Article

Predicting Sand Wave Dynamics

On the Netherlands Continental Shelf

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Abstract

The Dutch North Sea part is mapped by two authorities. Both developed a method for analyzing time series of bathymetric data and predicting future sea floor depths. The Netherlands Hydrographic Service can use deformation analysis to describe sand wave dynamics for a complete area and to predict depth changes for individual grid points. RWS North Sea maintains a spatio-temporal Kalman filter to estimate and predict local sea floor dynamics. We combine both approaches to obtain a state space prediction method that incorporates sand wave propagation.

Résumé

La représentation cartographique de la partie néerlandaise de la mer du Nord est assurée par deux autorités qui ont mis au point une méthode d'analyse des séries chronologiques des données bathyméthques et de prédiction des futures profondeurs des fonds marins. Le Service Hydrographique Néerlandais peut utiliser Tanalyse des déformations pour décrire la dynamique des fonds mobiles pour une zone complete et pour prédire les changements de profondeurs pour chaque point du quadrillage. RWS North Sea assure la maintenance d'un filtre de Kalman spatio-temporel pour estimer et predire la dynamique des fonds marins locaux. Nous combinons les deux approches pour obtenir une méthode de prédiction de l'état de l'espace qui incorpore la propagation des fonds mobiles.

Resumen

La parte correspondiente a los Países Bajos del Mar del Norte es cartografiada por dos autoridades. Ambas desarrollaron un método para analizar series de tiempo de dates *hidrográficos y predicción de profundidades futuras del suelo marino. El Servicio Hidrográfico de los Países Bajos puede utilizar análisis de deformación para describir la dinámica de las ondas de arena para una completa área y predecir cambios de profundidades para puntos individuates de grilla. RWS North Sea mantiene un filtro Kalman espacio-temporal para estimary predecir la dinámica local del suelo marino. Nosotros combinamos ambas l aproximaciones para obtener un método de predicción del estado del espacio que incorpore la propagación de la onda de arena.*

1. Introduction

The North Sea is a shallow, sandy sea in Western Europe. The Dutch part of it, the Netherlands Continental Shelf, see Figure 1, is largely covered by rhythmic features, like shore face connected ridges, tidal banks and sand waves. Sand waves are rhythmic patterns of a few meters high with wavelengths in the order of hundreds of meters (Van Alphen and Damoiseaux 1989). These bed forms are created by the action of tidal and wind induced currents on the sea floor sediment (Németh et al. 2002). At some locations sand waves are reported to migrate with meters a year, at other locations hardly any movement at all is detected, (Van Dijk and Kleinhans 2005).

It is essential to have reliable and up to date information on the depth of the Southern North Sea: it gives access to major ports like Rotterdam and Antwerp, while at many locations its depth is critical and constantly changing because of migrating bed forms. The focus of this paper is on the prediction of future depth changes based on available time series of depth soundings. These predictions are used for two management decisions. The first decision is on dredging. If a prediction indicates that a critical depth is not sufficiently guaranteed, a dredging project has to be scheduled. To reduce costs, nearby predictions are taken into account to optimize time and location of the dredging activities. The second decision is on when to schedule a resurvey, see Figure 2. If the depth of the sea floor in a relatively shallow maintenance area turns out to be changing due to e.g. sand wave dynamics, obviously a timely new survey is required. For a currently safe area where no changes are predicted, no new survey has to be scheduled yet.

Figure 1: Dutch coastal bathymetry, as stored *in the bathymetric archives of the Hydrographic Service. The empty spaces have not yet been resurveyed since the creation of the digital archives.*

Several approaches exist, to obtain insight in sea floor and especially sand wave dynamics. Important physical insight is obtained by establishing dynamical systems that analyze the response of a sea floor to parameters like grain size, wave climate, water depth and size and directions of tidal currents, e.g. (Hulscher and Van den Brink, 2001). The echo-sounding data in itself can be used to analyse the migration of a complete sand wave field, based on a pattern recognition approach that tracks the position of the sand wave crests through time (Knaapen 2005, Duffy and Hughes-Clarke 2005). In this paper, we describe, compare and combine two statistical methods as developed independently at the Netherlands Hydrographic Service and RWS North Sea, the two organizations that are surveying the Dutch part of the North Sea. Both authorities use echo sounding observations to monitor the sea floor depth.

The Hydrographic Service is part of the Royal Netherlands Navy and is responsible for the nautical publications of the Netherlands Continental Shelf. In order to design an optimal resurveying strategy, they developed a method for analyzing time series, based on geodetic deformation analysis, (Dorst 2004). The core of this method is a testing procedure to determine if the sea floor is static or if its depth is changing over time. This procedure is applied at two scales, for single grid-points or for a whole area. The point-wise analysis results could be used for predictions of future sea floor depths. Furthermore, they estimate sand wave parameters, like sand wave length, amplitude and location (phase), within the area analysis. This method is designed and has proven itself for the detection of past dynamics, for prediction the results are not yet complete.

