Introduction

In 2006, the United Kingdom Hydrographic Office (UKHO) began testing of the Vertical Offshore Reference Frame (VORF), which had been developed on their behalf by the Department of Geomatic Engineering at University College London. VORF was designed to integrate all vertical datums and reference surfaces used in the UK and Eire; with a particular emphasis on those used as the basis for marine charting.

This paper briefly examines the development of the VORF model, initial validation and its use on the Maritime and Coastguard Agency sponsored United Kingdom Civil Hydrography Programme as part of the UKHO testing regime. It also compares the results between traditional tidal modelling and the use of a GNSS tidal solution using the model to correct ellipsoidal heights to a sounding datum obtained on actual surveys over the last four years and its current and potential uses.

VORF - Model Development and Principles

The required VORF model transformation accuracies were as follows:

> An accuracy of 0.2m (vertical) at 2 standard deviation (sigma) or better for any point within Zone 1 “UK Inland & Near-Shore “. Inland (within 5km of the coastline as depicted on Admiralty Charts) and near-shore (within 20Km of the coastline as depicted on Admiralty Charts) areas bounded by the UK Continental Shelf.
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> An accuracy of 0.3m (vertical) at 2 standard deviation (sigma) or better for any point within Zone 2 “UK Off-Shore“. Off-shore (beyond 20Km of the coastline as depicted on Admiralty Charts) areas bounded by the UK Continental Shelf.

A number of different reference surfaces are used in hydrographic surveying. Figure 1 shows a summary of these, with their differences exaggerated for clarity. A land levelling datum, such as Ordnance Datum Newlyn (ODN) on the mainland of Great Britain, was a realisation of Mean Sea Level (MSL) at one particular place and time, and is therefore offset from the geoid as sea levels have changed. Chart Datum (CD) is referenced to the recognised land levelling datum, at many remote locations, however, reference may have only been made to local witness marks with only short periods of observations, meaning the determination of CD is not complete. CD is a close approximation to lowest astronomical tide (LAT) but in practice there are often differences between them. This is because in the 1960s CD was coincident with Mean Low Water Springs, and a descision was made to take it to LAT. In some locations LAT was known, but in others only MLWS was available. In such locations, a course adjustment (often 1 foot or 2 feet) was made. This accounts for the differences now found in the UK between CD and LAT.

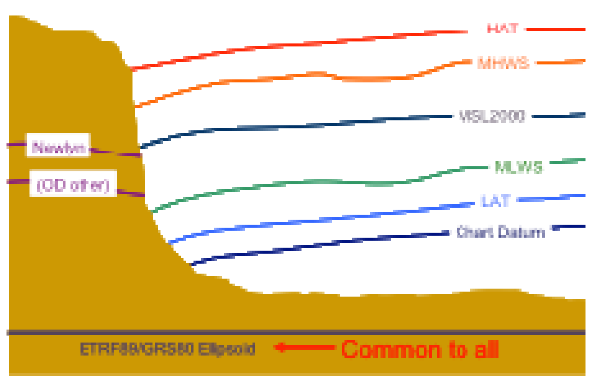

Figure 1. The relationships between different datum’s and surfaces

The biggest challenge facing the modern surveyor is how to account for the known changes in datum along an open coast or as a result of distance offshore from the coast. This is particularly relevant in this age of surveys achieving full seafloor coverage, as the capabilities of high accuracy integrated acquisition systems (positioning, motion and high resolution swathe bathymetry), shows quite clearly the results of not fully understanding or mapping the changes in datums. The table below illustrates the potential size of errors in tidal corrections as you move away from a tidal station based on tidal range and time differences:

Port Confines	Coastal Regions	Offshore
0.05m	0.1-0.3m	1.0m

Table 1: Estimate of tidal errors based on PP25
issued by the United Kingdom Hydrographic Office (1990).

Changes in CD from one port to the next with respect to the land datum are a result of several factors. Land and seabed topography along with coriolis are the main drivers of change, modifying the flow of the tidal wave. In other instances, the tidal regime may be the same with respect to mean sea level but the land levelling datum has deviated from it, or may even be different resulting in the stepped datums seen on long open coasts.

These changes, well recognised by hydrographic surveyors present a unique challenge in creating a model fit for use with modern surveying systems, allowing data to be delivered to ever increasing orders of accuracy as specified by the client. In order to determine a continuous surface for CD, UCL adopted a multi-step procedure.

