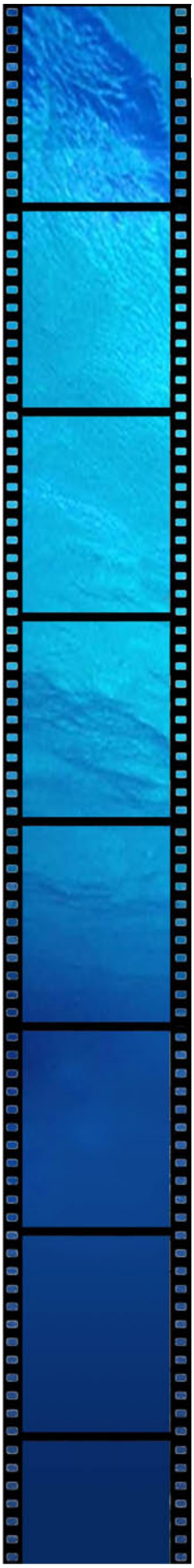


Note

TIDE ANALYSIS FROM BATHYMETRIC SOUNDINGS

A Method for Extracting Tidal Amplitude and Phase Errors from Overlapping Soundings

By Alex OSBORNE (UK)

Abstract

This paper describes a method for identifying phase and amplitude tide errors in bathymetric soundings. It is applicable to bathymetric surveys where tide is measured and then used to reduce raw soundings to datum (as opposed to absolute depth measured using kinematic GPS).

The problem of tide inaccuracy is briefly explained, along with a description of some of the key concepts which should be understood. The processing method is then explained and demonstrated using a real-world example. The optimum tide curve for this example dataset is identified based on analysis of the soundings.

Resumé

Le présent article décrit une méthode d’identification des erreurs de phase et des erreurs d’amplitude de la marée dans les sondes bathymétriques. Elle est applicable aux levés bathymétriques lorsque la marée est mesurée et sert ensuite à réduire les sondes brutes au zéro des cartes (par opposition aux profondeurs mesurées à l’aide du GPS cinématique).

Le problème de l’inexactitude de la marée est brièvement expliqué, en même temps qu’une description de certains des concepts clés qui devraient être compris. La méthode de traitement est ensuite expliquée et démontrée à l’aide d’un exemple du monde réel. La courbe de marée optimale pour l’ensemble des données de cet exemple est identifiée à partir d’une analyse des sondes.

Resumen

Este artículo describe un método para identificar errores de fase y amplitud de las mareas en las sondas batimétricas. Se aplica a los levantamientos batimétricos en los que se mide la marea, y se utiliza después para reducir las sondas sin procesar al cero hidrográfico (a diferencia de la profundidad absoluta medida usando un GPS cinemático).

Se explica brevemente el problema de la inexactitud de las mareas, junto con una descripción de algunos de los conceptos clave que deberían entenderse. El método de procesado se explica y se demuestra entonces utilizando un ejemplo del mundo real. Se identifica la curva de mareas óptima para la colección de datos de este ejemplo basándose en el análisis de las sondas.

Introduction

So-called 'tide busts' are a common problem during bathymetric surveys, and result from uncertainty as to the level of the tide in a given place at a particular time. This may be due to a lack of measured tide information and consequent use of predictions as a substitute. Alternatively, observed tide levels may be available but only at some distance away, leading to inaccuracies when applied to the survey area. During processing, tide error manifests itself as a difference in apparent seabed level measured in the same place at different times.

This paper describes a method developed by the author for analysing overlapping soundings in order to identify amplitude and phase errors in the tide corrections. It has only been used to date with multibeam soundings, but it seems reasonable to think that it could also be applied to singlebeam soundings, given enough overlapping data.

This method is not applicable to all situations. It requires soundings which overlap at various times during the tide cycle and are restricted to a limited geographical area (i.e. a fairly consistent tidal regime). An initial tide curve is required as a starting point. This may be a prediction or an interpolation.

