3-D desktop mapping and volume change estimation of the Northern Ameland Coast, the Netherlands

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ABSTRACT

At present, topographic and remotely sensed data are increasingly delivered in digital format. As an application, thematic mapping can make use of what these digitally formatted data can offer. Some thematic applications are mapping, assessment and monitoring of endangered coastal zones, through

(a) manipulating topographic and bathymetric data using digital terrain models (DTM’s),

(b) constructing, through sequential digital airborne and spaceborne imagery, stereo models, and overlaying existing DTM’s for further refinement of the DTM’s, and drafting the thematic boundaries with a stereo cursor directly onto the DTM’s,

(c) calculating coast-line and volume changes and progression in time, allowing hazard zoning, assessment and coastal zone management.

Various computer programmes have been evaluated, selected and adapted for application, and are being tested on the northern coastal zone of the barrier island Ameland, the Netherlands. The developed method is evaluated by verifying the results with the standard terrestrial and photogrammetric observations and calculations executed by the Survey Department of Rijkswaterstaat, Netherlands Ministry of Transport, Public Works and Water Management.

1. INTRODUCTION

Mapping a coast-line and quantifying the rate of historical shoreline changes is useful in estimating the highly dynamic processes and in predicting volume changes and progression in time of the coastal zone, allowing proper coastal hazard zoning, assessment and management.

As Leatherman (1983) already stated, a number of mapping and data collection techniques exist to acquire information on historical shore-line changes. So far, three main techniques are applied:

(1) comparison of temporal maps. However, projection, scale and accuracy, especially those from before 1850, may not be accurate enough to pinpoint the coastline and volume changes with precision.

(2) interpretation and comparison of sequential aerial photographs (AP’s). This implies that mapping of coastal dynamics is only possible from the time AP’s have been available, in principle, from the 1940’s onward. For accurate comparison and quantification of the changes, the AP’s have (besides the requisite of having been taken at comparable sea stages, which seldom occurs) to be corrected for tilt and relief displacement, and brought to one reference scale. Plotting instruments can be applied to eliminate, as much as possible, the deformed terrain image. Orthophotography might be a better solution to solve such problems. Mosaics of various sequential photo-coverages (if available) can be made in either optical/mechanical format or in digital/optical format, and annotated coastal zone changes can be compared and quantified.

(3) metric mapping, which involves analytic treatment of photogrammetry, characterized by the highest order of accuracy premised on mathematical models and numerical solutions, rather than on analog methods. As Leatherman (1983) stated, “this technique allows for the compilation of shore-line data from all available sources of accurate information”. All information will be digitized and metrically corrected. Thus, shorelines can be overlaid at a common scale and coordinate system format to indicate quantitative changes during the period of recording. Final maps can then be computer-plotted to form the basis for proper coastal hazard zoning, assessment and management.
One of the problems of technique 3, metric mapping, was that 3-D information and (semi)automatic updating through DTM’s and stereo data was, in coastal zone research, not applied in volume estimation and hazard zoning by coastal change modelling.

Over the last few years, a number of personal computer (PC) software packages for image processing and GIS applications, oriented toward planimetric mapping, have been placed on the market, some of which are capable of deriving terrain elevations from stereo image data in digital formats. In this way, the following goals can be established:

- feasibility of using off-the-shelf PC’s with both monoscopic and stereoscopic image data for planimetric, topographic, and thematic mapping tasks;
- reducing the complexity of image processing and mapping tasks by featuring key operations in pull-down menus;
- linking raster image processing to vector mapping and GIS applications;
- making mapping oriented image processing technologies available to educators and scientists, concerned with problems in e.g. coastal zone research and management;
- providing a path for PC software developments that will eventually enable the transfer of remote sensing, photogrammetry and GIS from highly specialized, costly technologies to a broad-based user community.

The principle of a desktop mapping system (DMS) is that map coordinates for ground control points (GCP’s) may be entered from the keyboard or digitized directly from a reference map. Determination of image coordinates to a fraction of a pixel governs the accuracy to which the image can be geo-coded (i.e. rectified): an important consideration for GIS applications. A least-squares solution of polynomial equations is then implemented to yield correction coefficients and to determine a root-mean-square error, indicating the fit between the image and ground locations of control points. Application of the correction coefficients on a pixel-by-pixel basis yields a geo-coded product, resampled (with cubic convolution, bi-linear, or nearest neighbour algorithms) to a pixel dimension of the user’s choice.