1. A gridded surface was computed modeling mean seal level at a new epoch (MSL2000) above the GRS80 ellipsoid from a combination of long and short term tide gauge data and satellite altimetry.

2. For each point in the grid, the tidal ranges of HAT, LAT MLWS, MHWS, and CD over the 18.6 year period centered on the epoch 2000 were calculated.

3. Grid files for the required surfaces were derived by applying the tidal range estimates to the MSL2000 ellipsoidal heights.

As stated above, CD and LAT are often not coincident around UK waters. The derived LAT surface was used inshore to create a continuous CD model by warping the surface to CD at known points. CD was gradually merged into LAT as you moved offshore. This is an important stage, as prior to this, CD was only ever a series of plane surfaces. Where different CDs overlapped, there would be an offset. This meant that on any one chart, soundings may be reduced to more than one CD.

In 2007, additional GPS observation campaigns were undertaken by the UCL team, the first in Ireland and the second in Scotland. 35 ports were visited, and successful GPS observations of benchmark heights at 28 ports were subsequently successfully determined within ETRF89.

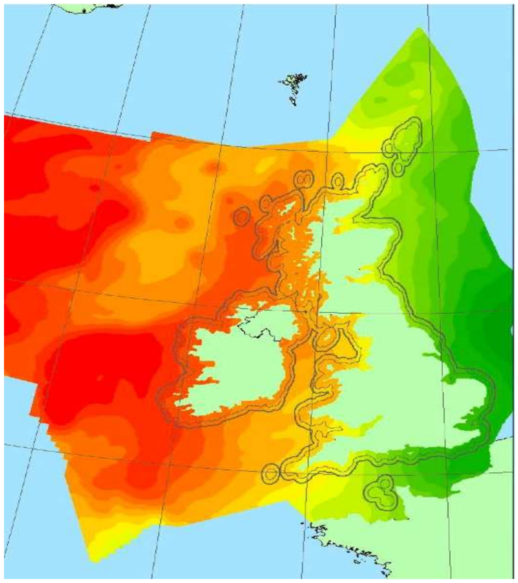

Figure 2. UK Coverage of the VORF Model.

Following incorporation of the results revised tidal modeling surfaces of CD, LAT, MLWS, MSL2000, MHWS and HAT (in ETRF89) were produced. To give an indication of the improvements in the surfaces: the range of the 1-sigma uncertainty of the original CD surface (with respect to ETRF) was 2 cm to 84 cm, while the new VORF CD surface has a significantly better uncertainty range of 2 cm to 22 cm.

Introduction of VORF to the Civil Hydrography Programme

In 2006/7, UKHO released preliminary data to contractors working on the Civil Hydrography Programme. Point values for tide station locations were extracted from the model. New geodetic benchmarks were established at these stations adjacent to the survey area. Results of the observations were tied into the local land datum and the results were compared with data extracted from the VORF model. This separation value was then applied to surveys lying within a reasonable distance of the gauge allowing continued comparison between the gauge and the offshore vessel reading. Initial results on the East coast of the UK were encouraging and the data was used in this manner for the Routine Resurvey Programme, which covers areas of mobile seabed in the Southern North Sea. Table 2 shows the results of comparisons between observations in the field and VORF values on the East Coast of the UK.

Location	Latitude	Longitude	Observed Separation Value	VORF Model	Difference
Great Yarmouth	52° 34' 18.65" N	1° 44' 05.13" E	42.77	42.76	0.01
Lowestoft	52° 28' 21.68" N	1° 45' 00.70" E	42.90	42.90	0.00
Felixstowe	51° 57' 28.55" N	1° 18' 04.58" E	42.76	42.69	0.06
Walton-on-the-Naze	51° 50' 37.17" N	1° 16' 46.28" E	42.46	42.48	-0.02
Fisherman's Gat	51° 28' 38.44" N	1° 23' 08.33" E	41.92	41.98	-0.05
Margate	51° 23' 29.96" N	1° 22' 57.37" E	41.90	41.90	0.00
Dover	51° 06' 51.95" N	1° 18' 53.67" E	40.60	40.62	-0.02

Table 2: Comparison of VORF and Observed Separation Models.