Concepts

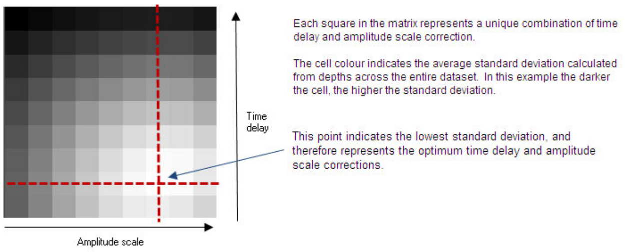
Some ideas and terms are used here which are not in mainstream usage. These are briefly described as follows.

- *Sounding group*

A group of depth soundings acquired at roughly the same time and place, which can therefore be represented by single time and depth values. Similar to gridded depth values except that multiple groups can fall within in single grid cell if the same area was crossed more than once during a survey.

- *Standard deviation matrix*

A matrix containing standard deviation values, where each represents the average of the standard deviations calculated from all individual cells in a grid. The standard deviation for each cell is calculated from the depths of the sounding groups within it. Therefore, broadly speaking the lower the number, the better the agreement between the overlapping soundings. The horizontal and vertical axes represent varying phase delay and amplitude scale factor. The lowest value in the matrix therefore represents the combination of phase delay and amplitude scale factor which results in the lowest average standard deviation across the entire grid, and therefore the minimum depth discrepancy between overlapping soundings. The concept is illustrated below in ***Figure 1***.



Each square in the matrix represents a unique combination of time delay and amplitude scale correction.

The cell colour indicates the average standard deviation calculated from depths across the entire dataset. In this example the darker the cell, the higher the standard deviation.

This point indicates the lowest standard deviation, and therefore represents the optimum time delay and amplitude scale corrections.

Figure 1 *- theoretical SD matrix before adjustment*

- *Cross-comparison plot*

A plot of 'apparent tide error' against time, where each point plotted represents the apparent depth error of a sounding group, based on a comparison against another sounding group in the same grid cell. Every sounding group is compared against every other group in the same cell, and each comparison results in two points on the cross-comparison plot. It is assumed that the error is equal i.e. if one group is a metre deeper than another, it is half a metre too deep and the other is half a metre too shallow. Although this is a slightly simplistic assumption, the trend is still visible if enough comparisons are made and plotted together.

Some other terms which are fairly basic and widely understood within the survey industry are still worth mentioning here because they are so central to the subject at hand:

- *Phase and amplitude*

Phase is a relative measure referring to the position of the tide curve on the x (time) axis. A phase shift applied to a tide curve moves it left or right. Amplitude refers to the height difference between low and high water. An amplitude scale factor applied to the tide curve has the effect of stretching it if greater than one, or compressing it if less than one. See ***Figure 2*** for an illustration.

- *Raw/reduced soundings*

Raw soundings are individual depth observations, uncorrected for tide. Reduced soundings are individual depth observations with tide subtracted, thus reduced to a vertical reference level (datum).

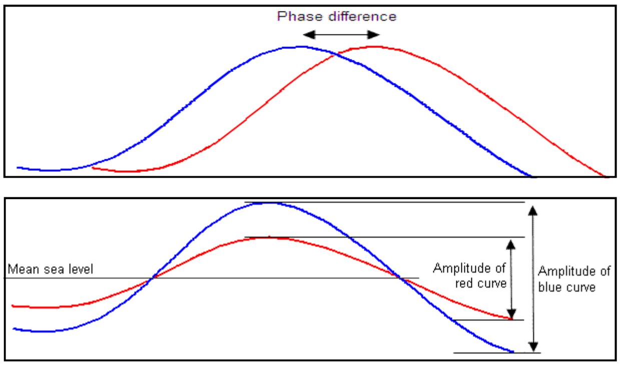


Figure 2 *-(a) Phase difference (b)- Amplitude difference*

A Note about Standard Deviation

Different measures of standard deviation are used in this analysis, depending on the purpose.

The standard deviation as calculated from *sounding groups* only represents areas of overlapping data, by definition. In areas which have been covered only by a single swath, there will rarely – if ever - be more than one sounding group in each cell, and therefore no meaningful comparison can be made. The standard deviation as calculated from *individual soundings* is calculated wherever there are multiple soundings in a grid cell.

The value calculated from sounding groups is a more pure measure of any change when tide adjustments are applied. The value calculated from individual soundings, however, is unbiased and better represents the whole dataset.

