

# Measuring sand wave migration in the field. Comparison of different data sources and an error analysis

M.A.F. Knaapen<sup>(1)</sup>

(1) University of Twente, Water Engineering and Management, P.O.Box 217, 7500 AE Enschede, The Netherlands, m.a.f.Knaapen@utwente.nl

## Abstract

Migration of offshore seabed waves is hard to measure due to the low migration rates and large measurement errors. Here, sand wave migration rates are determined from the change in the crest position deduced from bathymetric echo-sounding data. The crests are identified as local extremes in a bathymetric profile, after low-pass filtering. This approach is applied to profiles along a pipeline and to 2-dimensional data. A consistent migration rate of several meters per year is found. The accuracy of the estimates is analyzed using markers. The noise in the bed level data is small and does not affect the results, but the errors in the positioning system cause significant errors in the estimates rates. An increase of either the number of surveys or the observation period reduces these errors.

## 1. Introduction

The sandy shallow seas, like the Bisanseto Sea in Japan, the continental shelf between the Indonesian archipelago and the North Sea are intensively used. Many of the world's important harbors are situated near sandy shelf seas. Furthermore, pipelines transporting gas and oil and communication cables cross the seas. Therefore, it is important to understand the dynamics of the sandy beds of these shelf seas. In general the sandy shallow seas are situated in regions with fairly mild conditions in which sand is transported without being flushed away. The interaction between these conditions and the seabed results in a wide range of bed patterns (Table 1).

Bed form	L [m]	H [m]	T	c
Ripples	1	0.01	hours	1 m/hour
Mega-ripples	10	0.1	days	1 m/day
Sand waves	500	5	years	10 m/year
Long bed waves	1500	5	unknown	unknown
Shoreface-connected ridges	4000	5	decades	1 m/year
Tidal sand banks	6000	10	centuries	1 m/year

Table 1. Orders of magnitude of the characteristics of offshore sand bed forms: wavelength L, height H, the migration rate c and the typical time scale T in which the patterns evolve. For an overview and definitions see e.g. Dodd et al. (2003), Knaapen et al. (2001) and Hulscher (1996).

From these patterns, the sand waves are of special interest to human activity. They cover large parts of the sandy beds of shallow seas, can reduce the depth considerably (Katoh, 1998) and are known to migrate. And since they are much more dynamic than the larger sand ridges and sandbanks, they endanger to both the shipping and the pipeline and cables in the shelf sea. The migration of the sand waves may expose pipelines and cables, sometimes even resulting in free spans (Morelissen et al., 2003).

The migration of the sand waves can be caused by residual currents (Németh and Hulscher, 2002) and by tidal asymmetry (Besio et al. 2002). Although this migration can be modeled, it is difficult to estimate the migration rates. The models are idealized and depend on parameters and input that are difficult or impossible to measure or estimate theoretically, i.e. turbulent viscosity, bed friction and the residual current.

Another problem is the lack of accurate observations of migrating sand waves. Publications on observed migration are rare. Katoh et al. (1998) describe migration of sand waves on top of a shoal. However, clear rates have not been determined. Moreover, the observations result from monitoring after dredging. It is difficult to determine whether this migration is true migration or the result from the reformation after the dredging. Idier et al. (2002) observe clear migration of 9 to 17 meter per year of an individual sand wave in the English Channel between 1999 and 2001.

Morelissen et al. (2003) describe the migration of a few sand waves along two sections of a pipeline in the North Sea of 10 and 20 meter per year in the assumed direction of the residual current and Besio et al. (2002) find a migration of 3 m per year against the residual current. In all cases the migration has been determined using a visual interpretation of individual profiles. A determination of the accuracy of the available data is missing in all cases, but based on the description the measurement errors in the data will be small (see section 4 for an analysis).

This paper presents an approach to objectively analyze large number of sand waves on their migration (section 2). This approach is then applied to two echo-sounding data sets in (section 3), one profile along a pipeline, and one multi-beam data set. Since both sets are taken from the same area of the North Sea, they can be compared. The accuracy of both data sets is analyzed thoroughly.

## 2. Approach

The classical approach to analyze rhythmic bed patterns has been to determine the locations of the crest and trough. These positions are then compared to determine the length, height and other characteristics (O'Conner, 1992). This approach has been proven to be robust and reliable. This approach can easily be used to estimate migration as well. An automated procedure has been created to determine the crest and trough positions in both one-dimensional and two-dimensional bathymetric data.