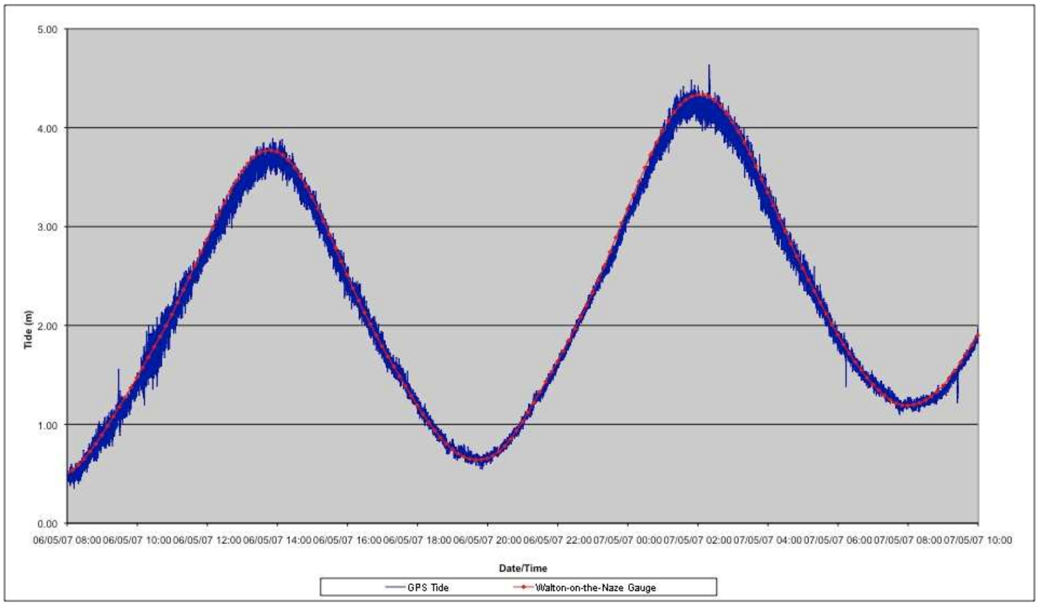

Figure 3. Comparison of Observed Tide and Vessel derived GPS Tide.

Second Stage of Testing

2007 saw wider testing of the data from VORF following the publishing of a new model. Testing now moved to using points ashore along with additional data points covering the limits of the survey area. Once again comparisons were conducted at known tidal stations, as a precursor to operations commencing. In some instances surveys were conducted in areas where existing vertical control was weak. In this instance new tidal stations were established and used to validate the model ashore. To check its use further offshore co-tidal models were used as a means of assessing the suitability of the new model. At the same time some contractors began to lay offshore gauges and compare long period harmonic observations with the calculated model surface.

An example of this was a survey conducted off the Thames Estuary. Ellipsoidal separation values were observed and compared with VORF data at Walton on the Naze. This value was compared with the VORF values for CD around the area (some 20km form the gauge) and differences of around 10-15cm were observed. Co-tidal modelling in the area would have introduced significantly larger tidal errors across the survey area. Figure 4 shows little or no tidal offsets between lines on a survey conducted in this area.