Whenever standard deviations are mentioned, it will be specified what the value actually represents.

Method

A co-tidal approach is used, based on the premise that the change in tidal regime between locations can be described in terms of phase and amplitude differences. This idea is well established and used by such authorities as the British Admiralty.

Given enough overlapping data, some number-crunching power in the form of a computer and a method that is suitably selective in its use of data in order to process it quickly and efficiently, it is possible to apply multiple phase and amplitude corrections to a dataset and analyse the results from each. When this is done systematically, and given suitable input data (i.e. meeting the criteria given above in the introduction) a pattern emerges in the standard deviations calculated from overlapping soundings recorded at different states of tide.

Processing starts by reducing the number of points to be processed, using a variation of a gridding technique. Groups of soundings are formed, whereby each group contains soundings from the same time and place (see '*Concepts*', above). The standard deviation for each cell is then calculated from the depths of each group, wherever there is more than one. The average is then calculated from the individual standard deviations, and this value is taken as being representative of the dataset as a whole.

This process is repeated multiple times, with phase delay and/or amplitude scale systematically altered each time, and applied to the tide curve. Each combination of phase delay and amplitude scale results in a unique standard deviation value. The results are then plotted as a standard deviation matrix, the lowest value of which indicates the optimum combination of phase delay and amplitude scale.

The optimum phase and amplitude corrections are applied to the tide curve. The process can then be repeated as required, with increasingly fine adjustments. When the optimum phase and amplitude have been identified and applied, the matrix will have the lowest standard deviation at its centre, as illustrated below in ***Figure 3***.

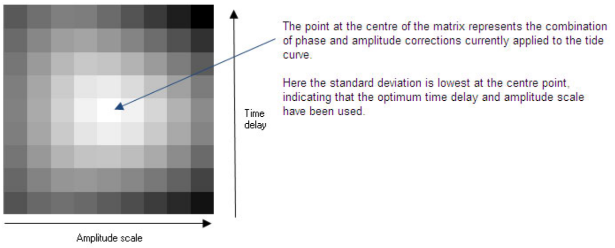


Figure 3- *theoretical SD matrix after adjustment*

Once the apparent tide phase and amplitude errors have been identified, the adjusted tide curve is used to reduce the raw soundings. The corrected soundings should exhibit less scatter than those reduced using the original tide curve.

The process is best illustrated using a real-world example.

Case study

A site survey was carried out in the Dutch sector of the North Sea in around 30m of water. Parallel survey lines were run with overlapping edges and some lines were run in a perpendicular direction, resulting in overlapping soundings which were recorded at quite different states of tide. Around thirty-four million soundings were recorded using a single-head multibeam echosounder over a period of about nine hours. Weather conditions were somewhat marginal and the effects of motion were visible in the dataset. Acquisition started and ended, coincidentally, at around low tide.

Predicted tide corrections were used for initial processing. Since the site was offshore and not particularly close to any one source of predictions, four tide curves were entered into the survey software, which used interpolation to estimate the tide height at the required place and time. There is a considerable amount of uncertainty when this sort of method is used since a simple interpolation can only be based on the assumption of linear (or at least regular) change in tide height over distance.

The tide stations in the vicinity of the survey area are listed in Table 1.

The tide stations in the vicinity of the survey area are listed in ***Table 1***.

Station	Latitude	Longitude	Distance from site (km)
Hoek van Holland	51° 59' N	4° 7' E	20
Scheveningen	52° 6' N	4° 15' E	22
Europlatform	52° N	3° 17' E	47
IJmuiden	52° 28' N	4° 35' E	58

