced approx to MLWS |
| 1977 Admiralty Chart of Courtmacsherry Bay | 1846 & 1907 surveys | UKHO | | depths to Chart Datum |
| Courtmacsherry Harbour sounding charts | 1991 (25/05/1991 & 06/09/1991) | DJ Fitzgibbon & Company Ltd | Irish Grid | depths to Chart Datum |
| Courtmacsherry Harbour sounding charts | 1992 (14/07/1992, 28/09/1992 & 02/10/1992) | DJ Fitzgibbon & Company Ltd | Irish Grid | depths to Chart Datum |
| Courtmacsherry Harbour bathymetric survey | 2006 | author | Irish National Grid | depths reduced to Chart Datum |
| XYZ GPS survey of the Argideen Estuary | 2006 | author | Irish Map Grid 1975 | OD Malin |
| XYZ GPS survey of the Argideen Estuary | 2007 | author | Irish Map Grid 1975 | OD Malin |
| XYZ GPS survey of the Argideen Estuary | 2008 | author | Irish Map Grid 1975 | OD Malin |

***Table 3.***
***Hydrographic data available for analysis***

## Argideen Estuary bathymetric and topographic datasets

Determination of sediment losses and gains in the the Argideen estuary were computed in Surfer by calculating volume change between datasets. The error associated with measurement was first determined for each dataset.

### 1845 soundings dataset

There are large temporal gaps in the bathymetric data available for the Argideen estuary and Courtmacsherry bay. The first major survey of the estuary was in 1845 by Commander James Wolfe on the H.M.S. Tartarus, during a survey of the south coast of Ireland from the Old Head of Kinsale to Calley Head, on a scale of 6.9 inches to 1 nautical mile. The resulting Admiralty Chart (number 2081) of the area was published in 1851 (UKHO, 2008, personal communication). The original survey sheet was used in this analysis. The current Admiralty Chart, published in 1977, is based on the 1845 survey (except for the channel which was resurveyed in 1907). No survey material was found in the UKHO (United Kingdom Hydrographic Office) archives for the period 1930-1980. Only high resolution digital images of the original survey sheets could be obtained as they were too large for the copying or scanning equipment in the UKHO. These images were taken perpendicular to the sheet to avoid distortion, but some alteration is likely to have occurred.

Some deformation will also have occurred during the process of georeferencing the images to the Irish Grid in ArcMap. Care was taken to ensure the RMS error was small during the georeferencing process for each image by using several fixed reference points, such as slipways, piers, roads and bridges. A slight shift of sounding positions as result of georeferencing was considered acceptable (***Fig. 1***) as depth points were interpolated to create a profile, and the measure of the 1845 coastline may not be as accurate the current coastline.

The vertical datum for the 1845 soundings was the level of low water of ordinary spring tides. This level was recorded as 33 feet and 7.5 inches (10.25m) below the sill of the middle window (lower edge of the stone) of the school house in Courtmacsherry Village. The soundings were recorded in feet inside the harbour and in fathoms outside. Depths were recorded to the nearest quarter of a fathom and half foot. The depths were reduced to low water springs and the heights on the drying banks were reduced to high water ordinary springs.

In order to compare the depths recorded in 1845 to values from the modern surveys, the values were converted to metres and reduced to the current chart datum, lowest astronomical tide (10.70m below the sill of the middle window of the school). Very few records exist of datum adjustments in the Argideen Estuary.