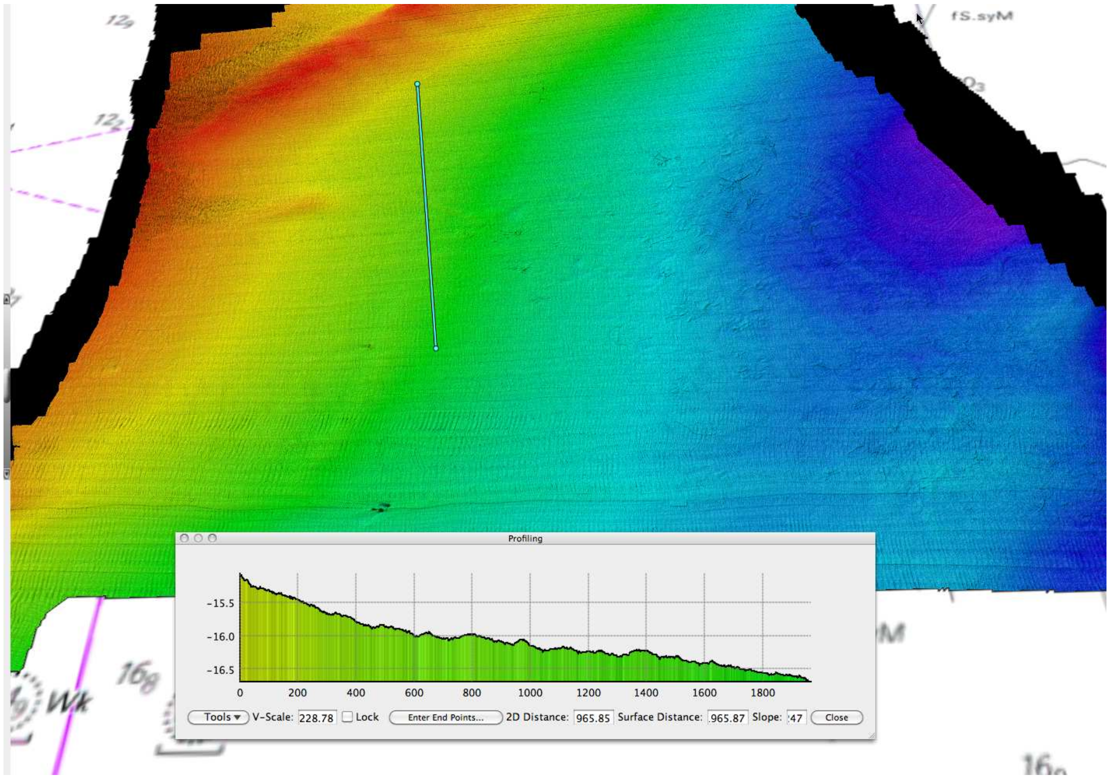

Figure 4. Results of an offshore survey using VORF.

Continued Testing and Use in the Field

In 2008, contractors were given full resolution models covering the area/region to be surveyed, allowing for the first time the ability to model the surface across the extents of the survey area as opposed to using discrete point values. As the model was to be used on major surveys, a three stage testing process was introduced in order to verify the models suitability, particularly in areas that may have less tidal information available or VORF has high uncertainty values. Firstly, geodetic observations are undertaken at new or recovered marks ashore to connect to land and CD and a separation value derived. This is compared with the VORF model.

The second stage involves a static comparison of the GNSS derived tide with an established tidal station over an 8 hour period. The vessel must be static within 1km of the gauge during this time. Current requirements for the validation require:

a. residuals (after coarse filtering) between the tidal and GNSS derived solutions are not to exceed 15cm.

b. the mean of the difference between the data sets obtained in the 8 hour comparison should have no offset greater than a 10cm .

Figure 5 shows an 8 hour comparison at the port of Dover with good agreement between the GNSS Tide and port gauge.

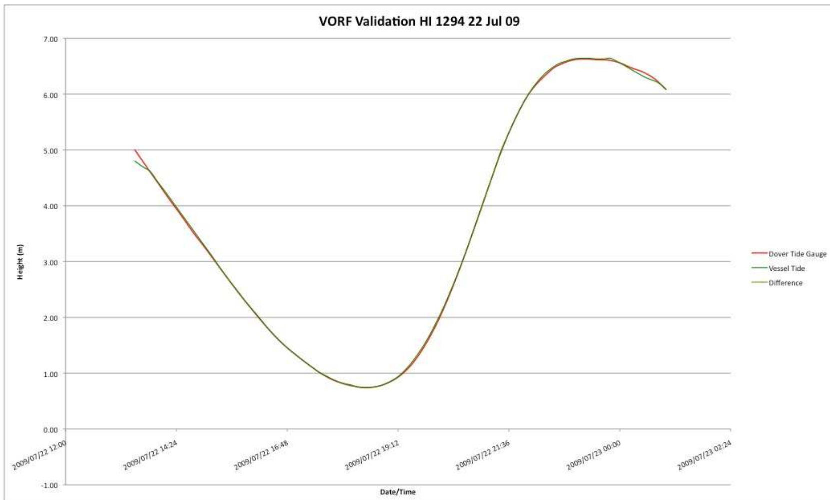

Figure 5. Results of an 8 hour static validation of VORF

As a check on the models accuracy, some method of comparing the GNSS tide had to be derived. NetSurvey and its partners have returned to previous methods of tidal reduction, computing a co-tidal correction to act as a gross check for phase and amplitude errors in the derived GNSS vessel tide in the areas surveyed. This in many instances around the UK coast is the only way of verifying and assessing the tidal curves suitability when offshore.