RWS North Sea, part of Rijkswaterstaat (RWS), which is the Dutch Directorate-General of Public Works and Water Management, is responsible for

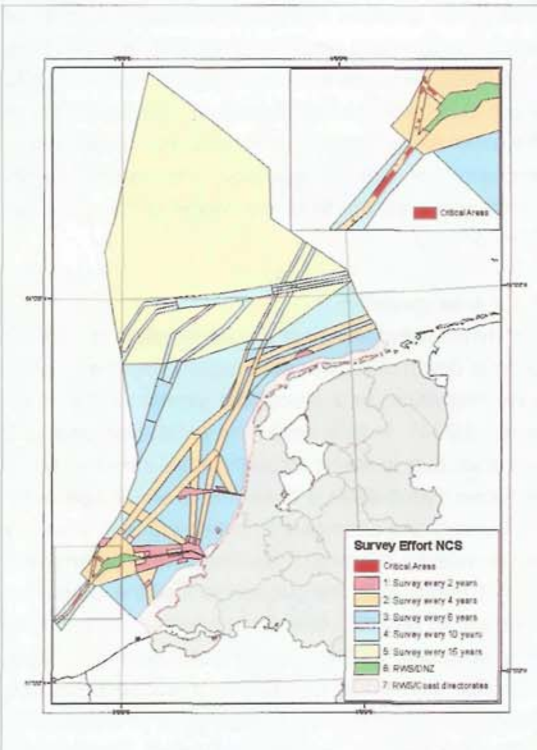

Figure 2: Current resurvey schedule, RWS/DNZ denotes RWS North Sea.

the maintenance of shipping channels, like the Euro Channel to the port of Rotterdam. For this channel, a guaranteed nautical depth is defined: when the depth in the channel becomes too shallow it has to be dredged. To predict the moment when the channel floor will rise above a critical depth (Wüst 2004) introduced a trend analysis model, based on a state space approach with Kalman filtering updating (Kalman 1960). In this method a space-time representation of the sea floor is estimated, using local linear growth models (West and Harrison 1997). The state at each grid point of the modelling grid consists of a constant depth part and a linear trend over time, together defining a local linear growth state space model. The states are updated when new measurements become available. The information of the relatively fine archive grid depth measurements is projected on the coarser modeling grid using a Gaussian kernel method. A probabilistic prediction of the future sea depth is made using the estimated state, consisting of depth values and trends, and its variance-covariance matrix. This method produces predictions for future depths together with a calibrated predictive uncertainty distribution. It is calibrated for predictions up to five years ahead.

Both authorities have developed a grid-point wise prediction setup. As a consequence, they only analyse vertical changes in depth. Horizontal changes, that occur when a sand wave migrates, are not taken into account. We propose a combination of both methods that allows incorporating an area wide sea floor representation into grid-point wise predictions. We first apply a deformation analysis to detect outlying surveys and to determine sand wave migration parameters. Furthermore, we extend the state space model with a local testing procedure and a sand wave propagation model, based on the parameters found in the deformation analysis. Results of all three methods are demonstrated on a time series of nine surveys in 11 years of an area with a moving sand wave.

2. Current Prediction Methodologies

In this section, two methods are described for predicting future depth values, based on repeated soundings. It should be noted that the methods as given here, represent the situation of 2004 (Dorst 2004 and Wüst 2004). First we sketch the method under development at the Netherlands Hydrographic Service, then we give an overview of the method as implemented back in 2004 at RWS North Sea. More recent developments in the methodology of the Hydrographic Service can be found in (Dorst et al. 2007).

2.1 Methodology Hydrographic Service

The applied estimation and prediction method of the Netherlands Hydrographic Service is based on a least squares analysis where alternative representations are statistically compared in a testing procedure (Koch 1999, Teunissen 2000, 2001). It is assumed that depth values and depth accuracies are given for the nodes of a fixed grid for each survey. The accuracies describe the combined effect of all the measurement and processing errors. In a first step the most appropriate static representation of the sea floor is determined. In the second step data from all available surveys is analyzed to determine the dynamics of the sea floor starting from the static representation.

2.1.1 Static sea floor representation

For approximating the sea floor, alternative representations are considered. The initial static representation is a horizontal plane, parameterized by one overall depth parameter, d. That is, the expected depth E{ d_p} at any point p of the sea floor equals d:

(1) $E\{d_p\} = d$, for any point p

One hypothetical extension is a sloping plane, using two additional parameters for the slopes in x- and y-direction. A second hypothetical extension is a plane superimposed by a sine wave representing a one-dimensional sand wave. That is a sand wave such that consecutive sand wave crests are straight and parallel. As a consequence, the orientation of a sand wave field can be described by one azimuth angle, East of North, perpendicular to the crest lines. The grid spacing has to be dense enough with respect to the wavelength of the sand waves, to prevent aliasing effects. Typical values are 50 to 100m. Wavelength is considered to be a constant here, both spatially and temporally.