Hence, map compilation and revision can be achieved from digital data sets by the provision of an overlay of existing vector files with attached attributes from raster image data, and a method for editing the vector files in digital format. With DMS multi-sensor, multi-resolution, multi-temporal image files can be merged, using intensity-hue-saturation (IHS) algorithms. The output data of DMS can be used as input for e.g. volume estimation and hazard zoning by coastal change modelling. For this purpose the coast-line area is modelled as a set of voxels (volume elements) with the property “earth”, while the component of the volume under consideration (which is either eroded or accumulated) is “air”. Arithmetic operations, such as counting, lead to statistical parameters of which average volume loss and displacement may be relevant in coastal zone research. The result of set operations on sets can be visualised in pseudo- perspective or stereo.

2. STUDY AREA

Ameland is one of the six Dutch barrier islands situated north of the mainland Friesland (figure 1). Its long axis is approximately 24 km and its width varies from 1.5 to 4 km. The island includes three dune complexes: in the West the Hullumer- and Ballumer-, in the centre the Nesser-, Buurder- and Kooi-, and in the East the Oerd dunes. These dune complexes were originally three independent small islands, separated from each other by tidal gullies or inlets. During the last two centuries these islands were connected with dikes and today they form one island. In this century the tidal flats, formed at the southern sides and between the western and central dune complexes, were reclaimed to become polders which are now used as grassland. The tidal flat between the central and eastern dune...
complexes is still a salt marsh. East of the Oerd-dunes, spit-like bars and initial- and fore-dunes developed (and still develop). These suffer from wash-overs and other forms of marine and aeolian sand transport.

The western end of Ameland is, in its middle and southern part, subject to erosion generated by the east shift of the Borndiep inlet and, thus, this area has to be protected against corrosion by groins, fascine mattresses, artificial seaweed and rubble dams. The NW area, however, is protected and is aggraded by sand accumulation. The material, originating from the Borndiep ebb delta, has resulted in large, re-curved shoals and wide beaches.

The study area is situated in the middle of Ameland. The Survey Department of Rijkswaterstaat has observed that this area is most vulnerable to erosion. This would mean that the narrow width (artificially stimulated) dune area will be eroded and the island will fall apart into two or more small ones. This is socio-economically unacceptable. Hence, the Ministry of Transport, Public Works and Water Management has executed beach nourishment to smoothen the beach profile and to raise and widen the beach and thus protect the fore-dunes against abrasion. The erosion which has taken place between 1989 and 1992 is well visible in the data prepared by the Survey Department. The effects of the sand supplementation/beach nourishment can be recognized by comparing the sequential photographs of 1992 and 1993. With the help of the methods developed for 3-D desktop mapping, the volume changes are estimated for the period 1989-1991, and compared with the terrestrial and photogrammetric methods, which are standard for the Survey Department.

3. BUILDING A SPATIAL (3-D VOLUME) MODEL USING REMOTE SENSING (RS) DATA

3a. Spatial model

With the availability of better software tools, like object oriented languages, such as C++, and relatively cheap computing and storage capacity, it is worthwhile to try to solve the problem of spatial modelling from first principles, i.e. units of space with certain constant properties per unit of space over a time interval. From these definitions other tools for modelling are derived (Mulder, 1993).

Such a spatial model must have simplices, i.e. simple objects in the three-dimensional domain (3-D), which we call “voxels” or volume-elements, defined by an identifier, parameters and a property. Voxel classes can be irregular tetrahedrons, regular cubes with volumes $N^3$, or triangular prisms.

The space under consideration here (the coastal zone) is sub-divided into voxels on the basis of volume properties or attributes. The bounding surfaces between voxels with different properties are put at positions where the properties change most as a function of position, i.e. the maximum gradient grad (property $(x,y,z)$). In the case of coastal zone modelling, the most obvious change in properties occurs at the interface between earth, water and air. Changes in soil, rock or water properties also need to be modelled. The advantage of the volume simplex (voxel) approach over the traditional 2 1/2-D digital terrain model (DTM) approach is that there is no problem with vertical surfaces, overhangs, notches and caves, nor with the inclusion of the time dimension. In this respect, the time dimension is modelled through a change of voxel-property as a function of time.

In the case of modelling the surface between earth and air, the choices for simplex representation are:

- rectangular (square) prisms → classical digital terrain model (DTM)
- irregular prisms or tetrahedrons → triangular irregular network (TIN)
- 2nd order surface on triangular prism or tetrahedron, resulting in classes of voxels which are based on node parameters with polynomial interpolation (figure 2).

![Figure 2](image-url)
The simplices are all instantiated through the binding (fixing) of parameters for each simplex, or example voxel (16,32,48,8) = cube (at x=16, y=32, z=48, side=8).