Figure 6 shows data from a series of surveys lying in the middle of the Dover Strait. There are some time and distance issues when comparing the vessel tide with the port gauge. However, comparing the vessel tide with the co-tidal model (this is an area where the co-tidal model is good) we see a good correlation. But, we are now beginning to see other features appearing in the tidal curve. Where co-tidal modeling is poor this comparison only gives an indication that vessel tides are following the tidal flows and range.

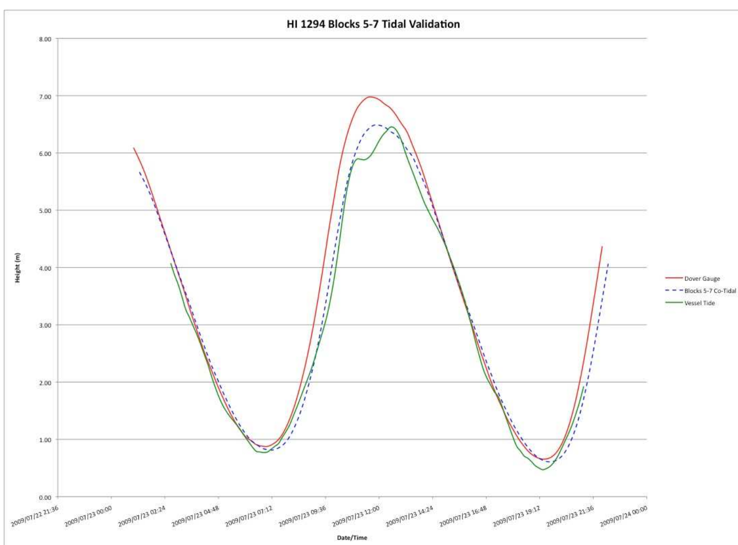

Figure 6. Comparison of Vessel Tide with co-tidal corrected tide.

As surveys have continued through 2009, contractors have laid a series of offshore gauges around the UK, for periods of 30 days or more to further enhance the model. On laying the gauges, the vessel remains within the vicinity of the gauge for 8 hours recording GNSS heights so that the model values can be compared following analysis.

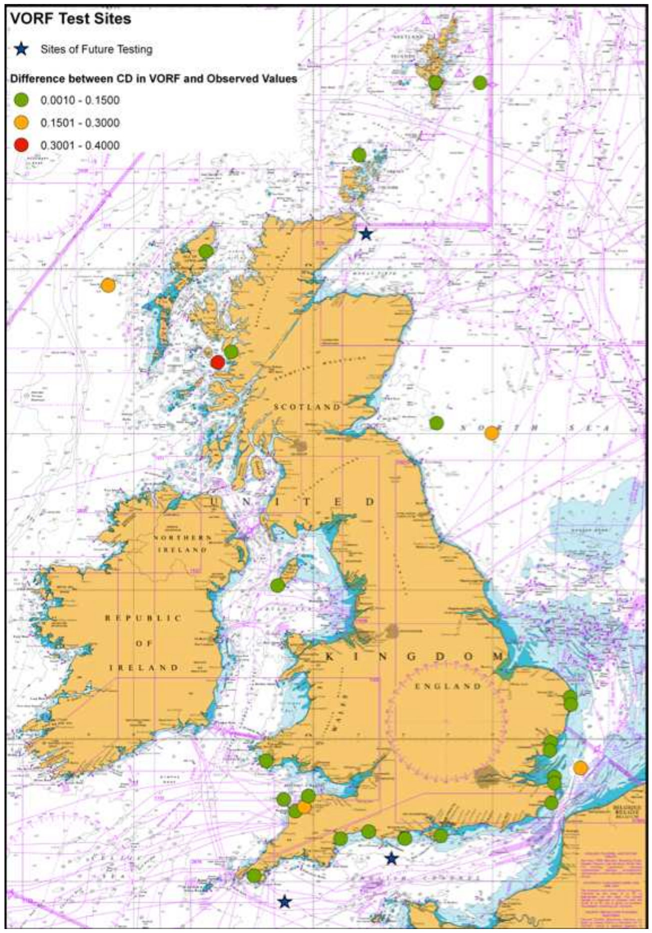

Figure 7. UKHO assessment of VORF Version 2 accuracies from additional offshore gauge observations before further adjustment.

