Bull. Nov. Comp. Center, Math. Model. in Geoph., 14 (2011), 17–28
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The Kuril–Kamchatka gridded digital bathymetry creation and analysis

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Abstract. In this paper, algorithms and an interface for creating detailed digital regular gridded bathymetry using digital sounding data are described, and examples of the data obtained for different regions of the Pacific are shown. In calculations of the depth at each grid point, the algorithm uses up to nine points from a data source. They are chosen using two criteria: the first one — they must be located in various sectors (N, NE, E, SE, S, SW, W, NW) from a calculating grid-point, and the second — they must be the nearest ones to this point in each sector. Then the spline interpolation is used for defining the depth value in the grid-point. Another algorithm uses linear interpolation for obtaining depth value at the grid-point. The new digital bathymery on a rectangular grid with 1 and 0.5 arc minute resolution has been created for the Kuril–Kamchatka region. These data consist of four rectangular arrays of depth, which cover a 200 km zone around the Kuril Islands and Kamchatka from 41.00° up to 61.00° Northern latitude. The comparative analysis of this digital bathymetry has been carried out.

1. Introduction

Currently, numerical modeling of different oceanologic problems and natural hazards in the ocean is widely used. For such a modeling, for example, of the tsunami wave propagation, a detailed digital bathymetry on a regular grid is required. At present, no reliable global gridded bathymetry data base with a resolution better than five geographical minutes is available for users. Therefore, for modeling local tsunamis, or another hazard, it is necessary to obtain somewhere or to create a detailed digital bathymetry for the area in question. There are a few ways to create such data arrays. There are several bathymetry information databanks now that are available. One of them is a global database "Marine Trackline Data" of the depth soundings from vessels (Marine Geological and Geophysical Data from NGDC) [1], that had been collected during a very long time period (from the beginning of the 20th century). In some coastal areas, the location of points from this data set are so dense, that using only this data makes it possible to create a regular array of depths with rather a small spatial step (less than one geographical minute). In the areas, where there are not enough points with such data, it is necessary to take into account additional information about the bottom relief. Isolines of depth represent another kind of information about the ocean bathymetry. The database of depths isolines "GEBCO"

(General Bathymetric Chart of Ocean) [2] is the best known global digital database, whose quality is of no doubt. However, the set and density of isolines are rather different for various regions. In the areas, where these isobaths together with echo sounding data of depth cover the area under consideration with enough densely without "white pots", it is possible to create a digital bathymetry of high quality. In those areas, where the density of Trackline and GEBCO data seems to be insufficient, it is necessary to input into computer the isolines of depth and "spot" data from available bathymetric charts (navigating, fishing or specially prepared). Then the program developed by the authors would be able to produce a detailed digital bathymetry on a regular grid.

2. Possible ways for creating the gridded bathymetry

First, let us consider what kind of information can be used as a source for creating the digital bathymetry on a regular grid. Information about the bottom relief can be taken from raster bathymetric (RBC) and raster navigation charts (RNC) (Figures 1–2). In such maps, the information about depths is presented as isolines and dot data of depth soundings. A lot of soundings have been collected in a digital form in the databases "Marine Trackline Data" (Marine Geological and Geophysical Data from NGDC) and "Hydrographic Survey Data" (Hydrographic Survey Data, CD-ROM data set) [3]. This base contains the data about measurements of depth taken during cruises of a large number of vessels and covers the data with a various density, practically, of all regions of the world ocean. Traces of these vessels cruises are shown in Figure 3.