The representation of the sea floor as a horizontal plane with a superimposed one-dimensional sand wave expresses the expected depth E{ d_P } at point p with horizontal coordinates (x_P , y_P) as

$$(2)\ E\{d_p\} = (1, \cos(2\cdot\pi\cdot x_p / L), -\sin(2\cdot\pi\cdot x_p / L))\cdot(d,u,v)^T$$

with d the mean depth of the area and L the sand wave wavelength. The parameters, $u = A\cos\varphi$ and $v = A\sin\varphi$ describe a one-dimensional wave, with A the wave amplitude, and φ its initial phase via

$$(3)\quad A\cdot\cos(2\cdot\pi\cdot x_p / L+\varphi) = \cos(2\cdot\pi\cdot x_p / L)\cdot u - \sin(2\cdot\pi\cdot x_p / L)\cdot v.$$

In this way, the depth d at position p depends linearly on the estimation parameters *(d, u, v).* By the back substitution $A = \sqrt{}$ (u^2 + v^2) and φ = arctan v/u, the sand wave amplitude A, and sand wave phase, φ, are recovered from the estimated parameters u and v.

Selection of the most likely sea floor model is done by a testing procedure. In such a procedure, the observations are first fit to the most simple sea floor model. Here the simplest model is the representation of the sea floor as a horizontal plane, see Equation (1). If the observations fit badly, alternative models are considered that are less simple, like for example the representation of the sea floor as a horizontal plane with a superimposed one-dimensional sand wave, Equation (2). In evaluating the degree of fit of the different representations, the number of model parameters and the quality of and possible correlation between the observations are taken into account. Subsequently, the model is extended with the most relevant extension. This procedure continues until none of the available alternatives significantly improves the fit of the model to the observations anymore.

2.1.2 Area dynamics

The dynamic behaviour of the parameters is used to deduce depth changes, sand wave growth and sand wave migration, in a procedure similar to (De Heus et al., 1994). In this case, the initial scenario is a sea floor that is static throughout all surveys. As alternative hypotheses a linear trend and single outlying surveys are considered. In this context, a survey is considered outlying if its describing parameters do not match with the parameters of the other surveys, either due to a change in sea floor, or because of a deviation in the measurement process. More complex, non-linear behaviour of consecutive surveys is represented as a combination of several outliers, possibly including a linear trend. The method starts with the static sea floor representation as determined in the static analysis step. Subsequently, a statistical hypothesis is set up for each extension, and a corresponding test statistic and critical value are calculated, again by incorporating an appropriate VC-matrix. Each test statistic is divided by its critical value, to obtain a test quotient. The critical value depends on the user defined level of significance, which is the probability that an extension is accepted by the testing procedure, while in fact it should be rejected. The extension with the highest test quotient is the most significant extension and is therefore added to the initial static representation for representing the dynamic behaviour. Note that this procedure is similar to the one described at the end of paragraph 2.1.1.

The dynamic model of a trend in the sand wave is constructed by extending an initial sea floor model for one epoch, as the one in Equation (2), with a time, t, dependent term

$$(4)\quad \cos(2\cdot\pi\cdot x/L)\cdot(t-t_0)\cdot\Delta u/\Delta t - \sin(2\cdot\pi\cdot x/L)\cdot(t-t_0)\cdot\Delta v/\Delta t$$

Here t_0 indicates the time of the first epoch. Fitting the observations of all available epochs into this model will result in wave propagation parameters

$\Delta u/\Delta t$ and $\Delta v/\Delta t$ that together describe a change in amplitude, $\Delta A/\Delta t$, and phase, $\Delta\varphi/\Delta t$, of the sand waves in the study area.

2.1.3 Outlier removal

Similar testing procedures can be applied to determine relatively small outliers that may remain after a first data cleaning procedure. The well-known w-test compares the fit of all observations to the fit where one observation is discarded. If the latter fit is significantly better, the discarded observation is considered an outlier, (Teunissen, 2000). Similar to the w-test for single soundings, also a single survey could be qualified as an outlying survey by the testing procedure, for instance if the depth is systematically overestimated, due to e.g. a systematic error in the measurements.

2.1.4 Point dynamics

In a similar way as for a complete area, dynamics can be estimated from the time series of depth values and depth accuracies as available at a single grid node. For a single node position, typically about four to ten depth values are available through time. Therefore, it is only feasible to represent the depth dynamics at a point location with only a few parameters. Particularly, the initial scenario of a static depth is tested against the alternative hypothesis of a linearly increasing or decreasing depth. It is also considered if one or more nodal depths should be disregarded because their depth value is not in line with the other depths, using the outlier hypothesis. Adaptation of a certain representation by the testing procedure does not only result in a statistical optimal estimation of the parameter values describing the grid point behaviour, but also in their variances, describing the adequacy of the representation. Note that in all cases described here the Hydrographic Service is processing in batch mode: the unknown parameters are estimated from all observations together and if a new survey becomes available, the computations are redone on all observations again.