The analysis has revealed that the model is achieving its initial design requirements, as can be seen in Figure 7. Two offshore tidegauge observations remain outstanding and once analysed it is hoped this data will be used to refine the model further and reduce the uncertainty in areas identified during research as being of lower quality. One area identified as having a larger than expected difference in values, lies around the Inner Isles on the West Coast of Scotland (a maximum value of 0.31m). The area has little tidal data available and surveying efforts are currently focussed in this area due to the growth in eco-tourism so it is hoped that this may be improved by new observations in the area enabling a better understanding of the tidal regime.

Application of a GNSS Derived Vessel Tide to Modern Surveys

The GNSS derived tide has been applied in a number of ways. Initially a smoothed tidal curve was derived from one second measurements of the ellipsoidal height, this was corrected by a single separation value. This smoothed curve produces a good tidal solution but unexplained artefacts were still seen in the data, whereby adjacent lines would develop busts for short periods then align again. Examination of positioning, sound velocity and offsets revealed no cause for these apparently random artefacts and they were assumed to be a result of changes of the actual tide itself.

Figure 8 shows a comparison of the raw and smoothed tidal curve from a series of observations undertaken whilst undertaking surveys along a 20km stretch of open coast during a single days survey on the south coast of England. The smoothed curve mirrors the rise and fall of the tide. Examination of the raw vessel tide shows that there appears to be shorter periods of rising and falls of the tide that have been filtered out by the smoothing used to generate the tidal curve. Examination of the survey data revealed that these changes in height correlated with changes in direction of the vessel. Having examined the tidal characteristics of the area and the likely flow of the tidal wave, it was inferred that these changes in height were a consequence of crossing or moving away from the crest of the flooding/ebbing tidal wave. It is also assumed that the larger spikes seen in the data may be a result of changes in altitude caused by vessel motion.

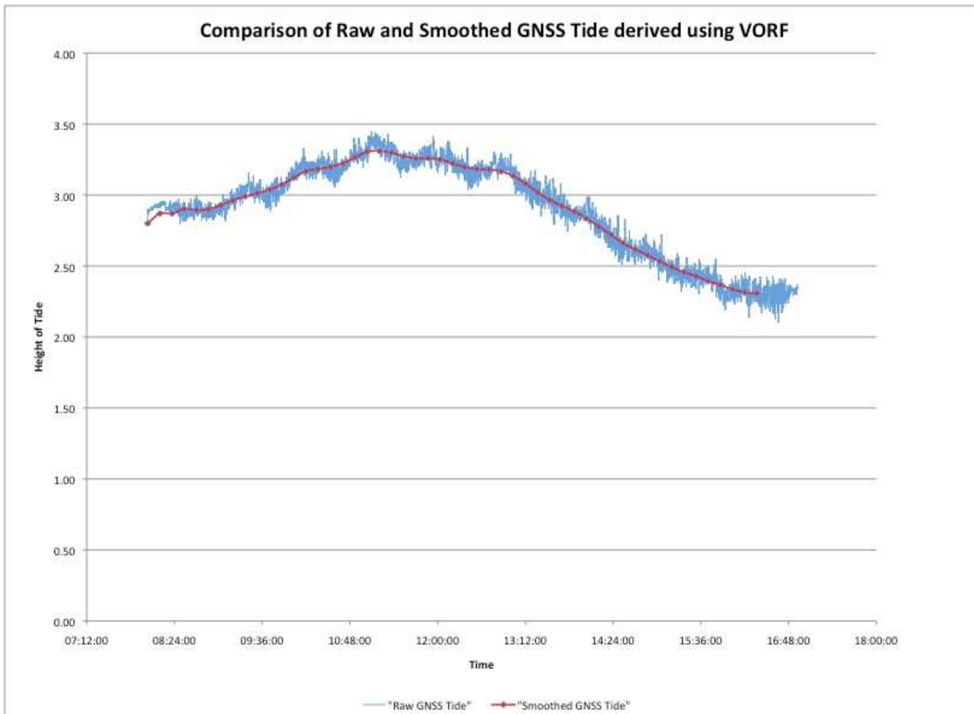

Figure 8. Comparison of a smoothed and raw GNSS tidal curve.

A survey off the Western Isles in Scotland revealed a more distinct step in the data as displayed in Figure 9. In this instance due to the geographical constraints the tidal wave was known to flow in a predominantly North/South direction. Survey acquisition was orientated East/West for navigational safety. The steps seen in the tidal curve equated to a change in direction of the vessel and confirmed that the vessels position in relation to the tidal wave at a fixed point in time could impact on the height of tide. Continued crossing back and forth over the data results in a curve, which is not sinusoidal in nature, but rather reflects the vessels position in relation to the advancing or receding tidal wave and explained the random tidal artefacts seen when applying a smoothed tidal curve on adjacent lines.