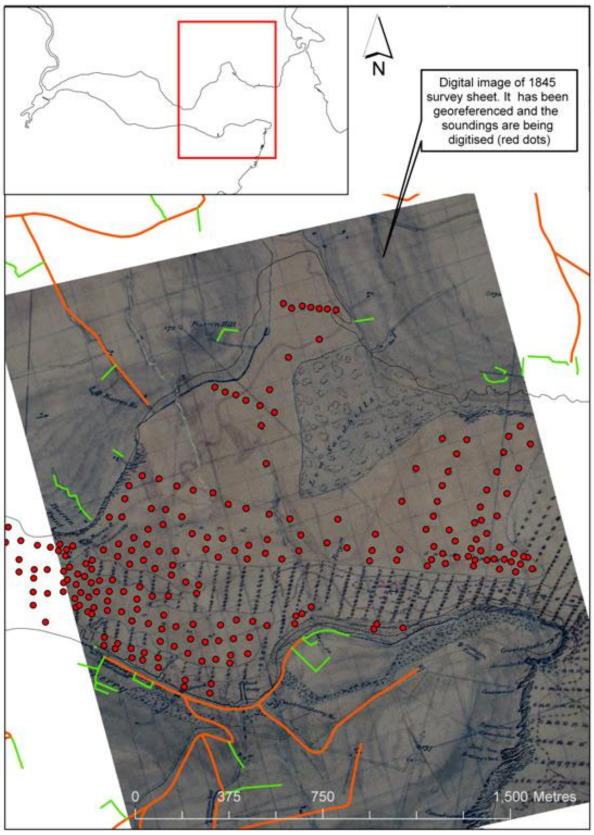


***Figure 1***
*Georeferencing and digitisation of the 1845 survey sheet in ArcMap*

However, there is a minute from Lt. Cdr. Powell, (1977) stating that 0.46m was subtracted from the soundings of 1845 to adjust them to LAT (UKHO, 2008, personal communication). This concurs with the difference between the two datums (0.45m) in relation to the benchmark at Courtmacsherry. Considering the tidal levels are only quoted to the nearest 0.1m, the additional 0.01m might have been subtracted for safety.

There are no available records of the mean tidal levels measured in the estuary during the survey in 1845. On the most recent publication of the chart, (1977) MLWS is 0.4m above LAT. The MLWS of 1845 was reduced by 0.46m to convert it to LAT so there is a 0.06m difference. From this it is assumed that the tidal ranges haven't changed significantly. The 0.06m difference is irrelevant in relation to the accuracy of tidal level recordings. This tidal information is required to calculate the level of MHWS on the 1845 sounding chart.

If tidal levels are assumed to be similar to today then the difference between MLWS and MHWS are also comparable. The heights on the drying banks were thus reduced to LAT using current tidal levels.

Using the information from the UKHO on the datum shift and the errors associated with historical sounding measurements outlined in the previous sections, the total error associated with these soundings could be estimated.

## 1845 error calculations

Based on the surveying methodology of the time, it is assumed the soundings of 1845 (measured in feet) were rounded down to the nearest half foot (0.153m). Therefore depths were underestimated by at most 0.153m. The accuracy of tidal readings and subsequent datum shifts must also be taken into account. It is not known whether the surveyors were present in Courtmacsherry during LWS. If it is assumed that they were not, the tidal levels would have been reduced by 1-2 feet (0.3-0.6m) for safety. A value of 0.3m is used here as the survey area analysed was within the estuary where depths are much shallower than the outer bay.

A total estimated error of +0.5m was calculated (rounding down of depths plus tidal levels and datum shift error margin). There is no negative error in this case because as the chart was produced for navigational safety all depths calculations have been rounded down.

## 1990s soundings dataset

Apart from a small survey of the main channel in Courtmacsherry Harbour in 1907 (data unavailable), the next bathymetric survey undertaken in the Argideen Estuary was in the early 1990s. The main channel was surveyed by Hydrographic Surveys Ltd for D.J. Fitzgibbon Company Ltd , both before and after dredging work.

These surveys were undertaken using rangefinders, digital echosounders and drawn up by hand. The accuracy of the echosounder used (Raytheon DE719D) is ±0.5% of the indicated depth. The soundings were measured directly from the paper records and the accuracy would have been to the nearest 5cm (Hydrographic Surveys Ltd, 2006, personal communication). Original survey sheets were obtained from Hydrographic Ltd., and the surveys dated May and September 1991 and July 1992 were used in the analysis. The surveys were scanned and georeferenced to Irish Grid in ArcMap in the same way as the 1845 survey images. Any slight distortion in the position of soundings as a result of the scanning or georeferencing was accepted, as depths between soundings were being interpolated. The total measurement error associated with these soundings is ±0.05m.