For this purpose the data is filtered using a low-pass Bartlett window. This removes all noise related to mega-ripples and ripples. The crests and troughs can then be identified as the local minima and maxima in the direction of the principle tidal axis, respectively. Figure 1 gives the resulting positions for the multi-beam data set.

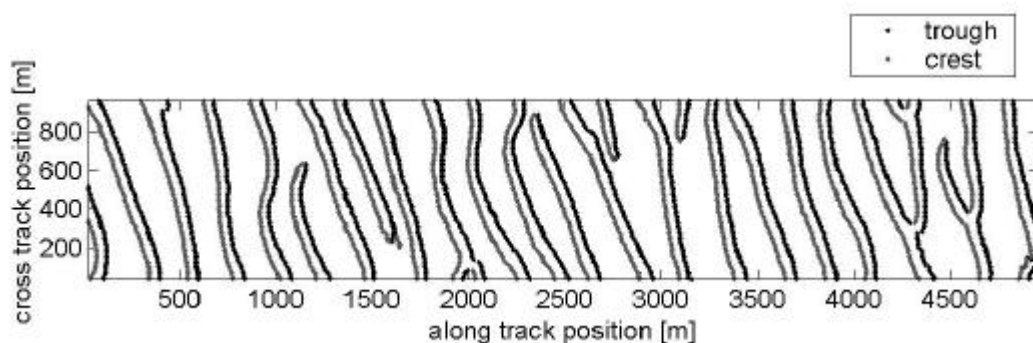


Fig. 1: Crests and troughs of the sand waves in the research area. The principal tidal direction is from left to right, with right being North-East.

If the crests and trough positions have been determined for all surveys, the displacement of these positions can be used to estimate the migration rate. The approach is explained for the crests, but the same method can be used for the troughs. Under the assumption that the migration rates are small compared to the wavelength, the crest positions of two consecutive surveys are compared.

All crests in one of the surveys that are close to a crest position in the other survey (i.e. the cross track position is the same and the difference in the along track is less than a predefined limit, here being 50

meter, 25% of the wavelength) are used<sup>1</sup>. The positions that do not have a match in the other survey are removed. Now, the difference between the couple crest positions gives the migration in the period between the surveys. The result is an estimate for the migration of all crests.

In this paper the approach is used to estimate sand wave migration. With a few adaptations however, it can easily be applied to other rhythmic patterns, like dunes or ripples)

### 3. Available echo-sounding data

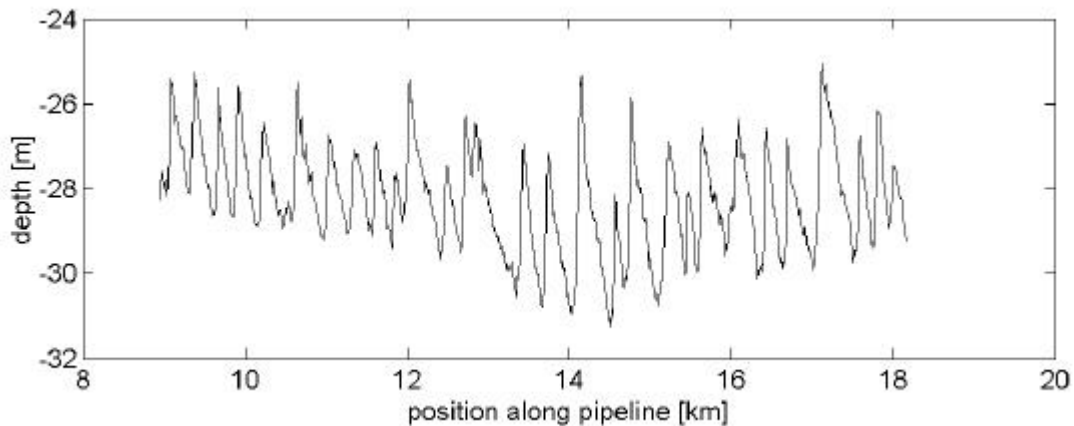
The approach described in section 2 is applied to two different data sets. Both sets contain bathymetric data of sand waves in an area in the southern bight of the North Sea, 20 kilometers east of IJmuiden in the Netherlands. The first set contains single beam data taken along a pipeline; the second set contains multi-beam data.

