Interpolation and Contouring of Sparse Sounding Data

By Hans Werner Schenke
Alfred Wegener Institute for
Polar and Marine Research
Columbusstrasse
D-27568 Bremerhaven
Germany

email: schenke@AWI-Bremerhaven.de

Executive Summary

The back of the moon and the surfaces of most planets of our solar system are better mapped than the seafloor topography of our own planet. There are several reasons for this. The main reason is that the seafloor is invisible and thus sonar signals must be used to pass through water as the medium in this case and measure the depths of the oceans. Another reason is that the inhospitable polar regions of the Earth can only be safely visited by ships during the short summer seasons. Thus, large regions of the northern and southern oceans remain "white spots" and their topography is widely unknown. At low latitudes expeditions can be performed year-round, sounding data can be recorded "en-route" and used for ocean mapping.

Digital Terrain Models (DTM) are widely used by many different disciplines in a broad spectrum of applications. Thus, a major task is to develop techniques to determine DTMs on the basis of primary soundings, existing contour charts or terrain models. Auxiliary information for the creation of a DTM can be obtained from satellite radar altimetry data. Variations of the measured sea surface heights over the geoid or of the gravity values can be related to changes in the seafloor topography or to density variations in the Earth's upper crust. The modelling approach presented in this paper has been used at AWI for several years. Results from three mapping projects in the Arctic and Antarctic are presented here. They document the validity of the chosen contouring approach in areas of sparse data.

1. Introduction

The largest part of the solid Earth's shape, the ocean floor, which covers more than 70% of the earth's surface, is invisible and thus its topography is widely unknown. It is not without reason that humankind has tried from time immemorial to lift the veil from the "myths and secrets of the invisible deep ocean floor". Philosophers, seafarers, natural scientists or explorers were borne by their strong desire to make the seafloor visible, to map the topography in order to answer questions about the Earth's geological history. However, until the beginning of the last century measuring the ocean depths was only possible with lead lines or stakes, creating spot soundings.

After the end of the First World War, sonar techniques were developed and used for measuring depth profiles across the oceans and the seas. Since the mid-20th century, approximately beginning with the Geophysical Year 1958, systematic surveys with parallel lines have been conducted for seafloor surveying. Finally, it is only 25 years ago that multibeam sonar techniques were introduced for hydrographic and scientific surveys, allowing full coverage and thus compilation of reliable large-scale charts of the ocean floor.

Since the seafloor is not visible, morphologically oriented surveys as on the dry land cannot be performed on the ocean. In order to map the complete topography with all features corresponding to the anticipated scale, a systematic survey without any gaps must be

performed. But in reality coverage of the world's entire oceans with multibeam is not possible in a foreseeable time frame.

However, various scientific disciplines need mathematical descriptions of the seafloor for modelling, mapping and visualising for their investigations today. Surfaces such as the surface of the ocean floor are continuous phenomena rather than discrete objects. To fully model the surface, one would need an infinite number of sample points, which would in turn require infinite data storage, even nowadays an impossible task for any digital system. Thus, in order to represent continuous surfaces (continuum) in digital form, a finite number of surface elements, and therefore a finite amount of storage, is used. Digital terrain modelling techniques have emerged to meet this demand. The term Digital Terrain Model (DTM) is generally used to refer to a digital representation of the topography from the Earth's surface as well as from the seabed. A DTM can be defined as a simplification of the real world in computer-readable form (Hake und Grünreich, 1994).

The DTM generation is based on sampling of original terrain data. The choice of data sources, the terrain data sampling techniques, and the density and distribution of sample points are crucial for the resolution and quality of the resulting DTM. DTMs are used nowadays not only in Geographic Information Systems (GIS), Remote Sensing and Geosciences, but also in climate modelling, ocean circulation studies, and modelling the solid Earth's surface and its interior. Major areas of application include terrain analysis (slope, aspect, drainage network), visibility studies, and visualisation (Schenke, 1989).

Visualisation plays a vital role in communicating the content of the DTM to the user, interactive visualisation that helps researchers to explore or refine the model, and static visualisation to present and display the result. Contour lines are still the most widely used techniques for displaying a relief, though the major drawback of contour lines is that they give no immediate impression regarding the topographic forms.

Relief shading, perspective views and combinations with 2D data are important visualisation techniques for improving the visual quality of a map and supporting the scientific interpretation.

2. The ocean mapping problem

The topography of the ocean floor is characterised by extremely different morphological structures, which were formed by exogenous (sedimentation, erosion, chemical interaction, living organism) and endogenous (tectonics, volcanism, seafloor spreading) processes. The oceans can be divided into three major regions: the continental margin, the ocean basin floor, and the mid-ocean ridges. Whereas in general the ocean basin floor requires no dense coverage of sounding lines due to the flat and smooth morphology, the continental margins and the mid-ocean ridges must be surveyed with full coverage in order to gain a full assessment of their complex topographic structures and to produce accurate large-scale bathymetric charts.

Today only small parts of the ocean floor are surveyed with full coverage and adequate accuracy. The surveys conducted by research vessels (R/V) or hydrographic survey ships concentrate mainly on selected areas that are of special scientific interest. During their transits the R/Vs only perform single beam sonar recording in most cases. The majority of the data is transferred to the IHO Data Centre on Digital Bathymetry (DCDB) in Boulder, CO. However, the spatial distribution is uneven and patchy, most of the track lines concentrate on the transits between major harbours. In particular the southern and northern oceans show many data gaps and widely spaced track lines. The situation is even worse in ocean areas covered with sea ice. These "white spots" shown on the Global Bathymetric Charts of the Oceans (GEBCO) were frequently visited by ice-breaking R/V's during the past years. At any rate, it may take another several decades until enough data are available to compile homogeneous bathymetric charts on those areas.

During the last years two areas with sparse sounding data were investigated in the framework of polar ocean mapping programmes at the AWI:

1. The Weddell Sea, Antarctica
2. The Arctic Ocean.

Both regions are subject to year-round ice coverage, thus resulting in a significant lack of depth data. For example, only few track lines run across the central Weddell Sea or the Arctic Basin.

Depth sounding has a long history in science as well as navigation. After the development of the Kelvin-White sounding machine in the mid-19th century, regular depth measurements were carried out by hydrographers, which led to the first crude ocean floor maps at the end of that century. Following the invention of the echo sounder just before the World War I, the first systematic surveys were performed in the mid-twentieth, for example by the R/V "Meteor" in the South Atlantic.

The accuracy of bathymetric chart products depends directly on the accuracy of the depth measurements in conjunction with the positional accuracy of the ship. Over the last 50 years the positional accuracy has improved from +/- 5 km (celestial navigation) to +/- 500 m (TRANSIT integrated dead reckoning) and then to better than +/- 15 m (GPS-SPS) today. This chronology explains clearly the heterogeneous data quality that we find in the databases. However, in areas that are rarely visited by ships, it is not suggestive to discard the "old" depth measurements; rather, it is necessary to combine them with "newer" soundings, taking into account both their positional and sounding accuracy. This combination is a difficult approach, which cannot be solved with the help of modelling software alone; auxiliary data such as depth information derived from satellite altimetry, must be utilised to check the quality and support the modelling (Udintsev, 2003).

For the determination of submarine DTMs, standard parameters for the modelling process such as search radius, fitting surface, weighting, and filtering, cannot be supplied, especially if the distribution of sample points is irregular and large gaps exist in the data set. These parameters have to be derived during the determination process.