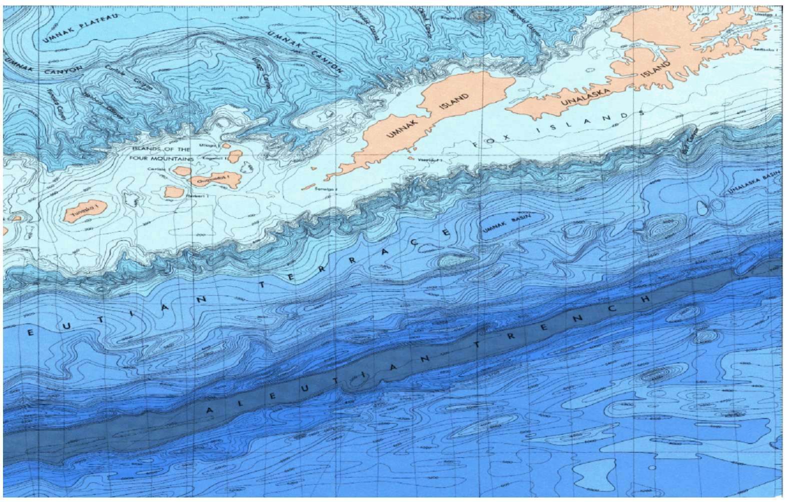

Figure 1. A raster bathymetric chart of the Aleutian trench

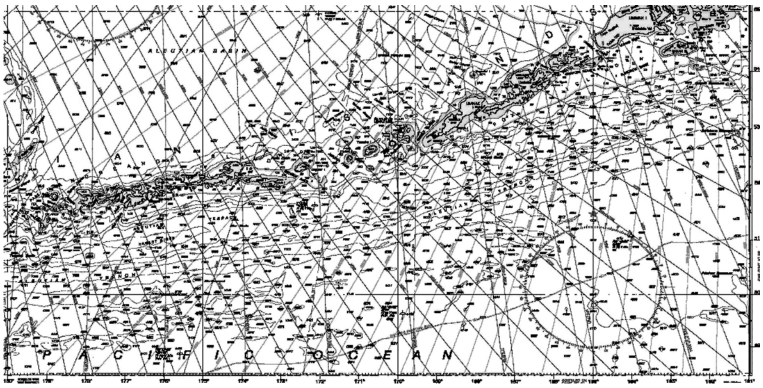

Figure 2. An example of raster navigation chart

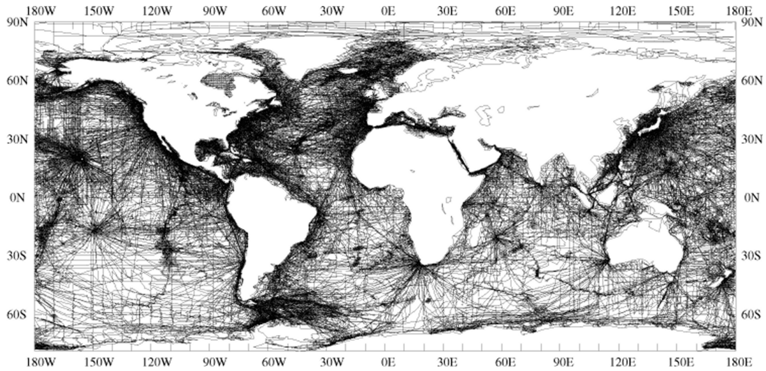

Figure 3. Marine track-line echo-sounding measurements locations

Each element of this database represents a trace of a vessel movement (track), along which with a very small step (about hundreds of meters) the values of measurements of depth are presented. In some coastal regions, tracks and soundings are located so close to each other, that only these data would be enough for the creation of a regular array of depths with rather a small step (less than one geographical minute). However, in other regions, distances between tracks are so long, that if we take into account only this kind of bathymetry information, it would be insufficient for creating the qualitative detailed digital bathymetry on a regular grid. Isolines of depth were collected in another global bathymetric database "GEBCO" (GEBCO 97 and GEBCO-2003 [4]), where some isolines of depth are stored in a digital vector form. This database covers all regions of the World Ocean. A set of isobaths values in this database depends on a region, and alongside with water areas, where this set is rather rich (in the Mediterranean sea, for example, it consists of about 40 values), there are also regions, where the density of these isolines is insufficient. Also it is possible to find some other

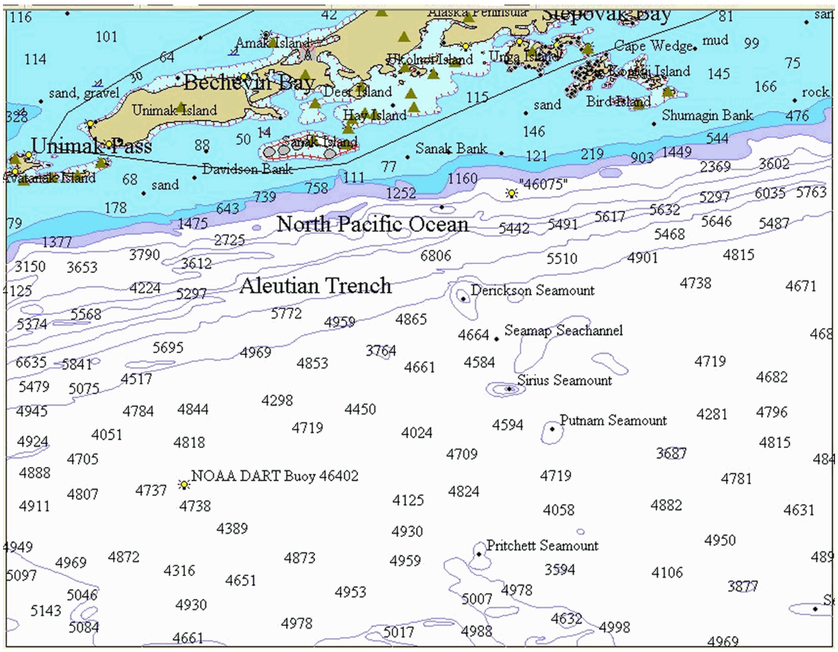

Figure 4. An example of electronic navigation chart

data about depth measurements that currently are not available for a wide range of the users.

Information of the Electronic Navigational Charts (ENC) (Figure 4) is being obtained by vectorization of depth isolines and depth measurements localities from raster navigational charts (see Figure 1). The ENCs are now widely used by vessels with modern electronic navigation equipment.