In the area, the tide is fairly 1 dimensional with the flow from North-North-East to South-South-West and vice versa. The tidal amplitude, averaged over a spring-neap cycle, is about 0.7 m/s. There is a small residual current to NNE with the velocity in the order of 0.1 m/s.

#### 3.1 Single-beam profiles along a pipeline

The first data set contains 5 surveys taken along a pipeline over almost 10 kilometres (Fig. 2). The surveys cover the period between 1995 and 2000. The data were gathered by digitising profile maps from the Netherland State Supervision of Mines. Although this digitisation induces additional noise, the data is still reliable enough to analyse the sand wave migration.

Fig. 2: The bathymetric profile along the pipeline. The principal tidal direction is from left to right, with left being North-North-East.



The pipeline is almost parallel to the principal tidal direction, and thus perpendicular to the sand wave crests. In the surveys, about 30 sand waves are present. They are about 2.5 m high, with standard deviation 1.2 m, and 285 m long (standard deviation 112 m). The sand waves decrease slightly in height and length in the northerly direction. The steepest slopes are facing in the direction of the residual current (NNE).

#### 3.2 Multi-beam bathymetry

The multi-beam data were taken in the context of the Delft Cluster project Ecomorphodynamics of the seabed, in which bathymetric, sedimentological and biological data were gathered and compared with each other. In 2001 and 2002, 5 surveys were taken of an 1 by 5 kilometre area covered with sand waves (Fig. 3). The wavelength of these sand waves is 220 m (standard deviation 35 m), the height is 1.5 m (standard deviation 0.3 m). These values are smaller than the ones found along the pipeline. However, the

<sup>1</sup> Note that this assumption limits the observable data to 50 metre. In general the sand wave migration will be less. If necessary it is possible to extend the algorithm to allow detection of unlimited migration

extremes in the area are 340 m and 2.1 meter respectively. Since the two-dimensional area is just North of the pipeline survey, the observations compare reasonably.

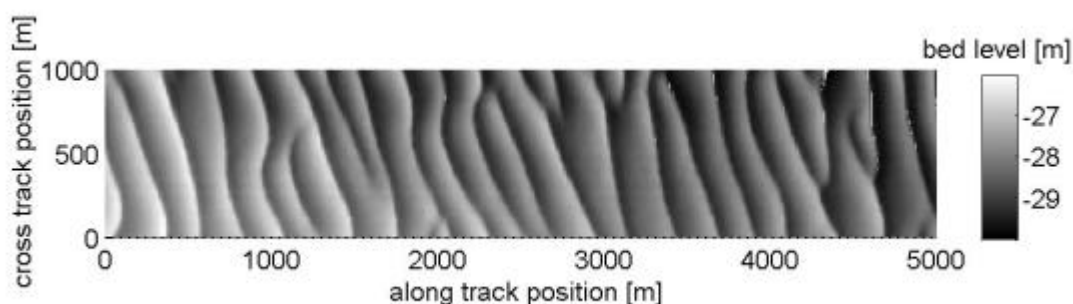


Fig. 3: Bathymetry as measured using the multi-beam echo-sounder. The principal tidal direction is from left to right, with right being North-North-East.

Again, the steepest slopes are facing in the direction of the residual current (NNE). To analyse the sand waves in profiles perpendicular to the crests, the multi-beam data was interpolated to a rectangular grid, with a 2.5m resolution in both directions. In the same project, a 70 by 800 metre detail of the area has been measured intensively. On three sessions (Sept. 2001, Apr. 2002, Sept. 2002) the detail area has been surveyed several times (14,4,4) within a few days (3,1,1). To check the accuracy of the survey data, three markers have been placed on the bed they consist of a two-meter diameter tire filled with concrete with a device to recognize them on the multi-beam images. Two have a floating buoy and one has a one-meter high iron frame. Since the migration of the sand waves within the sessions is zero, these repeated observations can be used to analyze the positioning errors in the observation.

#### 4. Error analysis and error correction

The bathymetric data contains a number of error sources, positioning errors, depth distortion due to tides and waves and bed level noise due to seasonal variation and small-scale changes. These sources result in errors when the migration is determined from the data. We analyzed the magnitude of the error sources to determine the accuracy of the migration estimates. The largest obstacle for practical use is the positional error in the bathymetric data. In this section, the influence of the errors is analyzed.