In general the assumption of normal distribution of the measurements is not valid for this kind of bathymetric data since the data density is maximal along the ship's track and minimal in the orthogonal direction. DTM modelling generally requires random point distribution in a density that corresponds to the projected mapping scale and depends on the seafloor morphology. However, in many cases the high density of the sample points along the track lines creates noise in the contour lines in particular near the tracks. A reduction of this impact can probably be achieved through variation of the search or selection criteria or special filtering procedures.

3. Use of Digital Terrain Models in Bathymetry

DTMs have been used at the AWI for modelling the topography of the ocean floor for twenty years. Determination of a DTM is generally based on depth measurements at known positions, creating three-dimensional coordinates of the target points on the seafloor. The density and distribution of the sample points is generally be used to define the geometric structure of the DTM. In the case of a high density of measurements, for example from a multibeam sonar system, a TIN (Triangulated Irregular Network) should be utilised as the basic DTM to determine the contour lines or perform terrain analyses (Buziek, 1994). If gaps exist in the data sets, gridded models should be used in connection with sophisticated interpolation functions.

The AWI has operated its ice-breaking research vessel "Polarstern" in Arctic and Antarctic waters for more than twenty years now. However, the bathymetric database is still far from complete. Especially in the regions of massive year-round sea-ice concentration in the western part of the Weddell Sea and in the Arctic Basin, large areas are unsurveyed or only passed by single tracks. This situation requires special attention in connection with DTM

modelling. Systematic surveys with complete area coverage have been performed only in selected areas, for example in the Fram Strait (Klenke and Schenke, 2003), and in the Porcupine Bay (Beyer et. al. 2002), where TINs were used for DTM determination. Most of the bathymetric surveys have been performed in deep waters. Due to the uneven and non-uniform movements of the ship, especially in ice, the data point distribution is inhomogeneous and contains larger gaps, caused by data errors or track planning. Thus gridded DTMs are generally used for this type of database. In any case, the need for a reliable interpolation method is essential for densification and regularisation. When smoothing or generalisation is required, a suitably controlled interpolation algorithm must be employed. Several interpolation schemes ranging from simplistic to elegant have been studied and investigated at the AWI. Some of them are briefly discussed in the following.

3.1 Method of "moving surfaces" TASH

This method was developed at the University of Hannover for modelling the terrain relief based on conventional survey methods and adopted for use in bathymetry (Claussen and Kruse, 1988). The kind of data distribution and the planned scale of the chart generally define the grid size. The three-dimensional coordinates of the sample points are used as input for the modelling process. The program calculates a regularly spaced grid in the ground plane (x, y) from the stochastically distributed sample points. To derive the DTM, the depth of each grid point, as represented by the height, has to be calculated. In this modelling approach the method of "moving surfaces" is used, whereby the terrain around each grid point is approximated by a fitted surface. The equation coefficients of the surface are generated by a least squares adjustment. Its parameter a_0 directly represents the height of the grid point.

The following four mathematical functions are utilised to obtain optimal results for different morphological relief types:

Elliptic Surface: $z_i = a_0 + a_1 x_i + a_2 y_i + a_3 x_i y_i + a_4 x_i^2 + a_5 y_i^2$

Hyperbolic Surface: $z_i = a_0 + a_1 x_i + a_2 y_i + a_3 x_i y_i$

Oblique Plane: $z_i = a_0 + a_1 x_i + a_2 y_i$

Horizontal Plane: $z_i = a_0$

One of these surfaces can be chosen by the user or automatically by the program. For the latter an elliptic surface is calculated first. If the standard deviation (S.D.) of the adjusted grid point exceeds a pre-defined value, the determination of the grid point must be repeated using the next lower polynomial function until the required S.D. is achieved.

Contour line points are determined through linear interpolation along the grid lines. These points are regarded as vertices of a polygon and the final contour lines are determined by fitting them to 5th order polynomials.

This DTM program was very successfully used for the creation of large-scale bathymetric charts (1:50,000 in 4000 - 5000 m water depth) from high resolution multibeam sonar data.

3.2 Height Interpolation using Finite Elements (HIFI)

The interpolation with finite elements is a numeric solution of differential equations (Ebner, 1980). A bi-linear spline function is applied to each raster element. The combination of all raster elements leads to the interpolation surface. This surface contains all sample points and has minimum curvature conditions. A local bi-linear spline function is applied at each raster point $P_{i,j}$ (Fig. 1).

The height h_k of a sample point P_k with the coordinates x_k, y_k in a certain grid element with the raster points $P_{i,j}$; $P_{i+1,j}$; $P_{i,j+1}$; $P_{i+1,j+1}$ can be put in a linear function of the four surrounding raster heights $h_{i,j}$, $h_{i+1,j}$, $h_{i,j+1}$, and $h_{i+1,j+1}$, and the accompanying coefficients are linear functions of the local coordinates Δx_k and Δy_k.

This software was mainly used for large-scale modelling in conjunction with terrain and relief analyses. HIFI was developed for photogrammetric application and not for marine mapping. The computation time was very high when using multibeam data as sample points.

However, the derived DTM and the terrain analysis were of very high quality. Due to the long processing time this software was not used further.
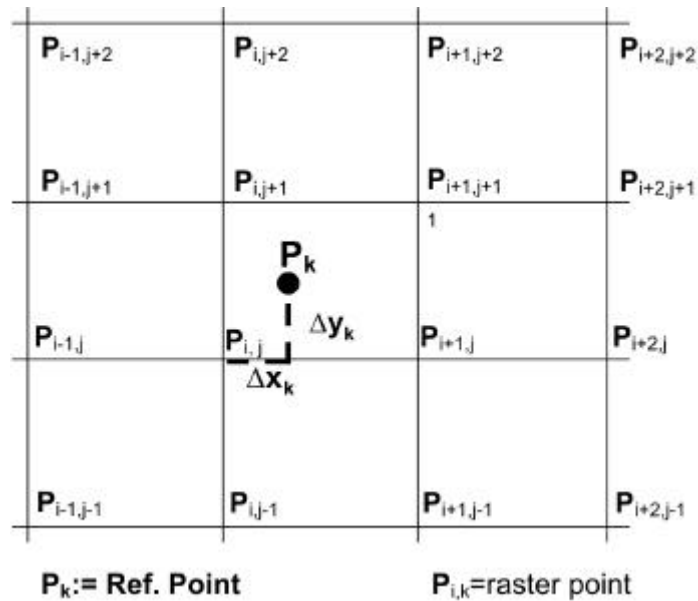

Fig. 1: Scheme of coordinate system used with the finite element method

3.3 Kriging

Kriging is an estimation technique based on geostatistics and used to interpolate preferably between normal distributed sample points of a semi-random type of surface (topography, bathymetry, land gravimetry, etc.). For hydrographers, the most important issue is that kriging specifies the sample points, which means that soundings are kept fixed and are not adjusted to fit some ideal mathematical surface (Herzfeld, 1989,) .

The concept of kriging is based on using subsets of the measured depths to determine a so-called semi-variogram, which generally reflects the terrain roughness of the studied area. The idea behind interpolation by means of kriging involves a combination of deterministic and stochastic elements which are applied to each interpolated value. The deterministic element is simply the calculated value from a least squares surface fit to the sample points, and the stochastic contribution is taken from the semi-variogram to interpolate the value at the grid position. The main advantage of kriging is that a realistic covariance matrix can be determined for the grid, supplying reliable error estimates for all grid points.

Kriging was used for large-scale mapping in areas with 50% to 80% data coverage. However, the computation time was also extremely long, and a new semi-variogram had to be determined for each grid point.