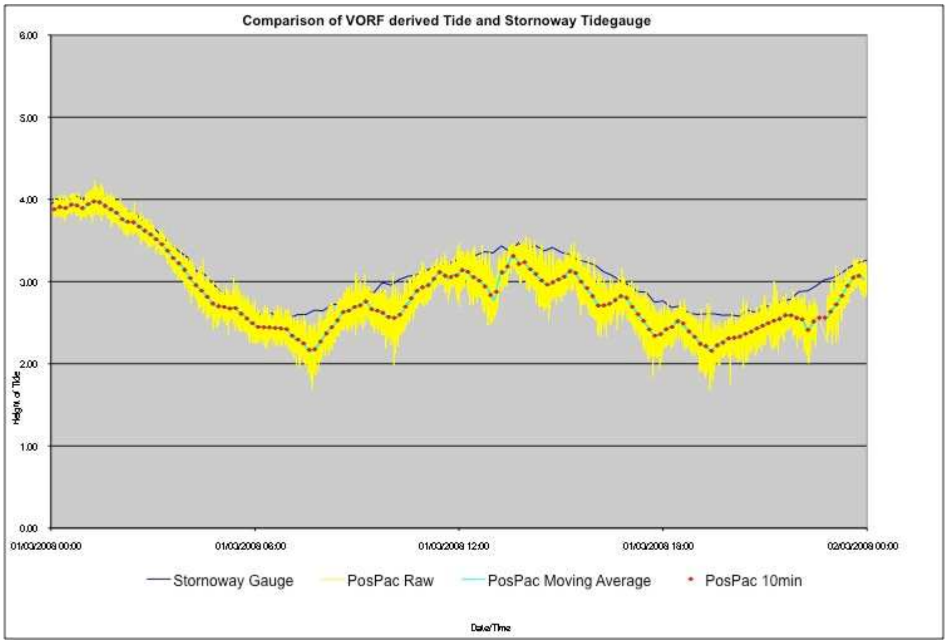

Figure 9. Changes in tidal curves due to vessel position.

At this point NetSurvey were using a post processed PPK solution in the form of a smoothed best estimate of trajectory (SBET) derived from Applanix's POSMV and POSPAC processing software to compute a tidal solution that met IHO Order 1 requirements. The altitude was extracted at 1 second intervals and a separation value was applied to the data to reduce it to a tidal height. The solution was then smoothed to derive a 10 minute tidal curve for reduction of soundings.

In order to reduce the tidal offsets seen in the data, a decision was made to use the ability to apply the full PPK solution using post processing software, re-applying a fully processed navigational and motion solution to the acquired data. VORF data could be loaded as a model and a full resolution GPS tide could then be calculated and applied. As well as providing a sub decimetre solution in x y and z this application of a high frequency tide resulted in the previously noted tidal artefacts having been almost completely removed. This application of tide on a ping by ping basis at point of sounding has for the first time allowed a true application of tide, irrespective of the vessels position in relation to the flooding or ebbing tide, which was effectively smoothed out in a traditional 10 minute sampled curve.

This application of tide at point of sounding has implications for data quality. Experience to date has shown that the removal or reduction of tidal artefacts in bathymetric datasets has allowed the cleaning of data to be improved using statistical based techniques such as the Combined Uncertainty Bathymetry Estimator (CUBE). As a result, data of much higher quality is delivered to the client where such modelling exists. The importance of merging datasets acquired using different systems at different times is of growing importance. In this era of "gather once, use many", the ability to transform data to and from different vertical datums allows the delivery of integrated datasets to different clients off multiple acquisition sources on a client specified datum. An example of such integration can be seen in Figure 10.