## 2006 bathymetric dataset

A complete resurvey of Courtmacsherry harbour, from the northern pier as far as Coolmain Point was undertaken in March 2006 with a single-beam echosounder by Irish Hydrodata Ltd. A Trimble NT300D DGPS was used to determine position and soundings were acquired using a Knudsen 320M dual frequency system (210kHz, 33kHz). The speed of sound profile in the water column was measured using an Odom Hydrographics Digibar and tide levels were measured using a Microtide self-recording tide gauge. Tide (and subsequently depth) levels were reduced to chart datum at Courtmacsherry. Due to the time of year that the survey was carried out the sea conditions were not ideal. Therefore, in order to allow for the effect of waves, the data was visually inspected by Hydrographics Ltd., to note the approximate period of the waves and a 'moving average' procedure was implemented to remove the effect of the waves. The accuracy of the echosounder system used was ±0.01m (Knudsen Engineering Ltd.). The presence of waves may have introduced a greater error but the total error in measuring depth, according to the 4$^{th}$ Edition of the IHO Standards should not exceed, with a probability of 90%, ±0.3m for depths less than 30m. Therefore based on this information a conservative error estimate of ±0.1m was assumed.

## 2006 -2008 topographic datasets

Three differential GPS surveys of the intertidal areas were undertaken annually by the author from 2006-2008 using the Trimble DGPS system with a ProXH receiver. This system provided real-time sub-metre accuracy with built-in SBAS, OmniSTAR and beacon capabilities. All areas reachable at low water were surveyed, including parts of the intertidal area that were surveyed during the bathymetric survey. This increased the resolution in those areas and provided a method of cross checking the bathymetric dataset.

Height and position readings (on Irish Grid) were taken along transect lines in these areas. The resolution varied in accordance with each location. In areas where there were significant changes in height over short distances the resolution was higher than in areas that were relatively flat and featureless. Elevations were corrected to Ordnance Datum Malin with RINEX base station data (Cork Station, ITM 563308.3 570435.3) downloaded from the Ordnance Survey Ireland website (http://www.osi.ie). The average vertical and horizontal error of the 2006 topographic dataset was a lot higher than desired and so the data was not used in the volumetric analysis.

The survey was repeated in 2007 and 2008 with more accurate results. The average vertical error of these surveys was ±0.16m and the average horizontal error ±0.16m, with some areas being more accurate than the average. ***Table 4*** presents the total vertical error estimation of each dataset used.

| Hydrographic Data | Total vertical error estimation |
|---|---|
| 1845 Admiralty Soundings of Courtmacsherry Bay | +0.5m |
| 1991 and 1992 Courtmacsherry Harbour sounding charts | ±0.05m |
| 2006 Courtmacsherry Harbour bathymetric survey | ±0.3m |
| 2006 XYZ GPS survey of the Argideen Estuary | ±0.62m |
| 2007 XYZ GPS survey of the Argideen Estuary | ±0.16m |
| 2008 XYZ GPS survey of the Argideen Estuary | ±0.16m |

***Table 4 Measurement error estimates of each dataset***

## Conclusions

Changes in hydrographic surveying methods over the last 150 years and sources of measurement error have been described. There are many uncertainties in both vertical and horizontal measurements and their respective datums which make the analysis of historical change challenging. The accuracy of historical data is often unknown, therefore when calculating morphological change in a coastal system, different sources of error need to be taken into account. Although the accuracy of modern survey methods is easier to determine, there are still uncertainties. This paper provides additional information on how to quantify the errors associated with historical surveys when comparing charts and analysing change. Quantification of these errors greatly helped in the determination of such change in the Argideen Estuary on the south coast of Ireland, where no meta-information of the first survey of the area in 1845 was available.

## Acknowledgements

The authors would like to thank the United Kingdom Hydrographic Office (UKHO) for providing images of the original (1845) sounding sheets of the Argideen Estuary and Courtmacsherry Bay and for their helpfulness in searching for any additional information on those surveys. Thanks also to Hydrographic Surveys Ltd. (Cork) who provided the 1991-1992 survey sheets of Courtmacsherry Harbour.

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