3.4 Bi-cubic spline interpolation

This approach is probably the most widely used interpolation method worldwide. The algorithm was developed by C. Briggs (1974) and translated into FORTRAN language by C.J. Swain (1976). The method produces a grid of values which approaches the smoothest surface passing through the sample points. To achieve this goal, the program solves differential equations, which are derived from the requirement of minimum total curvature for the surface at the grid points. The differential equations are solved in an iterative process.

This approach is optimal for potential field data (gravimetry, magnetics) and for relatively smooth topography. However, the topography of the seafloor is smooth in most cases due to the genesis and does not often show cliffs, steep scarps or extreme ridges. The use of this software was adequate in most applications for scales smaller than 1:250,000.

The data distribution plays a significant role. If the point distribution is not isotropic, as with single narrow beam sonar (NBS) data from ship tracks, the resulting contour lines in areas with pronounced topography may show peculiar behaviour.
However, for the combination of data from different quality and source, a modification of the bi-cubic spline program GIRA (Schenke et al., 1998) was successfully used for years, mainly for the generation of small-scale sheets (<1:500,000).

4. Database for seafloor mapping in ice covered oceans
In large regions of the polar ocean that are covered continuously by sea ice, only few tracks from research vessels (multibeam) or from icebreakers (single beam) are available. Furthermore, in most of these regions no spatial surveys have been or will be conducted since the research icebreakers are not survey ships and also ice barriers may prevent systematic surveys. Thus it is imperative to use all available data for modelling the seafloor topography. The following sets of bathymetric data plus auxiliary information are used to determine DTMs for map contouring and relief analyses.

a) <u>All available NBS and multibeam data in the charting area</u>
Digital and analog data are quality controlled (QC) and included in a database. An estimate of the positional and sounding accuracy is applied to the depth values.

b) <u>Original soundings that were used for contouring earlier GEBCO sheets</u>
Sheet Editors are asked for the original soundings they have used. If data in the form of recordings or plotting sheets are available, they are digitised and after QC incorporated into the database

c) <u>Intersection points between GEBCO contour lines and the track lines as pseudo depth measurements</u>
In regions where no original data are available, the intersections of contour lines and ship tracks are determined. The accuracy of these pseudo sample points is estimated.

d) <u>Bathymetric charts from other organisations</u>
Small-scale or large-scale bathymetric charts in selected research areas may be available from other national or international institutions. If the contour lines are available in digital form, a DTM can be determined and used for combination with new data.

e) <u>Nautical Charts (NC) from Hydrographic Offices</u>
In most cases NCs contain only a small number of soundings. In general, spot soundings are noted in NCs in near-coastal shallow waters where they are important for the safety of navigation. Since most NCs are not digital in those regions, the depths are digitised, qualified and included in the database.

f) <u>Morphological information of the seafloor predicted from satellite radar altimetry</u>
With the advent of several satellite altimetry missions in different orbits and with improving tracking and measuring techniques over ice, the quality and quantity of RA data has improved significantly. Especially the ERS-1/2 data have contributed substantially to the knowledge about the structures of the Earth's upper crust and the morphology of the seafloor. Combined products from several satellite missions have dramatically improved spatial insight into large tectonic structures. Combination with bathymetric data and sedimentation models resulted in a transfer function used to predict ocean depths in a resolution of a few miles.

g) <u>Free-air gravimetry from satellite radar altimetry and from airborne gravimetry</u>
Linear trends of plate boundaries, fracture zones and topographic structures on the seafloor can be recognised and their spatial expansion can be studied from RA free-air gravity anomalies and can therefore be used for morphological interpolation and extrapolation of depth measurements on the high seas.

h) <u>Information from ship-borne or airborne gravimetric and magnetic anomalies</u>
In addition to satellite radar altimetry, data from research vessels can be utilised to support and strengthen the modelling of the seafloor topography. Marine gravimetry can be used to ground-truth the satellite-derived gravity data, whereas magnetic anomalies could help to verify and scientifically explain certain structures of the Earth's upper crust, detected from RA data.

5. Procedure of ocean mapping in areas with sparse data

The AWI has many years of experience in map production in polar regions where the data coverage is poor. Due to ice coverage or weather conditions, systematic surveying is not possible in most cases. Thus the distribution of track lines is generally random, in other regions the survey lines may follow prominent morphological features. Often large gaps of tens of nautical miles remain, and must be filled by extrapolated data using meaningful methods. The working process used at AWI is shown in the block diagram in Fig. 2.

In the mapping area all available data are collected, quality checked and organised in a database. The postprocessing of the data sets encompasses the positional data and the measurements. Together with the multibeam data, other ship-borne measurements such as attitude and sound velocity data must be checked and verified in order to avoid any errors or conflicts. Wherever possible, cross-over comparison or even adjustments are performed in order to avoid systematic jumps or offsets. Track lines, navigated with GPS, are considered to be more accurate than those using TRANSIT-Satellites and dead-reckoning.

At first, a coverage plot supplies an overview of the data distribution and density. Then it must be decided how to fill the remaining gaps. If the existing GEBCO contours are based on a dense net of tracklines, the contours could either be utilised to determine a new DTM, or if the original data are available, they could be merged directly after verification with the new data.
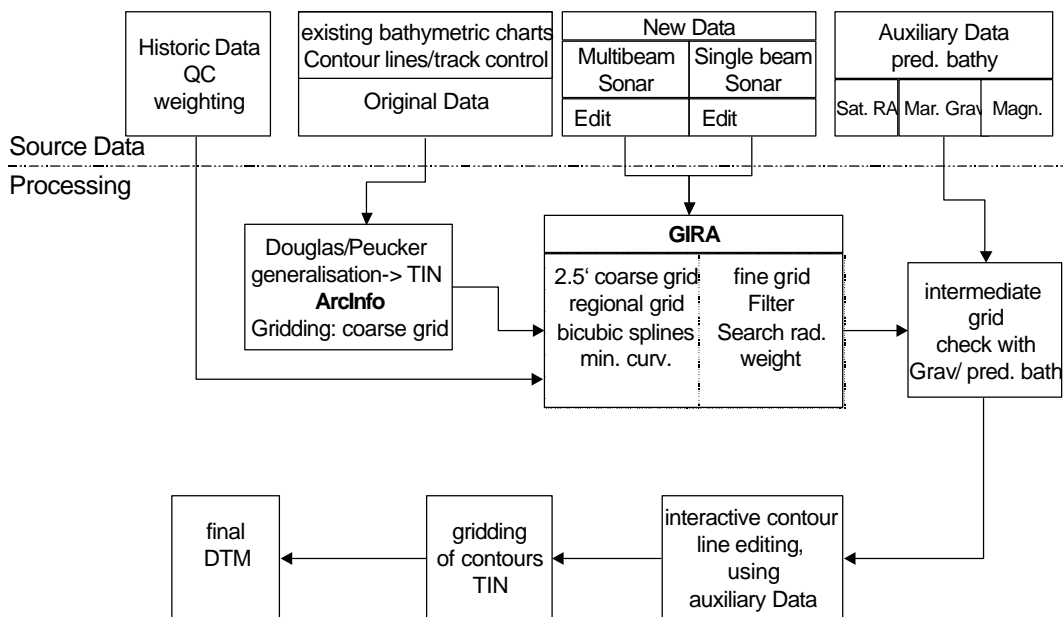

Fig. 2: Flow diagram for ocean mapping in sparse sounding data regions

The determination of a DTM from contour lines is carried out using ArcInfo tools. The steps needed to generate a grid are:

    a) Transformation of contours and coastlines to a specific map projection
    b) Generalisation of the contours and coastline
    c) Creation of a Triangulated Irregular Network (TIN)
    d) Making a lattice out of the TIN.