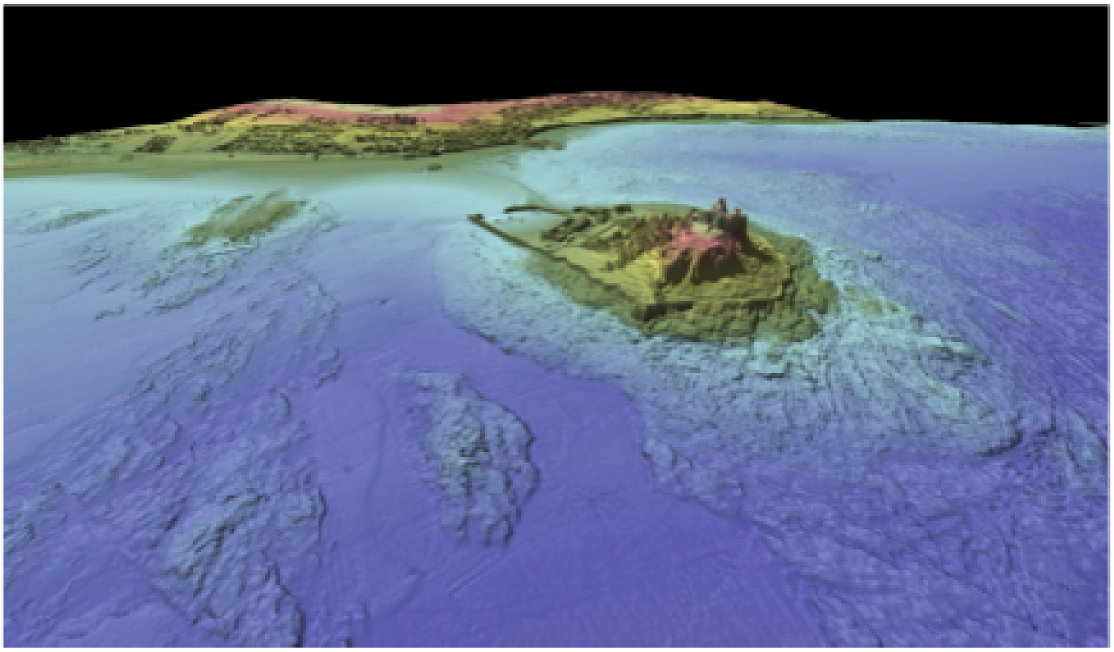

Figure 10. Combined LIDAR and Bathymetric Surveys on a common vertical datum.

Conclusion

The reference surfaces in VORF comprise 500m to 1kmkilometre resolution models of Mean Sea Level, CD and other tidal surfaces. To date 39 major surveys in support of navigational safety have been completed in UK waters using the VORF model to reduce data to a single common datum. The advantages in the field have been in the gains in speed of processing using statistical cleaning methods due to the lower vertical uncertainty at point of sounding due to the reduction in tidal errors, and are now allowing surveys to be conducted in validated areas without recourse to any tide gauge checks.

The model offers particular advantages along open coasts and offshore reducing errors and allowing efficiencies to be achieved in collection programmes. Close to an established gauge or in a small area close to a point where CD is well established the standard method of applying a single point separation value remains valid.

The improved quality offered by a single continuous plane as opposed to a stepped datum and the application of tide at point of sounding using a PPK solution at a high frequency is allowing a step change in the accuracies achieved in operations and opening new markets up to operators. The continued refinement of the model and its use across other government bodies in the UK is enabling more data gathered by different organisations to be shared. Once fully validated and accepted, the model should potentially remove the requirement to lay (and lose) offshore tide-gauges enabling cheaper and faster surveying by companies to a standard datum. It has and will continue to improve survey accuracy and repeatability, allowing greater integration of land and marine data sets with easy transformations between different vertical datums.

As of 2010, VORF paves the way for real-time offshore surveying in the UK and Ireland and data reduction using real-time corrections as software and hardware finally have the capacity to handle the processing required. Models for other regions of the world are now planned.

References

Ziebart, M., J. Iliffe, J. Turner, J. Oliveira and R. Adams (2007), VORF ¬ The UK Vertical Offshore Reference Frame: Enabling Real-time Hydrographic Surveying, proceedings of ION GNSS2007, Fort Worth, Texas, USA, September, 2007.

Iliffe, Jonathan, Marek Ziebart, James Turner, Joao F Oliveira, and Ruth Adams. "The VORF project – Joining up Land and Marine Data". GIS Professional. Issue 13, November/December 2006, pp 24 – 26.

Iliffe, Jonathan C., Marek K Ziebart and Jim F Turner. "The derivation of vertical datum surfaces for hydrographic applications". The Hydrographic Journal, No. 125, 2007, pp 3 - 8.