Predictions for future depth values are obtained by extrapolating the trends at each grid node into the future. The variance of a trend-based prediction will increase with the increase in time between the moment of prediction and the moment of the last sounding.

2.2 Methodology RWS North Sea

In order to schedule survey and dredging activities, RWS North Sea has developed a trend prediction model for monitoring the sea floor depth (Wüst 2004). There are two main differences with the previous approach. First a whole area, containing many grid points, is processed at once. This enables a joint accuracy calibration that takes correlation between nearby grid-points into account. Second, new observations are not processed in batch mode but recursively: the updated state estimate is a direct combination of the existing, previous state estimates and the newly available observations. Elsewhere, (Knaapen et al. 2006) it is demonstrated how, with a small adaptation, this trend prediction model can also be used to monitor regeneration of sand waves after dredging.

2.2.1 Kalman filtering

Recursive state estimation is generally known as Kalman filtering, after (Kalman, 1960), who initially described the methodology. A typical example of recursive estimation is navigation, where an updated estimate of the actual position has to be calculated continuously and instantly from for example the available GPS observations. In bathymetric processing a Kalman filter approach has been proposed for the automatic updating of depth estimates when passing a certain position several times within one survey (Calder and Mayer 2001). A bit of an inverse application is to track the position of an AUV or submarine by continuously comparing its soundings with a given georeferenced multibeam chart (Jalving et al. 2004).

The state-space model of RWS North Sea maintains a state vector xk through time, representing the state of the linear growth models which represent the dynamics of the sea floor at a suitable grid covering the area of interest. The state vector contains the local depth and depth trend for each grid point, d, i=l..J, that is

$$x_k = (d_1, \cdots, d_J, \Delta d_1 / \Delta t, \cdots, \Delta d_J / \Delta t) \quad (5)$$

Parallel to the state vector its variance-covariance (VC) matrix Q_{xk} is estimated, containing the variances of the state vector on the diagonal, while the off-diagonal elements contain the possible covariances between the state parameters. The state vector can be update in the following two different ways (Teunissen 2001).

2.2.2 Time update

A time update is performed when the state of the sea floor is needed at a moment when no surveys are available, e.g. in case of a prediction. The local depths and depth trends are extrapolated to the moment of the time update. In matrix notation this is represented as

$$(6)\quad \begin{pmatrix} \underline{d}_{k|k-1} \\ \dfrac{\Delta \underline{d}_{k|k-1}}{\Delta t} \end{pmatrix} = \begin{pmatrix} I_{J\times J} & I_{J\times J} \\ 0_{J\times J} & I_{J\times J} \end{pmatrix} \begin{pmatrix} \underline{d}_{k-1|k-1} \\ \dfrac{\Delta \underline{d}_{k-1|k-1}}{\Delta t} \end{pmatrix}$$

Here I_{JxJ} denotes the *JxJ* identity matrix. The upper part of the transition matrix Φ extrapolates all nodal depths $\underline{d}_{k|k-1}$ at time *k*, given the state at time *k-1* from the estimates of nodal depths $\underline{d}_{k-1|k-1}$ and the nodal velocities $\Delta \underline{d}_{k-1|k-1}/\Delta t$ at time (k-1). The lower part expresses that the depth trend does not change in a deterministic way at a time update step. As no new information is added to the system, the depth and depth trend accuracies will decrease according to a model uncertainty matrix Q_{mk}, given by

$$(7)\quad Q_{m_k} = Q_{x_{k|k-1}}(1-\delta)/\delta$$

The parameter σ denotes a suitable discount factor, chosen to be σ=0.91 after calibrating filter prediction results on real observations. This discount method is adapted from (West and Harrison 1997).

2.2.3 Measurement update

A measurement update is performed whenever a new survey becomes available at time *t*. In a Kalman filter update step, the state parameters are adapted to the new survey data. The effect of the new observations on the state parameter depends on the accuracy of the previous state, on the accuracy of the new observations and on the spatial relations between the observations and the state parameters. The exact formulas for a measurement update can be found in (Teunissen 2001) or in (Zarchan and Musoff 2000).

The variance of the depth values, available at a 5m grid, consists of two parts. One part is determined from the variability between the soundings that contribute to a grid cell value; the other part is a fixed measurement noise component that after calibration is set at 0.23 m^2. The measurement noise component takes both the accuracy of the echo sounder and short-scale variability due to the presence of small unpredictable morphological variation into account. The Kalman filter is calibrated to maintain depths and depth trends at a grid with a grid spacing of 17.5m. The functional relation between the depths at the model grid points and the 5 m observational grid is given by a weight matrix whose weights are determined according to the distance between the archive points and the model grid