All objects within the sheet have to be transformed into a common map projection. The extension of the charting area and its geographic position must be taken into account. For example, when covering a large area at high latitudes, the Lambert conical projection could be meaningful. Contour lines and the coastline are built up with arcs between nodes. These arcs would create a large number of vertices, resulting in a long computation time and considerable disk space requirements. It is thus useful to generalise contours and the coastline. The Douglas-Peucker algorithm, analysed in Kumler, 1994, is utilised for the generalisation

process by applying appropriate threshold distances. After the generalisation process all remaining points on the contour lines are triangulated in order to create the TIN. Finally a regular grid is determined from the TIN by simple linear interpolation on the TIN. It was demonstrated with different sets of contour lines that DTMs created using this procedure are of high quality. Even in the abyssal plains of the deep oceans no systematic or significant terracing effects were observed.

Such a DTM is used as a secondary or regional grid for the combination with new data of higher resolution and quality. The grid size of such final DTMs ranges between 0.5 and 3 km, depending on the quality of the original data.

The DTM calculation is generally performed using the GIRA program (Schenke, et al., 1998). GIRA is a program package which at first determines a regional grid from different bathymetric data (multibeam, sounding profiles, discrete depth measurements, or grids). This coarse grid in the second step is merged with actual measurements using bi-cubic spline interpolation to obtain the final gridded DTM with minimum total curvature at the grid points.
In order to account for the varying accuracy and quality within the data sets, special routines were included to apply proper weight to the observations.
If the mapping project covers large regions like the Weddell Sea, the working area is subdivided into regions of different morphological structures and different data densities to allow appropriate modelling approaches. For each area individual model parameters (grid size, weighting, filtering, smoothing, etc.) are chosen for the DTM calculation in order to account for special regional conditions such as data density or topography roughness of the terrain. Contour lines interpolated from the grids are analysed and investigated with respect to their morphological and topographic accuracy.

In regions without any bathymetric information, as in the western Weddell Sea or in the Amundsen Sea, additional information can be extracted from satellite radar altimetry. However, in ice-covered regions the use of satellite RA is limited due to the low quality of the signals. Special retracking algorithms used to analyse the RA wave from data obtained from the ERS-1/2 missions (Laxon and McAdoo, 1994) and new filtering techniques (Schöne und Schenke, 1997) were developed in order to determine representative free-air gravity models in the polar regions (Fig. 3).
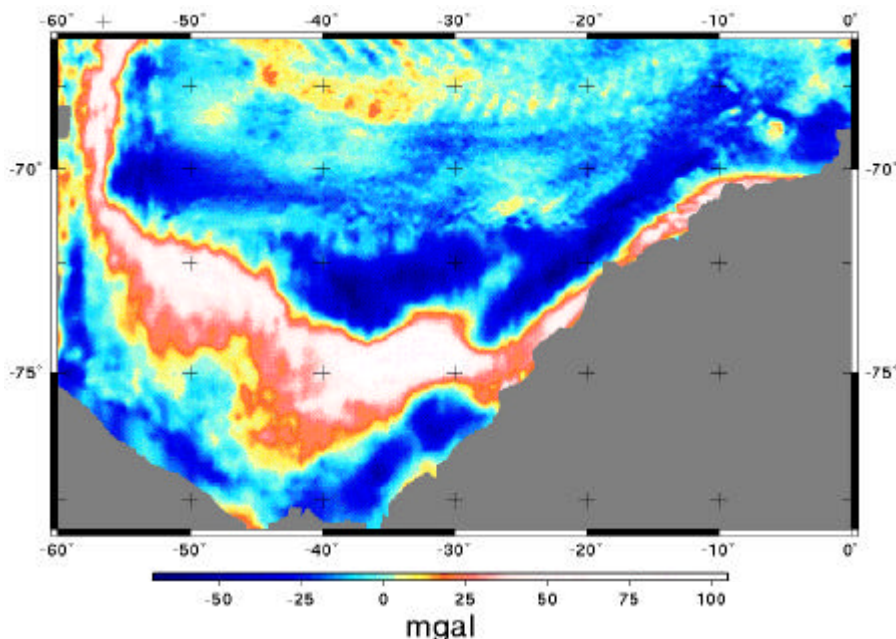

Fig. 3: Free-air gravity anomalies from ERS-1/2 (Schöne, 1997)

This information was used especially in the south-western region of the Weddell Sea to draw the contours. In other regions the "predicted bathymetry", which shows a good correlation with morphological structures on the seafloor, was utilised to support the contouring process (Sandwell and Smith, 1997, Schöne and Schenke, 1998). A good example about the comparison and correlation between the predicted bathymetry (ETOPO2) with results from a multibeam system is shown in Fig. 4. The area shown in this 3D-view is situated in the SE-Pacific and covers the Freeden Seamount in the area of the Eltanin Meteorite Impact.

The final contouring is performed manually, by visually comparing the contours from the DTM to the shape of the gravity field or with the "predicted bathymetry". Gravity anomalies are a composite of the density and the extent of topographic features on the seafloor. Ship-borne bathymetry and gravity measurements are utilised to determine a transfer function between altimetry and bathymetry. Comparing both data sets is useful to improve the interpolation of depth contours and also to detect erroneous depth measurements.
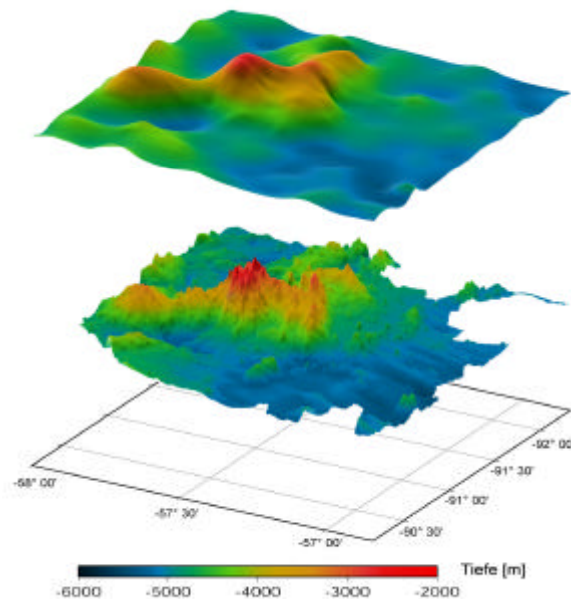
Fig. 4: Visual comparison between DTMs from multibeam and ETOPO-2 data (top)

The model analysis and the final correction of the bathymetric contours are conducted using an interactive editor. Finally the edited contours are gridded. This final DTM is used for general contouring, relief analyses or detailed marine geoscientific investigations.
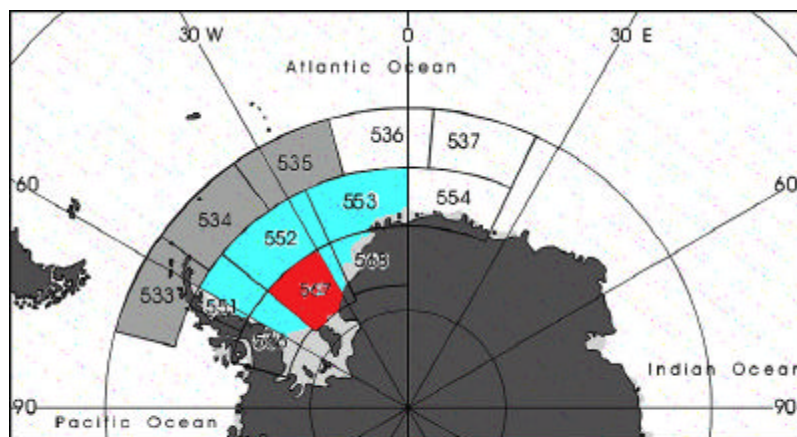