##### 4.1 Errors of the measurement systems

The bathymetric measurements are taken with a single- or multi-beam sonar system, which is combined with global positioning systems (GPS). Although these systems can reach high accuracies, the observations contain errors in the bed level estimates as well as in the determination of the position. Since the sand waves occur offshore, the positioning of the patterns has long been difficult. Before the development of satellite based GPS, only very crude estimates could be made. From the late eighties till the late nineties GPS became available. However, artificial noise added to the satellite system resulted in a positioning error that reduces from about one hundred meters in the beginning to about ten meters. Note that the lack of reference stations offshore made the use of differential GPS impossible. Starting around 2000, the use of integrated DGPS, in which DGPS is combined with speed sensors, reduced the positioning error to about 2 meters.

Another important source of the positioning error are inaccuracies in the GPS and geoids calculations and the latency of satellites. The Netherlands Hydrographic Service analyzed the accuracy of their single beam surveying system following the approach of Clarke et al. (1996). This resulted in random errors with standard deviations of 2 meter (Ronda and Appelman, 2003).

In the vertical direction the water level calculations, heave due to long surface waves and the estimate of the speed of sound in the turbulent salt water are the most important sources of errors. The error in the water level calculations can be distinguished, as it is an error that appears in large parts of data of one

survey. The standard deviation of these errors is about 20 cm (Ronda and Appelman 2003). If the data shows global deepening or shallowing, or a strong change in the main slope of the bed, this is most likely related to this error. The other error appears as random noise. According to the Netherlands Hydrographic Service this results in a random error with a 25 cm standard deviation (Ronda and Appelman 2003).

#### **4.2 Bathymetric noise**

Small-scale bed patterns are another source of inaccuracy in the observations. Superimposed on the sand waves, ripples and mega-ripples occur. These patterns can be tens of centimeters high (table 1) and are much shorter than the sand waves we are analyzing. The time scale on which the small patterns evolve is much smaller than the time scale of the sand waves and of the intervals on which the measurements take place. Since both the length scales of the ripples and mega-ripples and their time scales are much shorter, the bed level variations of these patterns can be treated as random noise. The standard deviation of this noise depends strongly on the hydrodynamic conditions during and before the survey. However, based on the observations, 10 centimeter is a fair estimate.

Since we are interested in horizontal displacement, the magnitude of the noise on itself is unimportant. However, on the crests and in the troughs of the sand waves, mega-ripples and ripples may result in displacement of the lowest and deepest point. Given the height of the patterns and the average slope of the sand waves (1:50), the standard deviation will be less than 5 m. The error in the crest positions will be larger than the error in the trough positions, since the sand-wave slopes will be gentler in the troughs. We estimate the standard deviation in the trough position at 5 meter, and in the crest position at about 2.5 meter.

#### **4.3 Single-beam profiles along a pipeline**

No markers are present in the profiles along the pipeline. Since the pipeline is buried, it cannot be used for a rectification of the positions. Therefore, we have to estimate the accuracy of the crest and trough positions based on other sources. The data set contains two types of error sources.

The first is related to the measurement system, i.e. the single-beam echo sounder and the positioning system. It can be assumed that the positioning offset between different surveys is negligible, as the positioning system can be calibrated against the known position of the oilrigs. The analysis of the system, described in the first part of this section, results in a random position error of about 5 meter. Which is equal to the noise due to small-scale bed forms (section 4.2).

The second error source is the digitization process. As only analogue maps are available for this research, these maps had to be digitized for further analysis. By recurrent digitization of another map, of which the digital data is available, results in a standard deviation of about 10 centimeter in the vertical. This results in a standard deviation of 1 to 1.5 meter for the crests. Due to the larger small-scale bed patterns in the troughs, the standard deviation in the trough position is almost 2,8 meter.

Combined, the standard deviation is will be around 10 meters for the crest positions and slightly larger for the trough positions.

#### **4.4 Multi-beam analysis**

The 22 detail surveys taken in the area of the multi-beam surveys can be used to analyze the accuracy of the multi-beam measurements. For the detail surveys, 3 markers have been positioned in the troughs of the sand waves. They can easily be identified as the local maximum in the part of the trough in which they are positioned. Figure 4 shows the found positions of the three markers in all surveys. Two things can be recognized immediately. First of all, markers 1 and 3 show a much bigger scatter than marker 2.