	Hydrographic Service	**RWS North Sea**
Stored archive values	Shallowest depth of SBES data in 5m grid cells	Mean depth of MBES data in 5m grid cells.
Survey archive quality description	A priori: derived from the specifications of the sensors	A posteriori: derived from the measurements
Main goal of time series analysis	Insight in sea floor dynamics	Prediction of crossing time of nautical limits
Method	Deformation analysis	State space model with Kalman filtering
Data assimilation	Batch	Recursive
Regridding	Archive data are regridded to coarse grid (e.g. 60m) by Kriging	Archive data are regridded to coarse grid (e.g. 17.5m) by Gaussian interpolation Kernel
Point-wise dynamics	Static, outliers, linear trend	Linear trend
Area-wise dynamics	Static, outliers, linear trend, possibly including a 1D sand wave	Not directly incorporated, but indirectly, via the stochastic model.
Prediction	Point-wise, based on detected dynamics	Point-wise, based on the local linear trends

Table 1: Overview methods RWS North Sea and Netherlands Hydrographic Service.

points by means of a Gaussian kernel function, (Lee et al. 2002). For the kernel width (standard deviation) also a value of 17.5m is used.

2.3 Comparison of both existing methods

In Table 1 an overview of both methods is given. MBES denotes multibeam echo sounding, SBES indicates single beam. The top part of the table shows that not only the methods itself differ, but that also differences exist in the storage of survey data. Both authorities process the raw soundings to a 5m grid. The Hydrographic Service uses the shallowest SBES-sounding per 5m cell for its analyses, while RWS North Sea is using the cell average of the MBES values. The latter approach is less sensitive to uncorrected measurement errors. As a consequence, both authorities would end up with different predictions, even when using the same prediction methodology and using the same soundings.

The main difference between both approaches logically results from their different goals: The Hydrographic Service decides between different dynamics using hypothesis testing methodology and determines predictions at a certain grid node based only on the available archive data at that particular node. RWS North Sea produces calibrated predictions using a space-time modelling approach.

A relevant practical difference is that the Hydrographic Service processes all historical data including the latest survey in batch mode while RWS North Sea applies a recursive method. As a consequence RWS North Sea only needs to process the new observations when updating the model, provided that the model state as estimated on the basis of the previous observations has been stored for later use.

3. The proposed new methodology

The sea floor prediction methods developed by RWS North Sea and the Hydrographic Service are both restricted to modelling sea floor dynamics in a vertical and local sense. So, horizontal aspects of sea floor dynamics, due to e.g. sand wave migration, are not taken into account, e.g. due to sand wave migration. This is demonstrated in a synthetic example in Section 3.1. In Section 3.2 a new method is introduced that allows incorporating spatial dynamics found for a complete area into node predictions. The method is described and demonstrated for an area covered by a 1D sand wave, but the principle also works for other types of spatial dynamics.

3.1 Synthetic sand wave migration

Consider a simulated propagating sand wave with 1 m amplitude and 300 m wave length. Every year, the crest is shifted 10 m to the right. Figure 3 shows the sand wave positions in four consecutive years. In Figure 4 the analysis results of a deformation analysis per grid-point are given. Points on the left of the crest become deeper, while points on the right become shallower. This simulation clearly demonstrates a shortcoming of predictions based on local linear trends: the prediction quality decreases with time, as these points in reality do not show a linear trend in time but a harmonic trend. Such predictions can be improved by incorporating a spatial, area based sand wave model into the grid-point wise predictions, as this allows for modeling the sand wave propagation. The essential extension is that in this case a global model is used for predicting local dynamics.

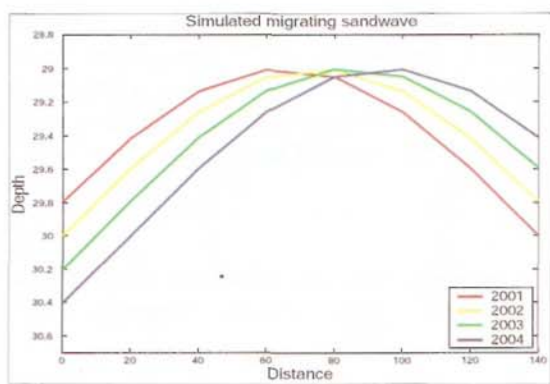

Figure 3: Profile of a simulated migrating sand wave.

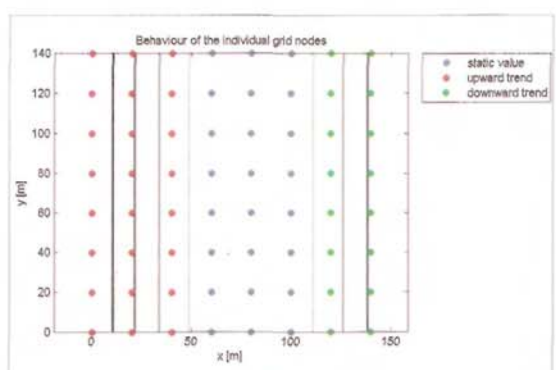

Figure 4: Depth predictions.