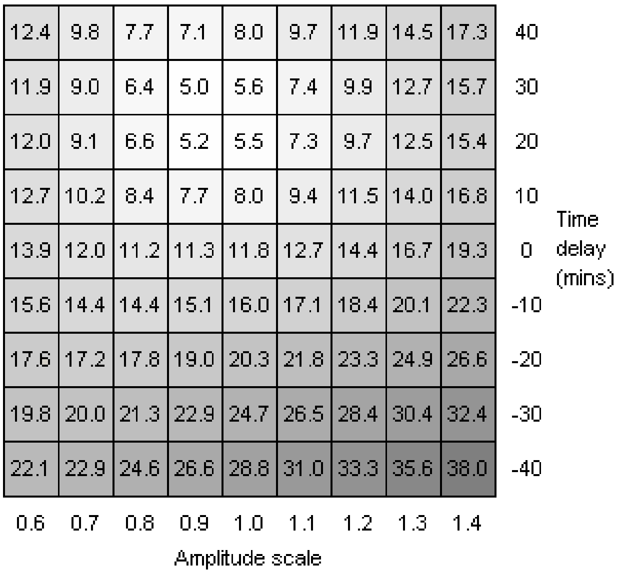
Table 1

Analysis and Adjustment of the Original Tide Curve

The method just described was used to analyse and optimise the tide correction, using the interpolated tide curve as the starting point. An increment of 0.1 amplitude scale and 10 minutes phase delay was used to create the first standard deviation matrix shown in ***Figure 4a***. The total range covered, with four steps each way, was amplitude 0.6 to 1.4 (representing a vertical compression or stretch of 40%) and phase delay +/-40 minutes.

Given the step sizes of 10 minutes and 0.1 amplitude scale, it was not possible to be very specific at this point about the optimum correction, but it was evidently somewhere in the region of +30 minutes delay, and 0.90 scale factor. These corrections were applied and the process was repeated, this time with increments of only 2 minutes delay and 0.02 amplitude scale. After a further iteration, the second matrix shown in ***Figure 4b*** was produced, using 1 minute and 0.01 scale increments. The optimum phase and amplitude corrections are found to be +25 minutes and ×0.93, respectively.

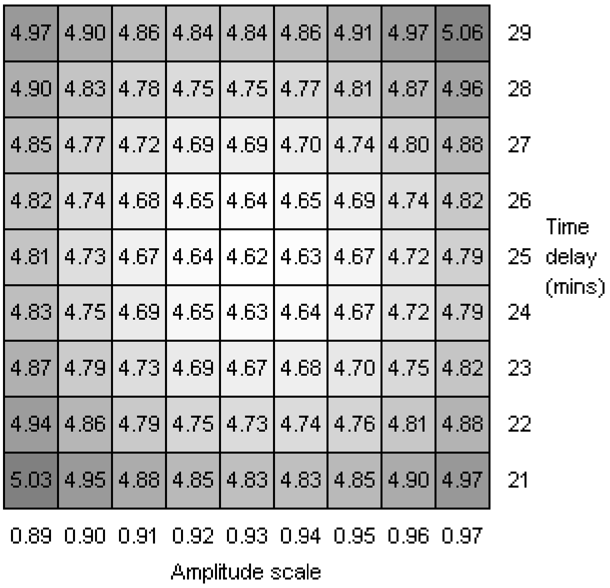
Standard deviation is shown in centimetres for clarity due to the small numbers involved, and limited space for zeros.



									Time delay (mins)
12.4	9.8	7.7	7.1	8.0	9.7	11.9	14.5	17.3	40
11.9	9.0	6.4	5.0	5.6	7.4	9.9	12.7	15.7	30
12.0	9.1	6.6	5.2	5.5	7.3	9.7	12.5	15.4	20
12.7	10.2	8.4	7.7	8.0	9.4	11.5	14.0	16.8	10
13.9	12.0	11.2	11.3	11.8	12.7	14.4	16.7	19.3	0
15.6	14.4	14.4	15.1	16.0	17.1	18.4	20.1	22.3	-10
17.6	17.2	17.8	19.0	20.3	21.8	23.3	24.9	26.6	-20
19.8	20.0	21.3	22.9	24.7	26.5	28.4	30.4	32.4	-30
22.1	22.9	24.6	26.6	28.8	31.0	33.3	35.6	38.0	-40
0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	