Apparently, the floating buoys are having a significant drift relative to the tire. Therefore, we will only use marker 2. The position of Marker 2 has a bimodal distribution. It appears that the first survey session, with fourteen surveys, has a clear offset to the next two sessions with four surveys each. This can be explained by the fact that the first session was taken with a different research vessel (Ms. Zirfaea) than the other two (Ms. Arca). There is about two meter offset between the positioning systems of these two vessels.

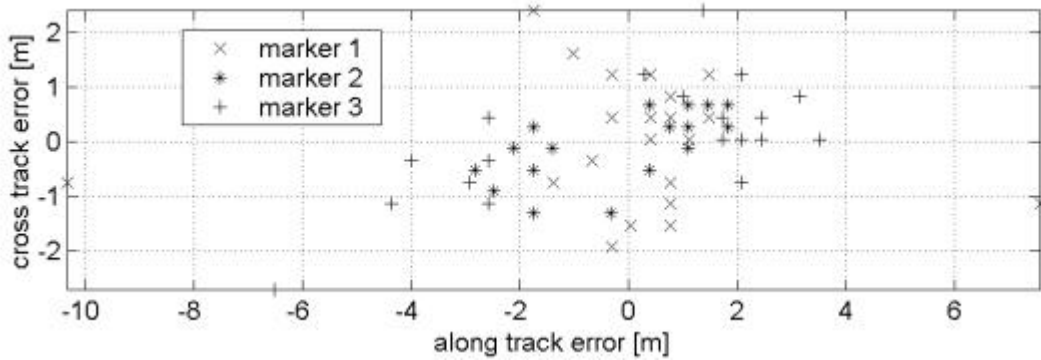


Fig. 4: All observed marker positions. Markers 1 and 3 differ from marker 2 and show more scatter.

Next the positions of the sand wave crests are determined using the approach proposed in section 2. Figure 5 shows the mean values and the standard deviation of the migration relative to the first survey. The standard deviation of the session with the Zirfaea is remarkably smaller (0.5 m), than the standard deviation of the sessions with the Arca (0.75 m).

The crest positions show a large variation in all three sessions. The positions are then corrected for the known positioning error, which has been determined from the marker position. The marker positions have a standard deviation equal to the standard deviation of the individual surveys (0.5 for the Zirphaea session and 0.5 and 1.0 for the Arca sessions). More importantly, this positioning error shows a 1.8 m offset between the first and the second session. The offset between the first and the third session is 2.4 m.

After the correction, the correlation of the estimated crest positions in all three session is a lot higher. For all three sessions, the standard deviation from the mean is 0.5 meter, which is comparable to the standard deviations for the individual survey. Almost all crest position estimates are within one meter from the mean within the session (Fig. 5).