3.2 Local-global predictions

All ingredients needed for local depth predictions while incorporating a spatial dynamic model have been introduced in Section 2. Here we will show how to incorporate the dynamics of the area in the local prediction of the Kalman filter and how to build in a procedure to detect and eliminate outliers.

3.2.1. Using sand-wave parameters for local depth predictions

Let us assume that the test procedure of the Hydrographic Service shows that the area at hand is best described by a horizontal plane with a superimposed 1D sand wave. We assume that the sand wave orientation and length are given. The observations from all available, say, *K* surveys are used to describe the dynamic behaviour of the area through time by means of the procedure of Section 2.1. This analysis results in parameters $\Delta u/\Delta t$ and $\Delta v/\Delta t$ describing a constant sand wave propagation velocity and a constant change in sand wave amplitude as indicated in Section 2.1.

In order to express this above dynamic sand wave representation in a state space format, the state vector x_K as introduced in Section 2.2 has to be extended by the parameter values *u, v,* describing the global sand wave itself, and by $\Delta u/\Delta t$ and $\Delta v/\Delta t$, describing the change of the sand wave over time:

$$x_k = (d_1,\cdots,d_J,\Delta d_1/\Delta t,\cdots,\Delta d_J/\Delta t,u,\Delta u/\Delta t,v,\Delta v/\Delta t) \quad (8)$$

The transition from state *k* to state *k+1,* with $A' = (A_k + \Delta A)/A_k$, for the sand wave parameters only is given by:

$$\begin{aligned} u_{k+1} &= A'\cos\Delta\varphi \cdot u_k - A'\sin\Delta\varphi \cdot v_k \\ \Delta u/\Delta t_{k+1} &= \Delta u/\Delta t_k \\ v_{k+1} &= A'\sin\Delta\varphi \cdot u_k + A'\cos\Delta\varphi \cdot v_k \\ \Delta v/\Delta t_{k+1} &= \Delta v/\Delta t_k \end{aligned} \quad (9)$$

This transition should be added to the transition matrix Φ, compare Equation (5). For initializing the extended Kalman filter, the sand wave parameters values are taken from the test procedure while the change in sand wave is initially set to zero. Similarly, the initial variances of the sand wave parameters are as obtained from the testing procedure. Without giving the details here we mention that an outlier removal procedure as sketched in Section 2.1.3 can easily be incorporated in the Kalman filter as well, (Teunissen and Salzmann, 1989).

3.2.2 *Local-global prediction algorithm*

The steps leading to a grid-point wise prediction, as explained in some detail above, are summarized in the following algorithm.

Input: Data grid available in K surveys. At every grid point a depth value and a depth variance is available.

1. Determine sand wave length and sand wave direction.
2. Determine sand wave velocity, sand wave amplitude and outlying surveys from a deformation analysis of all *K* surveys. Remove outlying surveys if found.
3. Run a state space model on the remaining data. At every Kalman filter update step, grid-point wise outliers are identified and eliminated.
4. Perform state space evolution step for a prediction at an arbitrary future moment.

Output: grid-point wise predictions.

4. Prediction Algorythm Results

Here results of the methods of the Hydrographic Service and RWS North Sea on a real data set representing a regular sand wave are compared to results obtained by our new, combined method. All three methods were implemented in Matlab.

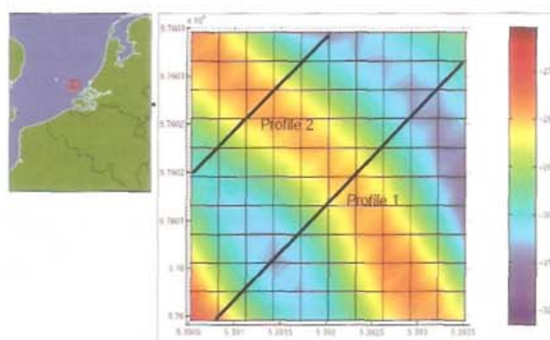

Figure 5: Left: position of area NA. Right: depths of area NA in 1991 in meters. Coordinates are in UTM31-WGS84.

4.1 Data set NA

Area NA is located in the Euro channel at about 35 km off the Dutch coast, see Figure 5, left. This area of 330 x 330m has been monitored by Multi Beam Echo Sounding in all years between 1991 and 2001, except for 1992 and 1998. The data are available on a 5m grid; therefore every survey is represented by 4,356 grid points. Each grid point value is the average of the soundings in the corresponding grid cell. RWS North Sea is responsible for guaranteeing the depth in the Euro channel. The depths in 1991 are shown in Figure 5, right. In the middle of the figure the crest of a sand wave is visible. This sand wave has a wavelength of about 225m and its average orientation is 47 degrees east of North.

4.2 Deformation analysis results

Least squares adjustment of all the available surveys to the dynamic sand wave model as described in Section 2 gives a sand wave amplitude of about 1.4 m and a sand wave propagation velocity of 1.6 m/year. In Figure 6, nodal predictions as derived from the point-wise deformation analysis method are given on a 33m grid, showing upward and downward trends on opposing sides of the sand wave crests. These trends are caused by the sand wave migration.