Amplitude scale

Figure 4 a *- actual SD matrix before adjustment*



									Time delay (mins)
4.97	4.90	4.86	4.84	4.84	4.86	4.91	4.97	5.06	29
4.90	4.83	4.78	4.75	4.75	4.77	4.81	4.87	4.96	28
4.85	4.77	4.72	4.69	4.69	4.70	4.74	4.80	4.88	27
4.82	4.74	4.68	4.65	4.64	4.65	4.69	4.74	4.82	26
4.81	4.73	4.67	4.64	4.62	4.63	4.67	4.72	4.79	25
4.83	4.75	4.69	4.65	4.63	4.64	4.67	4.72	4.79	24
4.87	4.79	4.73	4.69	4.67	4.68	4.70	4.75	4.82	23
4.94	4.86	4.79	4.75	4.73	4.74	4.76	4.81	4.88	22
5.03	4.95	4.88	4.85	4.83	4.83	4.85	4.90	4.97	21
0.89	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	

Amplitude scale

Figure 4 b - *actual SD matrix after adjustment.*

Based on these results, applying a phase delay of 25 minutes and an amplitude scale of 0.93 should result in a significant reduction in depth mismatches between overlapping soundings.

It would not be advisable to apply this sort of adjustment without checking carefully that it was really correct, and not just best-fitting some other non-systematic error(s) in one place whilst making things worse in another. The validity of the correction should be checked by analysing what effect it has across the entire dataset.

There are various ways in which the 'before' and 'after' cases can be compared. Four checks will be demonstrated before moving on to a comparison of results using tide curves from the different stations in the vicinity of the site.

F,igure 5 below, shows cross-comparison plots (see '*Concepts*', above) before and after tide adjustment, each with a third order polynomial trend line shown in red. The fact that the apparent error is almost symmetrical around zero in the second plot indicates that the time-varying component has been largely removed.

The plots were generated using comparisons only between sounding groups with a standard deviation below 0.2m, as calculated from the soundings within them, and a time difference of at least three hours. (Although the trend is much the same when less strict criteria are used, there is more noise.)

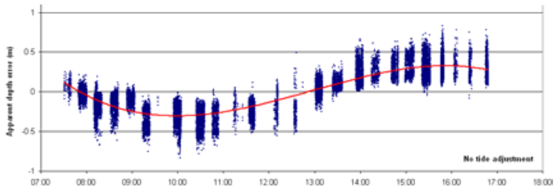


Figure 5a *- cross-comparison plot before adjustment*

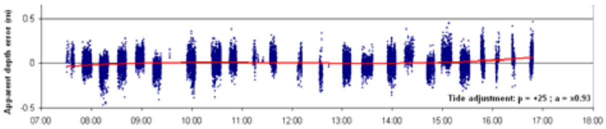


Figure 5b

Figure 6 comprises two difference plots showing the effects of the tide adjustment.

The first plot shows the change in standard deviation, calculated from all soundings within 2.5m grid cells. Green indicates a decrease in standard deviation, and therefore a reduction in depth mismatches between soundings. Red indicates the opposite. An improvement is seen across most of the survey area, which demonstrates that the tide adjustment has had the intended result.

The second plot shows change in depth. Red indicates a depth increase, and green indicates a depth decrease. The fact that there are roughly equal amounts of red and green shows that there the overall depth has not been significantly affected by the adjustment.

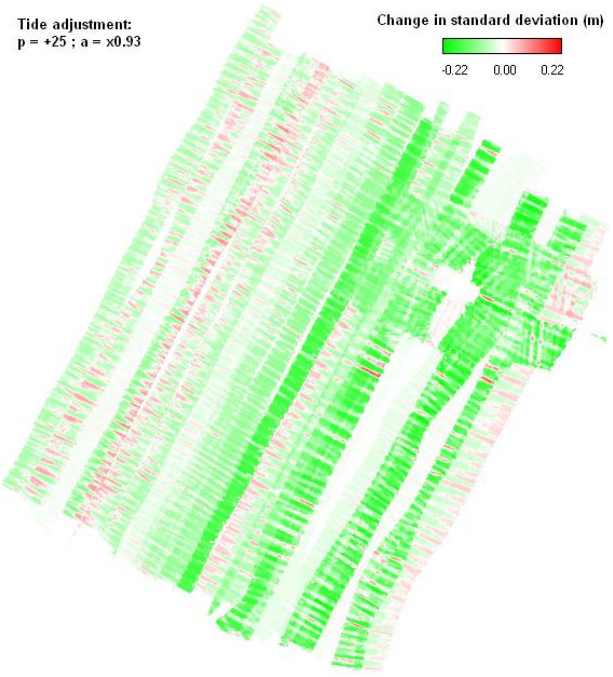


Figure 6a- SD change.