Fig. 5: Scheme of the AWI Bathymetric Chart of the Weddell Sea

6. Examples:

AWI Bathymetric Chart of the Weddell Sea (BCWS)

The creation of the 9 sheets AWI BCWS (Fig. 5), which took place during the last five years in collaboration with the Vernadsky Institute in Moscow, is an impressive example of bathymetric mapping in regions with sparse data. The compilation process is well described in Hinze, 1994 and Schenke et al., 1998. The BCWS sheet 567, which covers the region of the Filchner Trough (Fig. 6), is used to demonstrate the validity of the utilized procedure.
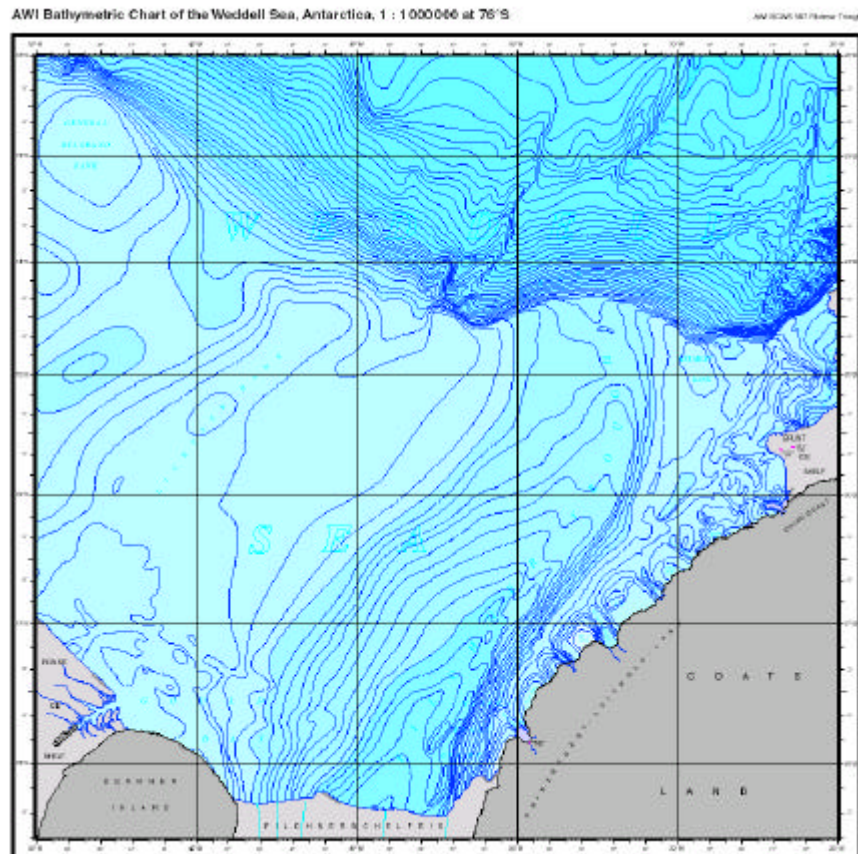
Fig. 6: AWI Bathymetric Cahrt of the Weddell Sea, No. 567, Filchner Trough

Sheet 567 represents a region with varying data distribution and density. Some parts are well covered by single beam and multibeam data, and others contain no sample points at all. The map was compiled in a similar form as describe above.

In order to make the sheet useful for scientific users as well as for hydrographers, the map contains extensive information in the complex legend concerning data coverage and sources and about the positional accuracy of the contours. This enables the user to evaluate the quality of the map.

Areas where other information besides soundings was used for contouring can be identified on the relevant side map (Fig. 7a) which shows the source data distribution on the sheet. Special focus was placed on the evaluation of the estimated accuracy (Fig. 7b). The mathematical formula used for the determination is also given on the map.

In the south-eastern section along the Antarctic continental shelf and along the Filchner-Ronne Ice Shelf system, a large amount of bathymetric data was available for the DTM determination. However, in other regions, such as in the north-western part, only a very small number of depth measurements was available.

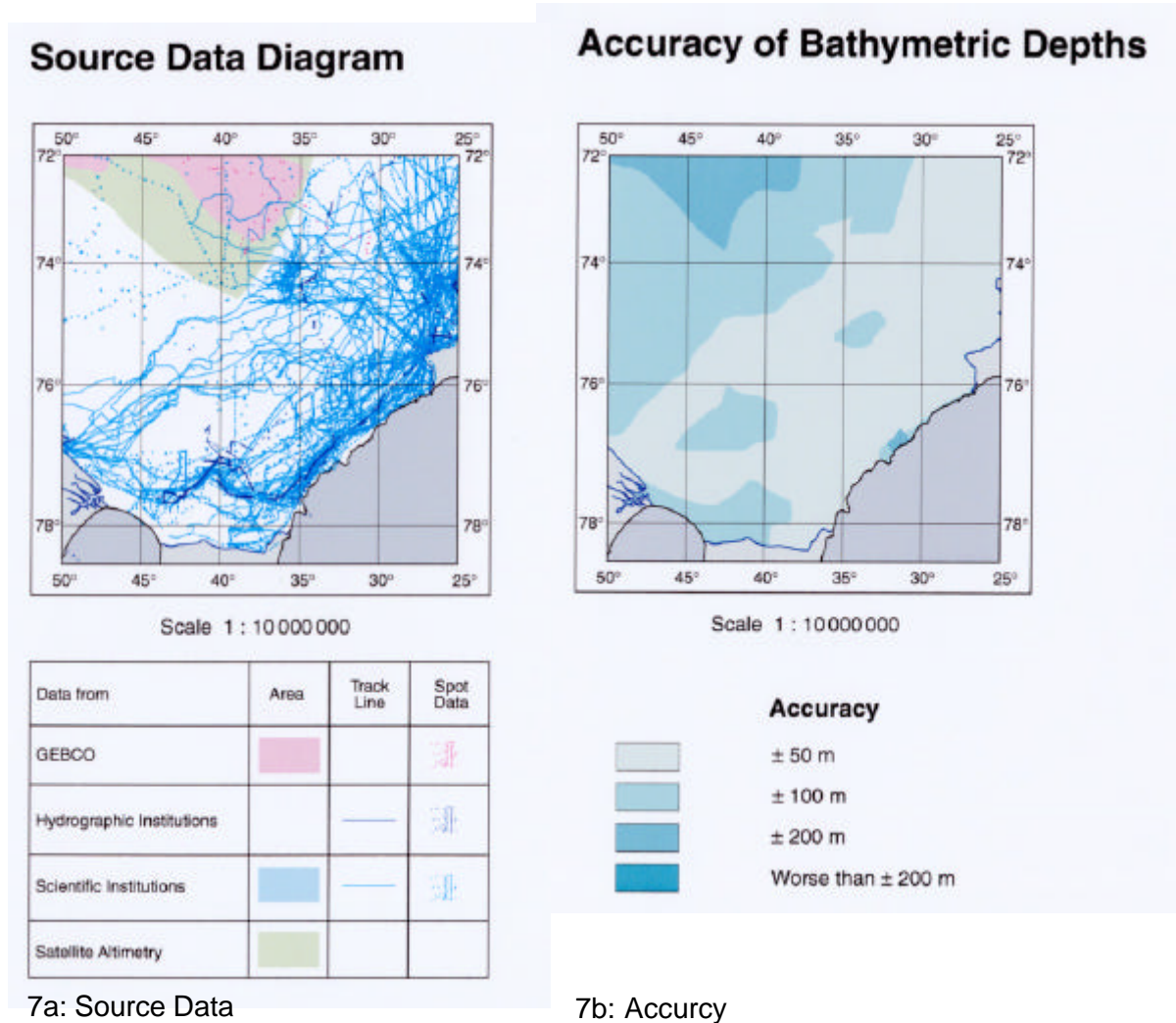7a: Source Data   7b: Accurcy

Fig. 7: Side maps indicating the accuracy and source data of the contour lines on sheet 567