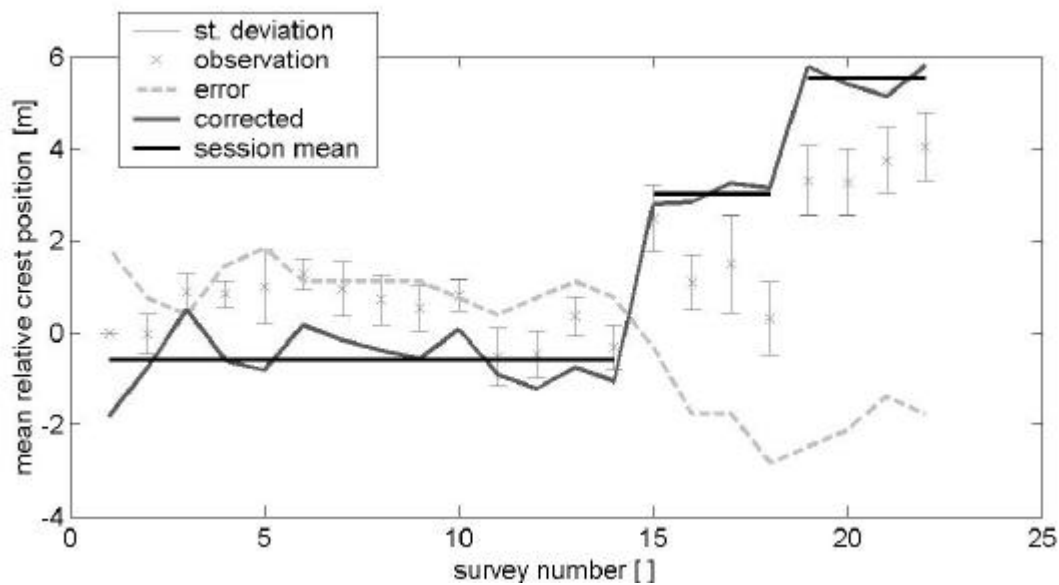


Fig. 5: Observed sand wave positions for 22 surveys divided over 3 sessions of 14, 4 and 4 surveys, relative to the positions of the sand waves in the first survey. The estimate of the positional error is based on the observed position of Marker 2 relative to its mean position.

### 5. Migration rates

The results of the analysis are plotted in figure 6. The estimates from the pipeline profiles and of the detail multi-beam surveys agree well. The multi-beam analysis without correction (large area) for the positioning gives 4 meters migration per year. However, the corrected value (small area) is 6 meters per year. The pipeline profiles have an average migration rate of 5 meters per year. Note that both values are significantly less than the values found by Morelissen et al. (2003).

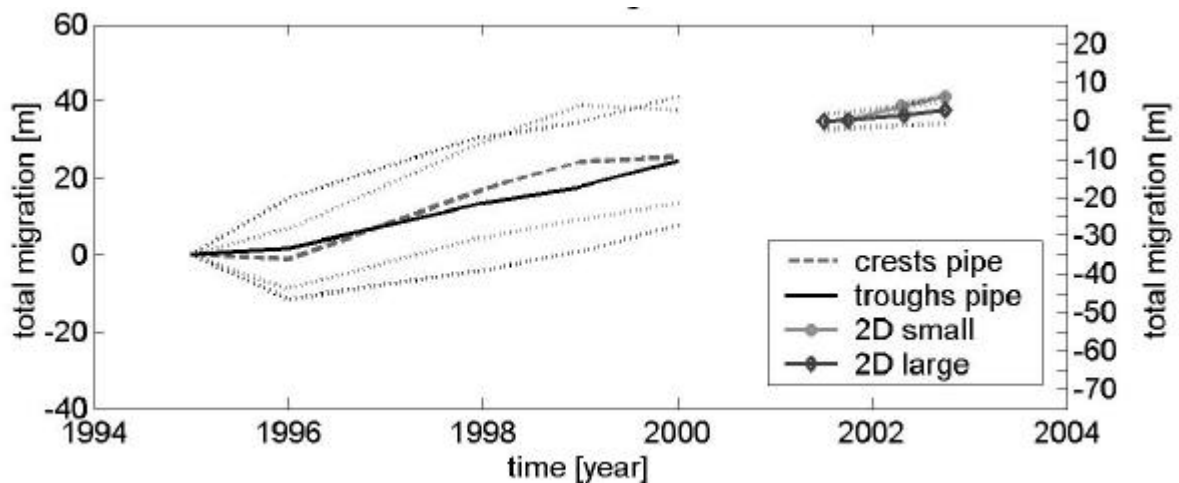


Fig. 6: Predictions of the migration of sand waves along the profile based on crest (dashed) and trough (solid) positions (left axis), respectively, and in the multi-beam surveys, in which the small area (rounds) estimate are corrected for a positioning offset and the large area estimates (diamonds) are not (right axis). The dotted lines give the standard deviations.

The standard deviation of the pipeline data is about 12 m for the predictions based on the crest positions, and 16 m based on the troughs. As there is no increase in the standard deviation over time, the variations are related to the measurement errors. In the troughs the errors are bigger due to a stronger effect of the small-scale bed patterns.

The accuracy of the multi-beam data is much higher, with a standard deviation of only 4 meter. The 2-dimensional data results in several estimates for the same crest. Averaging over these estimates filters the

noise due to small-scale patterns and the random errors of the measuring equipment out. The difference between the estimates with and without correction is within the range of the standard deviation. Surprisingly, the analysis of the multi-beam data shows no seasonal effects after correction for the positioning offset (i.e. the small area). The migration rate in the summer period is the same as the one in the winter period.