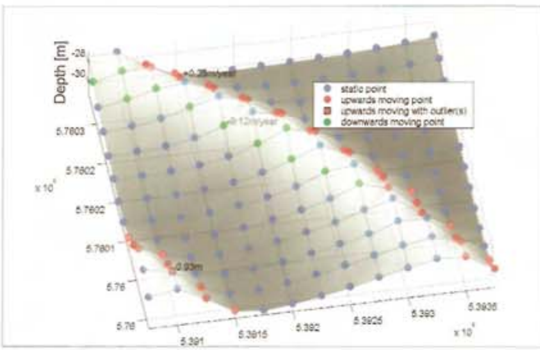

Figure 6: Results of the deformation analysis per node, colour intensity corresponds to size of the trends found. Additionaly, values for the maximum trend and the outlier are given. Coordinates are in UTM31-WGS84.

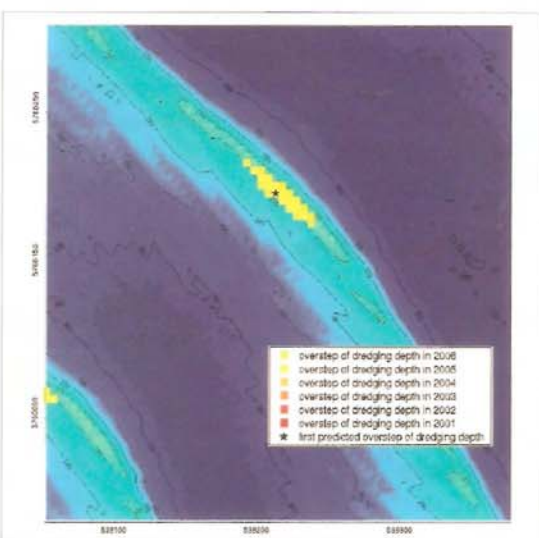

Figure 7: Predicted moments of crossing of the dredging depth as determined by the state-space approach. Coordinates are in UTM31-WGS84.

4.3 Local Kalman filter results.

In Figure 7 predictive moments of crossing of the dredging depth are shown as determined by the local Kalman filter approach using all surveys. These overstep moments are based on the mean values (50 % probability). The Kalman predictions are in agreement with the deformation analysis results: crossings of the critical depth are predicted to occur at the North-East side of the two crests. As the sand wave migrates to the right, these points were moving upward in most surveys. The continuously decreasing depth at these positions results in an overstep warning. In reality one might expect that, after passage of the crest, the sea floor at these critical points is becoming deeper again.

4.4 Results local-global algorithm

In Figure 9, the actual data in 2001 and profiles from the sand wave representation as obtained from running the local-global Kalman filter for 10 years are shown. The location of the profiles is indicated in Figure 5, right. In contrast to similar profiles for 1991 (not shown) at the initialization of the Kalman filter, the profiles fit well. It is also clear that the shape of the sand wave is not a sine in reality.

Figure 8 gives predictions one year ahead for the individual grid points based on the new local-global algorithm. That is, the differences between the observations of the last survey and the predictions for one year ahead are displayed. Clearly, the motion of the sand wave in North-East direction is visualized by the pointed triangles, indicating upwards or downwards movements of at least 5cm. A validation of the prediction results is obtained by comparing predictions for e.g. 2001 to the actual grid wise observations. The mean absolute difference between prediction and observation is +12cm, with maximum values of +45cm and -12cm. Maximal differences occur near the crests and are probably due to the mismatch between the sinusoidal representation and the actual sand wave shape. The main benefit of the local-global approach is that it allows incorporating obvious global dynamics in predicting depth changes at individual grid points. As a consequence, more reliable predictions can be obtained in case of regular, horizontal sea floor dynamics.

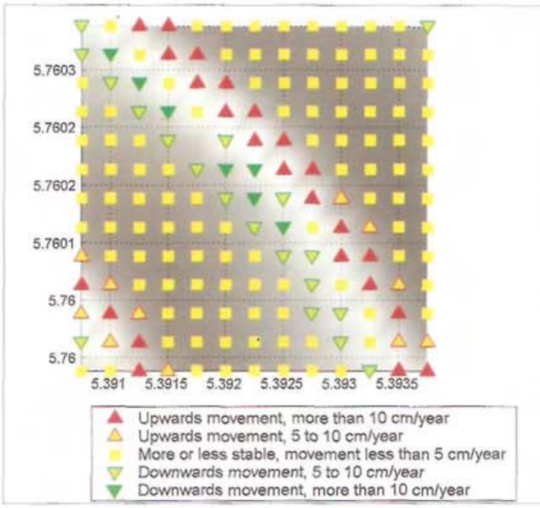

Figure 8: One year ahead predictions as derived by the local-global algorithm.