In this region special attention was given to different data quality since the data from other expeditions or hydrographic surveys were extremely erroneous. Information from satellite altimetry was drawn up to support the interpolation of the contours in the north-western regions of this map (Fig. 6). It can clearly be observed that the morphology in this region is smooth. It can be seen from Fig. 7a that only a little of soundings exists in this region. Thus information from the gravity data was used to support the interpolation and modelling of the bathymetry. Fig. 8 shows the free-air gravity anomalies, the bathymetric contours are in 500 m equidistances overprinted. The agreement between the gravity field information and the bathymetry is excellent also in regions where soundings exists.
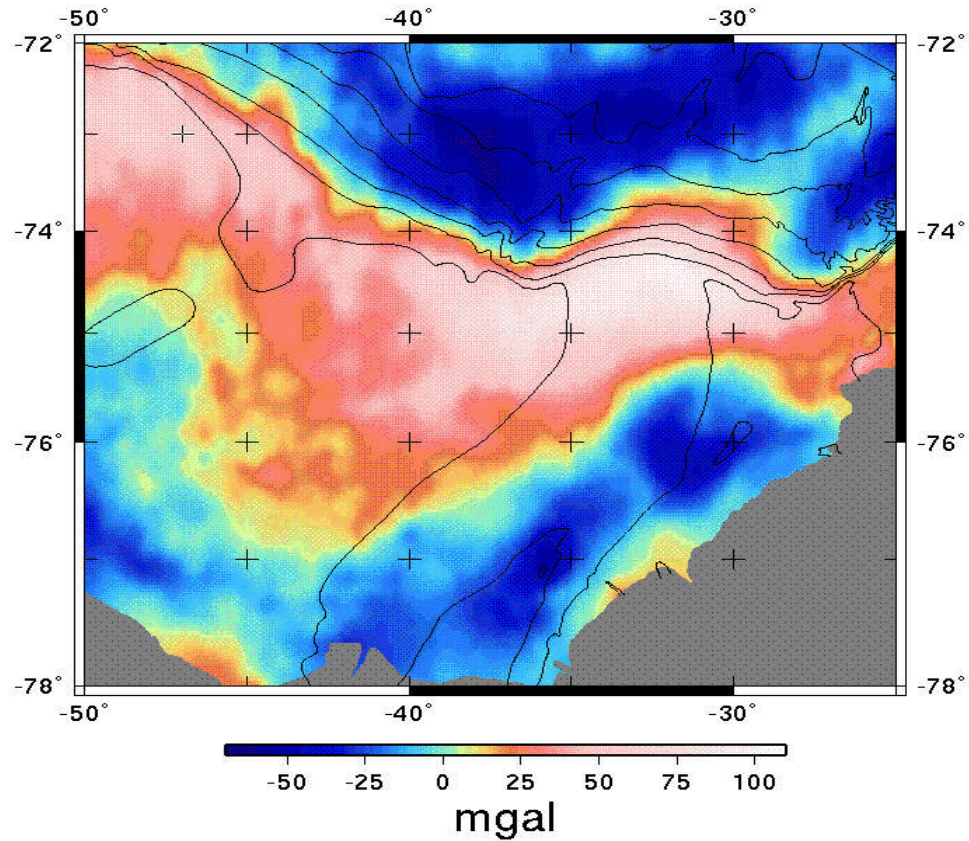
Fig. 8: Free-air anomalies from ERS-1/2 with bathymetric contours in 500 m interval

Southern Weddell Sea
In order to demonstrate the capacity and usefulness of GIRA for modelling in regions with sparse data, a set of multibeam sonar data collected by "Polarstern" was selected in the southern region of the Weddell Sea.

This region is marked by some characteristic topographic features, such as scarps and flat bottom. In this region bathymetric information exists from the AWI Bathymetric Charts of the Weddell Sea (AWI BCWS) (Schenke, el al., 1998). From these contour lines a DTM with a grid size of 2.5' by 2.5' was determined using ArcInfo tools as described in section 5 (Fig. 9a). Figure 9a contain 200 m contour lines. On the right, Fig. 9b, displays the swath coverage from the multibeam lines, and the final DTM, which is shown here as contour lines. The contour lines are relatively smooth in areas without data, but their trend follows morphological principles. However, this result also documents that real measurements cannot be replaced with models or interpolated depths.
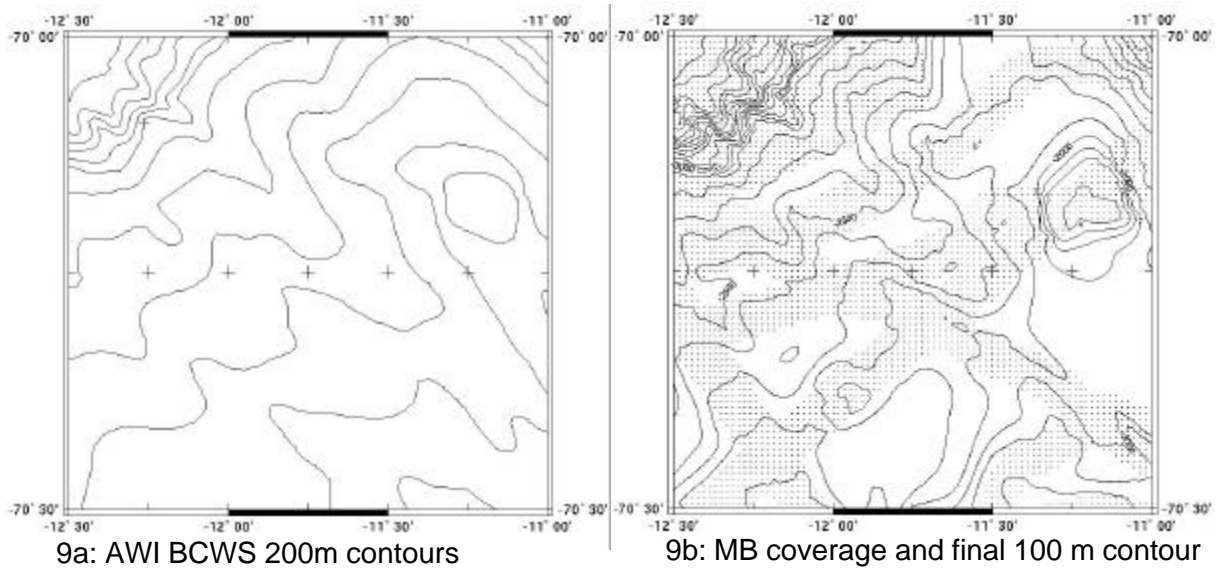
9a: AWI BCWS 200m contours
9b: MB coverage and final 100 m contour