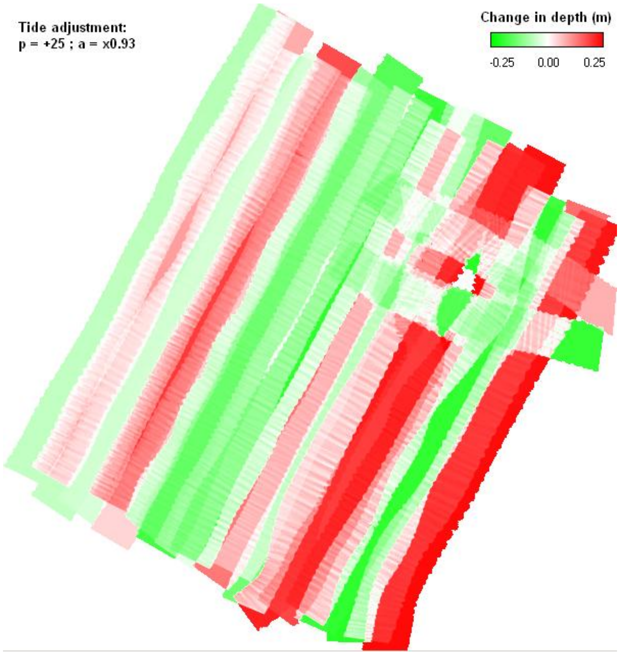


Figure 6b - depth change

A comparison of illuminated gridded bathymetry also indicates a noticeable and consistent improvement. A before/after comparison of the southern part of the site is shown in *Figure 7*. The NNE/SSW striping is much more pronounced in the upper image. Where it remains in the lower image, this may have as much to do with increased noise at the swath edges as with tide error.

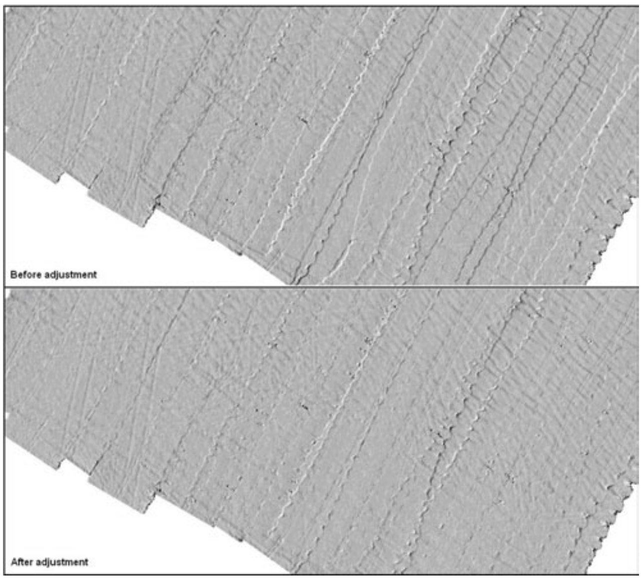


Figure 7 - illuminated bathymetry.

Comparison of Available Tide Curves

Having hopefully optimised the tidal corrections using the original interpolated tide curve as a starting point, the question remains as to how any of the predicted tide curves from the four closest stations, without any interpolation, would compare.

To investigate this, the same process as was used for the original tide curve was repeated in turn for each of the individual tide stations, yielding results summarised below in ***Table 2.*** Standard deviations are shown for sounding groups and individual soundings, since both are relevant and results may differ. Note that phase adjustments are given in terms of phase delay, so a negative number indicates a shift to the left on the time axis.

Station	Phase delay (minutes)	Amplitude scale	Standard deviation (from sounding groups)[1]		Standard deviation (from individual soundings)[2]	
			Before	After	Before	After
Original interpolation	+25	0.93	0.111	0.046	0.125	0.087
Hoek van Holland	-3	0.95	0.048	0.044	0.088	0.086
Scheveningen	-21	0.92	0.099	0.047	0.118	0.087
Europlatform	+63	1.15	0.224	0.056	0.209	0.091
IJmuiden	-75	1.04	0.222	0.057	0.208	0.093

It is clear from this comparison that the tide curve from Hoek van Holland is the best on all counts. It requires less adjustment than any of the others to produce a best fit. Furthermore, it results in the lowest standard deviations both before and after adjustment. Although this might not have been originally anticipated, the tide from Hoek van Holland appears to match the actual tide at the site better than the interpolation used originally.