## 6. Conclusions & discussion

A fast and robust algorithm has been developed to estimate sand wave migration from bathymetric data from echo sounders. From consecutive surveys, the crest and trough positions are determined. The changes in these positions then give the migration. This approach can be used on both 1-dimensional profiles and 2-dimensional multi-beam maps. The approach can be used for all types of (seabed) waves, from mega-ripples to tidal sand banks. The observed migration rates vary between 5 and 6 meter per year. These values are much lower than the values reported in literature.

The crest-trough analysis of 2-dimensional multi-beam data, results in detailed information on the migration of sand waves. The standard deviation within the migration estimate is about 4 meter. However, an offset in the positioning system results in errors up to 2.5 meter in the migration distance. In this experiment this offset could be corrected based on markers that were placed on the seabed. In general these markers will not be present. To reduce the effect of these offsets on the estimates of the migration rates, one has to use surveys with long periods in between and/or many surveys in time.

The pipeline profiles are very useful to determine sand wave migration. The mean estimates of the migration rates are quit consistent. This consistency is created by a verification of the positioning system against the known position of the oilrigs. However, the standard deviations are rather high. For each sand wave only one position is given, whereas in multi-beam data the positions of each sand wave is estimated several times.

The high-resolution multi-beam data show no seasonal effects. Although the data only covers one winter and one summer period, this result disputes the theory that seasonal effect are important.

## Acknowledgment

The author would like to thank the State Supervision of Mines for providing us with the North Sea data set. Technology Foundation STW, applied science division of NWO and the technology program of the Ministry of Economic Affairs (project number TWO.5805) funded the research described in this paper. We thank the EU for supporting this research, which is being carried out in the framework of the project HUMOR, contract number EVK3-CT-2000-00037.

## References

- G. Besio, P. Blondeaux, M. Brocchini, and G. Vittori, Migrating sand waves, In H. Burchard et al. (eds), *Conference on Physics of Estuaries and Coastal Seas*, pp. 263-267, Hamburg, Germany, 2002.
- J.E.H. Clarke, L.A. Mayer, and D.E. Wells, Shallow-water imaging multibeam sonars: A new tool for investigating seafloor processes in the coastal zone and on the continental shelf. *Marine Geophys. Res.*, Vol. 18 (6), pp. 607-629, 1996.
- N. Dodd, P. Blondeaux, D. Calvete, H.E. De Swart, A. Falques, S.J.M.H. Hulscher, G. Rozynski, and G. Vittori, The use of stability methods for understanding the morphodynamical behaviour of coastal systems. *J. of Coastal Res.*, Vol. 19 (4), 2003.
- S.J.M.H. Hulscher. Tidal-induced large-scale regular bed form patterns in a three-dimensional shallow water model, *J. of Geoph. Res.*, Vol. 101 (C9), pp. 20727-20744, 1996.
- D. Idier, A. Ehrhold and T. Garlan, Morphodynamique d'une dune sous-marine du détroit du pas de calais. *C.R. Geoscience*, 334, pp. 1079-1085, 2002.



K. Katoh, H. Kume, K. Kuroki and J. Hasegawa, The development of sand waves and the maintenance of navigation channels in the Bisanseto Sea. In *Coastal Engineering '98*, pp. 3490-3502, ACSE, 1998.

M.A.F. Knaapen, S.J.M.H. Hulscher, H.J. De Vriend, and A. Stolk, A new type of bedwaves. *Geoph. Res. Letters*, Vol. 28 (7), pp. 1323-1326, 2001.

R. Morelissen, S.J.M.H. Hulscher, M.A.F. Knaapen, A.A. Németh, and R. Bijker, Mathematical modelling of sand wave migration and the interaction with pipelines, *Coastal Eng.*, Vol. 48 (3), pp. 197-209, 2003.

A.A. Németh and S.J.M.H. Hulscher. Modelling sand wave migration in shallow shelf seas, *Cont. Shelf Res.*, Vol. 22 (18-19), pp. 2795-2806, 2002.

B.A. O' Conner, Prediction of seabed sand waves, in W. Partidge, editor, *Comp. modelling of seas and coastal regions*, pp 322-338, Computational Mechanics Publishers, Southampton, 1992.

M. Ronda and J.C.P. Appelman, Meet + side scan sonar observations + wreck sweep observations, Techn.report, Netherlands Hydrographic Service, The Hague, 2003.