Fig. 9: Combination of existing contour lines from GEBCO with new Multibeam data

Eastern Fram Strait

In the past years "Polarstern" has performed a large number of expeditions east of the central Fram Strait along the continental shelf off Greenland, during which single beam and multibeam data were collected. The track lines are irregularly distributed. However, on the ARK XVIII/2 expedition multibeam data were collected simultaneously to seismic surveys, the tracks were organised in parallel lines with a spacing of 10 to 15 nautical miles (Fig. 11a). This data set including old "Polarstern" data will be used to compile three new charts (Fig. 10a) on a scale of 1:400,000 as an extension of the AWI mapping project AWI Bathymetric Chart of the Fram Strait (Klenke und Schenke, 2003).
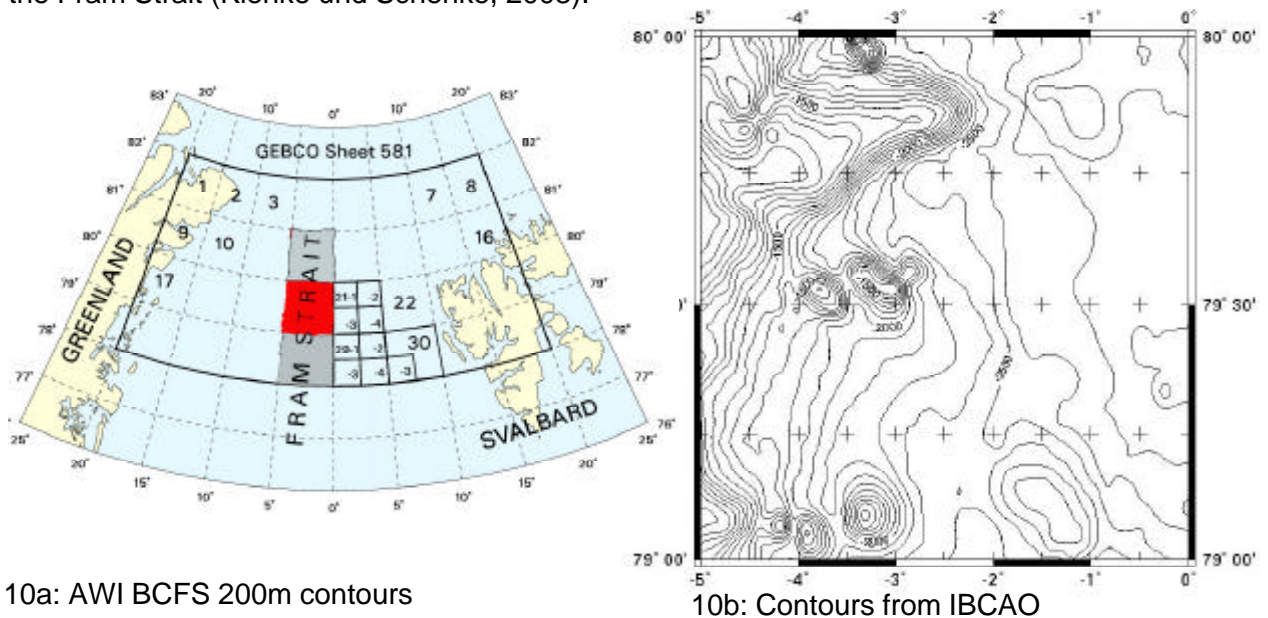

10a: AWI BCFS 200m contours
10b: Contours from IBCAO

Fig. 10: Working area between the central Fram Strait and Greenlang

The sheet marked with red colour is used in this investigation. Since relatively large gaps remain (Fig. 11a), the GIRA software was used to determine the DTM based on corrected and edited sonar data. In order to fill the gaps it was planned to use either the IBCAO grid or contours (Jakobsson, M., et al, 2001). It can be seen (Fig. 10b) that the IBCA contours. However, large differences exist between the IBCAO and the measured soundings. Thus it

was not possible to combine the new multibeam data with any existing information. The Satellite RA (Laxon and MacAdoo, 1994) also does not show a good agreement (Fig. 12), like in other areas. Thus it was decided to present only the bathymetric contours which were derived from original measurements.
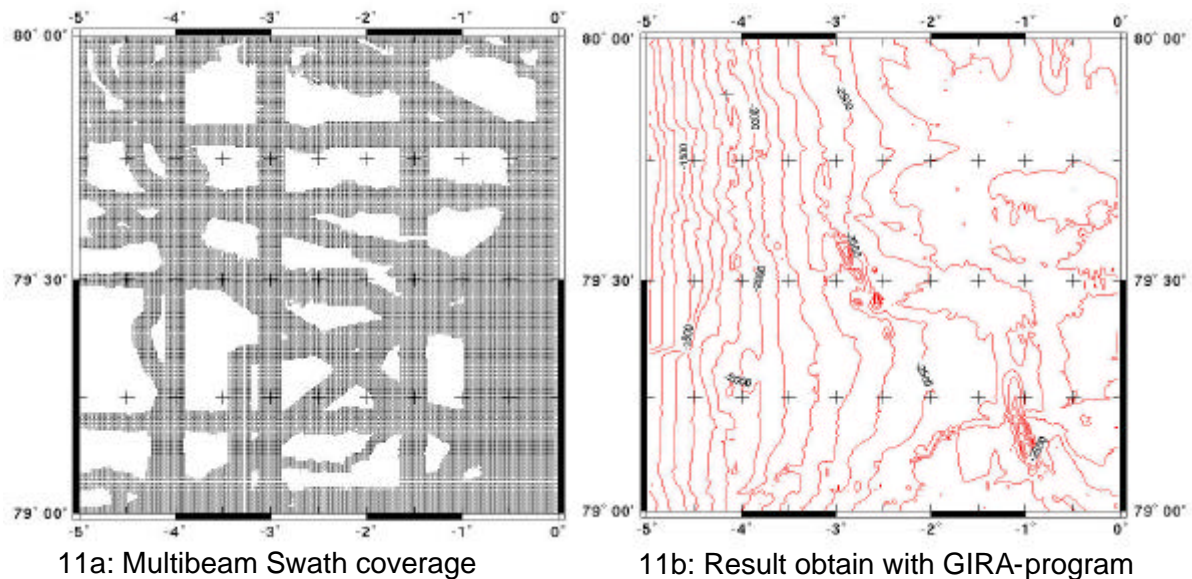