The histograms shown in ***Figure 8*** bear this out. Europlatform and IJmuiden have not been included here since the statistics indicate that the degree of fit from these curves is noticeably worse than the other three. They are also significantly further from the site than Hoek van Holland and Scheveningen. Standard deviation as shown in the histograms is calculated from all soundings in 2.5m grid cells.

When an illuminated plot of the gridded soundings as reduced using the adjusted Hoek van Holland tide is compared with the equivalent plot using the adjusted interpolation, there is a visible improvement in one area of the site, where striping is slightly reduced. This will not be demonstrated here as a side-by-side comparison of illuminated bathymetry since the difference is very subtle and may not be visible in a reproduced image. The end result is that using the adjusted Hoek van Holland tide curve does appear from a visual inspection to produce the best result.

The adjusted Hoek van Holland tide curve, as found to best fit the data, is shown below in ***Figure 9*** along with the interpolation which was used originally.

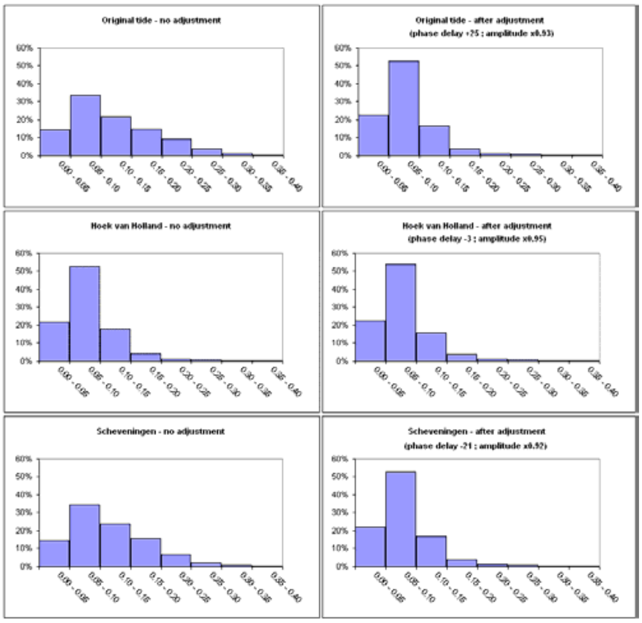


Figure 8 *- histograms showing frequency distribution of standard deviations from three sets of tidal corrections.*

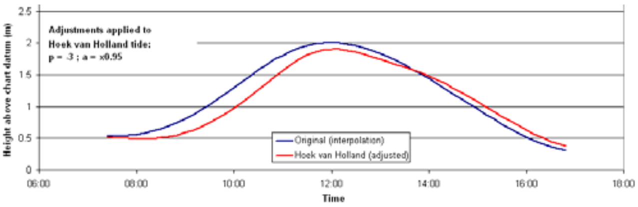


Figure 9 *- comparison of original and optimised tide* curves.

Conclusions

It has been demonstrated that it is possible to measure apparent phase and amplitude errors from overlapping bathymetric soundings, given suitable source data. Correcting the observed errors can significantly reduce depth discrepancies in the reduced soundings.

As well as improving the appearance (and hopefully absolute accuracy) of the final product, a useful insight can be gained into the actual tidal regime at the survey location. At the site shown in the example, the tide curve from Hoek van Holland was found to fit the soundings significantly better than any other that was tried. This would not have been apparent or expected based purely on proximity, since the site is roughly equidistant from Hoek van Holland and Scheveningen.

Biography of the Author

Alex Osborne, BSc (Hons), MSc graduated from Plymouth University in 2000 with an MSc in Hydrography and works worldwide as a freelance hydrographic surveyor, mainly on offshore projects.
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[1] From sounding groups within 5m grid cells
[2] From all soundings within 2.5m grid cells

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