As a consequence, the model is truly object oriented; it only has the class of a voxel; all other “things” are instantiation parameters, e.g. a piece of rock in an environment of non-rock can be described as: Segment (#1023, Tetrahedron(#1003), Block(#823), Triapism(#1063))rock). The relationship between the spatial model and RS images is one of projecting 3-D to 2-D RS data through a camera model, a model for the interaction of radiation with matter, and a model for the atmosphere. For example, when the radiation source is the sun, and the sensor a mono-chromatic frame camera, then we can predict an image by going through a simulation sequence (ray tracer):

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\text{Sun}(x,y,z) \rightarrow \text{Scene}(x,y,z,\text{size}), \text{reflectance} \rightarrow \text{Atmosphere}(\text{path length}, \text{scatter coefficient}) \rightarrow \text{Camera}(x, y, z, o, x, o, y, o, z, \text{ focal-length}) \rightarrow \text{Photo}(u,v,R) \rightarrow \text{Scanner}(\Delta u, \Delta v) \rightarrow \text{Image}(u,v,R)
\]

Mulder and Fang (1992), and Mulder and Schutte (1992) describe how real images compare with predicted images. The “difference” between predicted image and measured image produces an error image. For the whole image a cost of error (over various types) is calculated. In our basic research programme we aim for an automated solution of the problem of finding the minimum cost(parameters).

In the application of coastal (hazard) zones mapping, we use the same software environment (Mulder and Schutte, 1992), which allows the software supervisor/planner to bind some parameters and let others be found by the minimum cost-of-error parameter estimator. In the application experiment reported here, we have applied the automatic TIN generation method, followed by the interactive adjustment of surface patch parameters. The remaining parameters, like the camera parameters, can then be automatically incorporated, and should not concern the application expert.

For the representation of coastal zone voxels, we opt for a prism representation with vertical sides and triangular cross section. At the boundary between earth, water and air of the sandy coast of Ameland, we use linear surface patches; in the case of sand dunes, parabolic (second order triangular) patches are preferred. Further analysis, such as determination of eroded volume or transported debris, is rather trivial in a 3-D+time GIS, as the elementary objects are volume+property; this will be explained in section 4.

Comparison between our approach and the conventional DTM generation approach shows that our method removes a number of problems, introduced by trying to use 2-D CAD packages for 3-D+time modelling. Classical 2 1/2-D methods lead to justified complaints by application experts about its complexity in use and in documentation. Even object oriented programming does not take away the problems introduced by treating points, lines, polygons etc. as “objects”.

As our interface has an implicit comparison between the data and the model, the user can visually check the amount of error remaining in e.g. the refined TIN relative to the displayed stereo image.

### 3b. Available software

The goal is to instantiate a volume model of a coastal zone with selectable volume resolution at the active erosion or accumulation boundary. It is recommended, that minimum time should be spent on re-developing software, but some porting may have to be done from UNIX workstations to MS DOS PC’s.

For display and editing of contour lines overlaid onto stereo photographs in anaglyph display, we use the Desktop Mapping System/Softcopy Photo Mapper (DMS/SPM) version 3.1 (1991-1992), R-WEL, Inc. PC package. The transformation from contour lines to irregular triangles (top layer of triangular prisms) can be done through the TIN option in ARC/INFO (ARC version 6.1.1 (23 Dec. 1992), Environmental Systems Research Inst., Inc. The software for interactive refinement of triangular prisms is being developed in-house on a PC-based platform.

For the analysis of the data, we resample the data (1 pair per time interval) to the highest common resolution. The Cartesian cross product1 of the property (earth, air) gives the volume and distribution of \([\text{prop t1}, \text{prop t2}] \rightarrow [(\text{prop t1}), (\text{prop t2})] = [(\text{earth, earth}), (\text{earth, air}), (\text{air, earth}), (\text{air, air})].\)

The most frequent query will be to:

- Select-all \((\text{prop t1}, \text{prop t2}) = (\text{earth, air})\).
- display all selected voxels (anaglyph, perspective)
- Sum all selected voxels, report total volume lost.

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1. The set of all pairs from domain 1 and domain 2, if A∈A, B∈B and C∈C then C = A x B → C = (a,b).
4. VOLUME CHANGE ESTIMATION

The goal is to model the volume change of a coastal zone through a set of voxels with the voxel relation: identifier, parameters, property.

The lower surface of each prismatic voxel is bound to an arbitrary ground plane; the identifier. The top surface is to be defined by parameters (figure 3), while the property is “earth”, with the complement of the volume under consideration “air” (there is, in our example, no direct contact between earth and sea water).