5. Discussion and Conclusions

We propose a method to incorporate an area wide morphological sea floor model in a state space Kalman filter model for the purpose of grid-point wise change predictions. In this particular case a propagating sinusoidal sand wave was modeled. The test results indicate that, using the new approach, potentially more reliable and therefore more cost-effective predictions are obtained for areas with 1D moving sand waves. A remaining problem is that sand waves are in reality not sinusoidal. Because the proposed method includes a stochastic component, a not-optimal fit will automatically result in predictions with a larger variance. Still it is recommended to consider alternative low parameter representations of sand waves.

Dynamic areas with an irregular morphology can be automatically reported by the deformation analysis component as fitting badly to any tested dynamical model. In such a case the area could be segmented in more regular sub-areas. Suspect areas should not only be resurveyed more often but also analyzed at higher resolution than relatively safe areas. In the methods described here, it is silently assumed that changes occur regularly. It is not clear to what extent this assumption exactly holds.

A large inventory of bathymetric data of the Netherlands Continental Shelf will increase the insight of the applicability of the discussed methods, the kind of sea-floor representations needed and the validity of the assumptions made. For this purpose an overall systematic data analysis procedure could be performed on the available soundings in the bathymetric archives of e.g. the Hydrographic Service or RWS North Sea for those specific areas where several surveys are available.

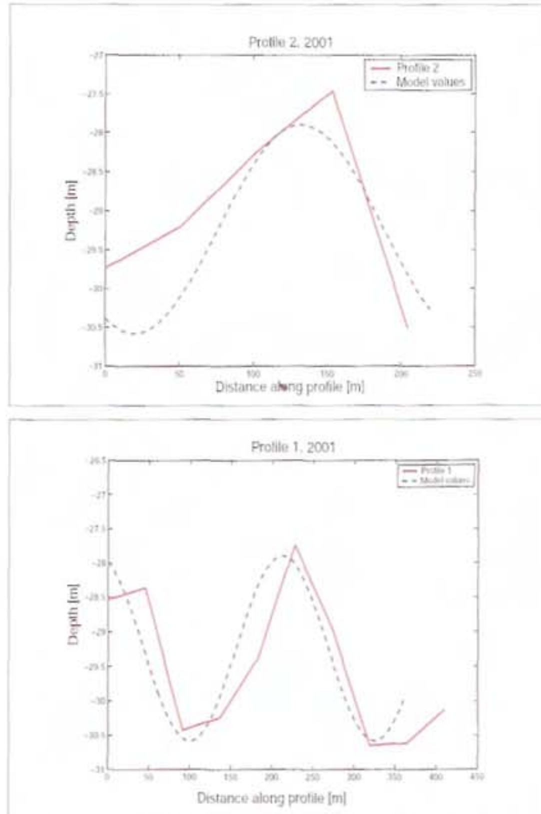

Figure 9: Two profiles of the modeled (blue) and real (red) sand waves. The location of the profiles is indicated in Figure 5.

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Biographies

Roderik Lindenbergh studied Mathematics at the University of Amsterdam. He obtained a PhD in Mathematics from the University of Utrecht on his work on Voronoi diagrams. After his PhD he joined Delft University of Technology to work in the section of Mathematical Geodesy and Positioning. Current research interests include deformation analysis, spatio-temporal interpolation and quality control of large spatial data sets. Roderik works on the integration of GPS and MERIS water vapor data and is involved in the analysis of ICES at full waveform laser altimetry data and in the quality aspects of terrestrial laser scanning.

Leendert Dorst finished his MSc in Geodetic Engineering at the Delft University of Technology in 1999. He has been employed at the Netherlands Hydrographic Service since. His tasks include consultations on hydrographic surveying, maritime positioning, coordinate systems, and technical aspects of the law of the sea. He participates in the IHO S44 working group on Standards for Hydrographic Surveys. Since 2004, he has been a PhD candidate at the University of Twente, studying the analysis of time series of bathymetric surveys using deformation analysis, to improve the resurvey policy of the Netherlands.

Hans Wüst studied Naval Architecture at TU Delft. He worked at Rijkswaterstaat North Sea on probabilistic admittance policy and on hydro-meteorological predictions like water level, current, and swell using neural networks. He developed an operational error correction method for systematic periodic errors of numerical water level predictions using Kalman filtering and Bayesian techniques and a Kalman Filter sand wave prediction model. Currently he is working at the Rijkswaterstaat Centre for Transport and Navigation as statistical consultant.

Peter Meriting studied Geodetic Engineering at the TU Delft. He wrote his master thesis on the detection and prediction of sea floor dynamics. In this research he compared the methods of Rijkswaterstaat and the Hydrographic Service to analyze time series of echo sounder measurements. By analysing time series of measurements, it appeared to be possible to predict the behaviour of the sea floor, especially when covered by sand waves. Currently he is working as a project manager at Fugro-Inpark, where he works on various land surveying projects.