11a: Multibeam Swath coverage   11b: Result obtain with GIRA-program

Fig. 11: Example of creating a bathymetric chart based on Multibeam data

The comparison and analysis of the different data sources reveal large differences in the major structures at the slope off the Greenland Shelf (Fig. 10b). The IBCAO data could not be utilised as a regional grid for the automated combination with new data from "Polarstern" since large differences of more than 10 km were found in the geographic position of the slope. Therefore, we used only the new data for DTM determination with GIRA. The result is relatively good (Fig. 11b). However, not all existing single beam sonar data have been retrieved from our data archives so far, thus improvement is expected from further modelling. The comparison between the Satellite RA and the contour lines from the multibeam data reveal large differences (Fig. 12). Thus it is not possible to use the RA data for interpolation.
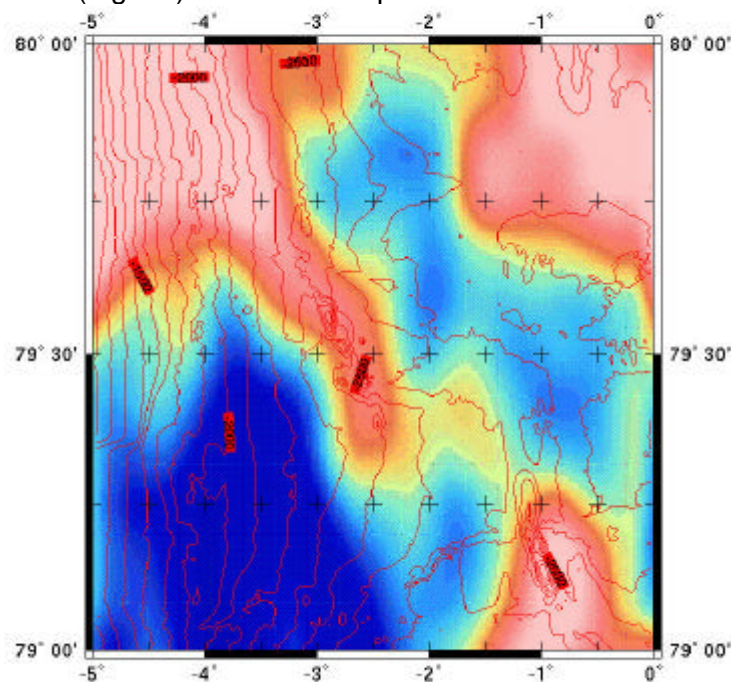

Fig. 12: Free-Air Gravity Anomalies derived from Satellite RA compared with bathymetry

7. Summary and possible future development

The approach of contouring using bi-cubic splines by combining grids of different size and special statistic parameters, as discussed in this presentation, has supplied useful results in areas with sparse data. Applying appropriate weight to sonar measurements and navigational data has led to reliable DTMs that can be used for the interpolation of contours. In areas where no new bathymetric data are available, other existing information from bathymetric charts, such as contours, spot soundings or track data, can be used for the creation of a regional grid. This coarse grid is then refined by using properly weighted new data, creating a DTM of higher resolution and quality. However, the resulting grids must be verified and morphologically analysed regarding their accuracy. In case of sparse or even no data in certain regions, auxiliary information from satellite altimetry can be used to improve the interpolation of the contours. A final re-gridding of the contours using sophisticated ArcInfo tools and TIN creation produces high-quality DTMs that are useful for many scientific disciplines.

With an increasing number of expeditions, which may go to extreme polar regions, more real measurement of the ocean depths will be available in the future. They can be used for further improving the DTM modelling techniques and better inclusion of information from satellite radar altimetry in these calculations. In the future interpolation techniques should apply sophisticated interpolation functions which can be derived from the statistic behaviour of the surface topography (kriging, least squares collocation, etc.) more extensively. Since more systematic surveys in the areas of mid-oceanic ridges or continental margins may be performed in the future, data archiving as well as modelling of DTMs could be improved using for example modern quadtree techniques. The quadtree data structure is widely used in digital image processing and computer graphics for modelling spatial segmentation of images and surfaces. This technique, also used in land topography, could be very helpful for combining data from densely covered (multibeam) and from sparsely covered single beam sonar data into one model.

8. Acknowledgement

9. Literature

Beyer, A., H.W. Schenke, M. Klenke, F. Niederjasper, (2002) High Resolution Bathymetry of the Eastern Slope of the Porcupine Seabight. Marine Geology (in print)

Briggs, I.C. (1974) Machine contouring using Minimum Curvature, Geophysics, 39(1), 39-48

Buziek, G., (1994). Analyse und Optimierung hydrographischer Punktfelder als Grundlage der Modellierung des Unterwasserreliefs. Wiss. Arb. der Universität Hannover, Nr. 157, Hannover

Claussen, H., I. Kruse (1988) Application of the DTM-Program TASH for Bathymetric Mapping. Int. Hydrogr. Review, LXV (2)

Ebner, H., Hofmann-Wellenhof, P. Reiß, F. Steidler (1980) HIFI – Ein Minicomputer-Programmsystem für Höheninterpolation mit Finiten Elementen. Zeitschr. f. VermWesen, 105, 215-225

Hagen, R. A., H. Hinze, J. Monk, F. Niederjasper, H.W. Schenke, T. Schöne, T. (1994) Applied marine geodetic research in polar regions. Mar Geod,17,81-94

Hake, G., D. Grünreich (1994) Kartographie, 7. Auflage, de Gruyter, Berlin New York

Herzfeld, U.C. (1989) Variography of Submarine Morphology: Problems of Deregularization, and Cartographical Implications. Mathematical Geology, Vol. 21, No. 7, 693-713

Hinze, H. (1994) Charting the Bathymetry of the Weddell Sea, Antarctica. Mar Geod, 17, 139-145

Jakobsson, M., and IBCAO Editorial Board Members (2001) Improvement to the International Bathymetric Chart of the Arctic Ocean (IBCAO): Updating the Data Base and the Grid Model, EOS Transactions, American Geophysical Union, v. 84.

Kumler, M.P. (1994) An Intensive Comparison of Triangulated Irregular Networks (TINs) and Digital Elevation Models (DEMs), Cartographia, Vol 31, Nr 2, Monograph 45

Klenke, M., H.W. Schenke (2003) A new bathymetric model for the central Fram Strait. Marine geophysical researches (submitted)

Laxon, S., D. McAdoo, (1994). Arctic ocean gravity field derived from ERS-1 satellite altimetry. *Science* **265**, 621-624

Sandwell, D. T., W.H.F. Smith (1997). Marine gravity anomaly from Geosat and ERS-1 satellite altimetry. *J.Geophys. Res.* **102**, 10,039-10,054

Schenke, H.-W., S. Dijkstra, F. Niederjasper, H. Hinze, B. Hoppmann, T. Schöne (1998) The new bathymetric charts of the Weddell Sea: AWI BCWS. In: Ocean, Ice, and Atmosphere: Interactions at the Antarctic Continental Margin, Stanley S. Jacobs and Raymond F. Weiss (eds.). Washington, DC: AGU, Antarctic Res. Series; 75, 371-380

Schenke, H. W. (1989) Digital terrain models in marine cartography. Lighthouse, 40, 13-15

Smith, W. H. F., D. T. Sandwell, (1994). Bathymetric prediction from dense satellite altimetry and sparse shipboard bathymetry. *J. Geophys. Res*. **99**, 21,803-21,824

Schöne, T. H.W. Schenke, (1997) The gravity Field of the Southern Weddell Sea from GEOSAT and ERS-1. In: The Antarctic Region: Geological Evolution and Processes (C A Ricci, ed) Terra Antarctica Publ , Siena,1123-1128

Schöne, T. (1997) Ein Beitrag zum Schwerefeld im Bereich des Weddellmeeres, Antarktis, Nutzung von Altimetermessungen des GEOSAT und ERS-1. Reports on Polar Research, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, 220, 145 pp

Schöne, T., H.W. Schenke (1998) Gravity field determination in ice covered regions by altimetry in: Forsberg, Feissel, Dietrich (eds.): Geodesy on the Move, Springer Verlag, IAG Symposia, Volume 119, 156-162

Swain, C.J., (11976) A FORTRAN IV Program for Interpolation Irregularly Spaced Data using the Difference Equations for Minimum Curvature, Computers and Geosciences, 1, 231-240.

Udintsev, G.B., Teterin, D.E., Schenke, H.W., Scott, D.P.D. (2003) Development of Methods used in the Compilation of the Bathymetric Charts of the Ocean Floor. In: International Geophysical-Geological Atlas of the Pacific Ocean (in print). Published by the International Oceanographic Commission of UNESCO, Paris.

_____