Alternatively, the rough TIN can be generated from a set of $Z(x,y)$, obtained from commercial “stereo correlation” software, and the domain knowledge added later for refined parameter estimation.

4b. Improving volume estimation

In the linear surface approximation mode, the user, presented with a stereo display overlay of a pair of stereo photos and the rough TIN, will first edit the parameters (coordinates) of the raw TIN, using as criteria “volume fit” and “slope fit”.

Secondly, the triangulation will be densified in those areas where more precise information is needed, e.g. at an erosion front. The densification progresses in a quad tree or a tri tree fashion (figure 4).

4c. Estimation of volume changes

Time sequence analysis takes place by applying the set operations of e.g. intersect and union to the sets of voxels, e.g.: \{ voxel(-t0) \}, \{ voxel(-t1) \}. The result of the set operations can be viewed in pseudo perspective or stereo. The arithmetic operations, such as counting, will provide statistical parameters of which the average volume loss, displacement, etc. are most relevant in coastal hazard zoning (figure 5).

5. APPLICATION OF THE MODEL AND PROBLEMS ENCOUNTERED

The method described is being tested on the central-northern coast of Ameland, The Netherlands. Detailed topographic maps (scales varying from 1:5,000 to 1:25,000;...
contour lines .2 m.) and bathymetric (scale 1:2,000; contour lines 1 m.), sequential AP coverages (scales varying from 1:5,000 to 1:18,000) and reliable ground-control points are available. The test area is characterized by a sandy beach and fore-dunes which are subject to severe erosion by wave attack and the W→E long-shore current. The middle part of Ameland is particularly prone to flooding by sea water. Hence, in 1992, the Ministry of Transport, Public Works and Water Management executed beach nourishment in that part of the island. The beach became wider and the beach profile smoother, which implies that the fore-dune area will be less severely attacked by the (winter) storm waves. A part of the eroded beach sands will, however, be transported eastward and deposited on the shoals, beach and dune zones (washovers) of the eastern part of Ameland.

To estimate the volume changes the Survey Department has, for a small section of the study area, (i.e. central Ameland), created two DTM’s directly from the stereo photo pairs at an x,y resolution of 1.4 m. These were used, in combination with our TIN’s and sets of voxels, to determine volumetric changes.

One of the problems encountered by analyzing sequential aerial photography in our 3-D metric mapping method is that the coast-line retreat is not constant in time (erosion of the beach and foredunes or the cliff collapse may not happen for years) and that vegetation growth and new man-made constructions obscure the “natural” cliff changes, hindering change detection. A second problem is related to the resolution of the AP’s and DTM’s used, as compared to the rate of beach and fore-dune position and volume changes. The AP resolution is in the order of .2 to .6 m. (1-2 K of the flying height) and that of the topographic/bathymetric maps c.q. DTM’s is in the order of .3 to 1 m. Digitizing the AP’s on 300 to 800 dpi level, however, will imply that the resolution drops 4 to 2 times, respectively. This means that the stereo DTM updating method, in combination with digital annotation of the thematic mapping unit boundaries, has an accuracy between approximately .4 and 2.4 m., depending on the original photo scale and photo scanning. If sequential AP’s with an interval of 1 to 5 years are used, and the average yearly cliff retreat in these periods is about 1 m. (which means in total 1 to 5 m., respectively), then the mapping accuracy is only slightly better than or equals the default limit of the method. In the last case, the data are not accurate enough to be applied for volume change estimation and hazard zoning. In our test zone the beach and foredune retreat is approximately 1 to 6 m. per year, depending on the local wind- and wave climate conditions. A simple and cheap solution to the resolution problem with a given, e.g. 800 bpi, scanner is to scan the relevant sections from enlarged prints (combined with scanner calibration), thereby providing sufficient accuracy to measure the changes to an acceptable detail.

A third problem is induced by the limited editing functions of the DMS/SPM software package. The interactive editing of the grid based DTM is restricted to grid point operations. Flexible editing facilities, including application of surfaces with gradually changing elevations are not available. As a result, estimation of volumetric changes depends mainly on the (in)accuracy of the automatic DTM extraction procedure.

To improve the overall method, modelling the coastal zone changes can be a solution. Where severe beach and fore-dune retreat is expected the refined parameter model is applied. The expected retreated coastline, as calculated from the model, is thus compared with the likely position of the coast-line as mapped from the sequential AP’s. In this way, future measurements will be restricted to the vulnerable sites.

The desktop approach could be improved by the development of an anaglyphic TIN editing and TIN refinement software package, enabling the user to edit a coarse DTM, and refine where necessary.
REFERENCES