Now let us describe some ways of creating arrays of depths on a regular grid using available bathymetric data. These arrays can then be used for the mathematical simulation of processes in the ocean. David Sandwell made an attempt to use the gravimetric data obtained from a satellite for creating a gridded digital bathymetry [5]. Using this kind of data as well as depth sounding data, he has constructed a global two-minute gridded digital bathymetry. However the trackline data [1] in some coastal regions do not correlates well with the bathymetry obtained with the use of the analysis of gravimetry. In Figure 5, a fragment of the Sandwell's digital bathymetry that covers a region of the central Japan and surrounding water areas, is presented. The traces of vessels cruises (when the measurements of depths were taken) can be clearly seen on the bottom surface (almost all of them are converging in region of the Tokyo bay). In the deep-ocean areas, the quality of Sandwell's digital bathymetry is sufficient for modeling the oceanic processes.

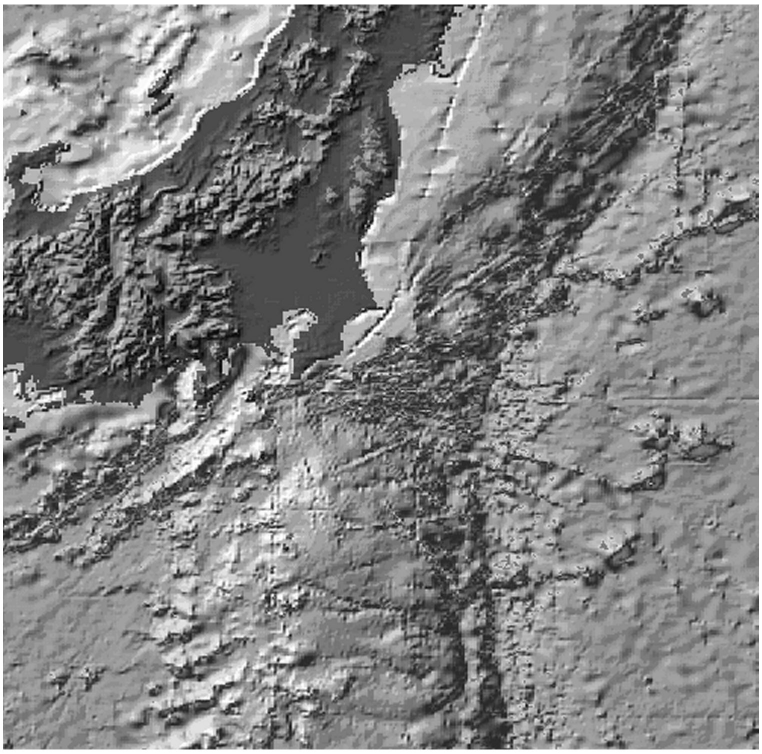

Figure 5. A 3D shaded image of Smith–Sandwell's relief around the central Japan area

3. Recalculating randomly distributed depth soundings onto the regular grid

Let us describe the technology of creating the gridded digital bathymetry for the case, when the points of depth soundings sufficiently densely cover the area under consideration. At the first step, it is necessary to choose from the whole database "Marine Trackline Data" a subset of points that are located in this area. This will be a file, each string (line) consisting of the three numbers: longitude, latitude and measured depth. Then we should decide, what length of a step between grid points can be set, where the depth values are to be found. The last stage of creating the process will be execution of the program of recalculation of a randomly distributed depth data (depth soundings) onto regular rectangular grid.

First, let us describe the recalculation algorithm, which uses the linear interpolation. The program considers one-by-one all our new grid-points. For every grid-point it is necessary to determine its geographical coordinates. Then we look through all points of the depth measurements finding distances from the considered grid-point up to each of them. If among them there is one or several points located closer, than one twentieth part of the new grid step length, then the value of depth in such grid-point is assumed to be equal to the depth value at the nearest point. If the Trackline database does not contain points, located to a new grid-point closer, than the distance established, then we take from its nearest neighborhood such three points (from the Trackline database) that would contain grid-point a located inside the triangle, formed by these three points. Then, using known values of depth at these three points, with the help of the linear interpolation, the value of depth at a considered grid-point, can be defined. As the variation of this method it is possible to estimate the depth value at a grid-point using six nearest soundings, which are located in different sectors of the Cartesian coordinate system with the center at the grid-point under study. So, considering one-by-one all the points of a new regular grid, we find approximate values of depth at each of them. It is obvious that a better dense coverage of the area with soundings provided a higher quality of the gridded digital bathymetry created.

Another method is based on a more complicated interpolation method by radial functions. The method proposed uses up to nine points from a data source. One point is the nearest one among all. The other eight points are chosen using the two criteria: the first — they must be located in various sectors (between N, NE, E, SE, S, SW, W, NW directions) of the Cartesian coordinate system with the center at a grid-point in question, and the second – they must be the nearest ones to this point in each sector. When the algorithm takes into account more that one point in each sector, the quality of gridded data will be better, but computations will take much more time and resources. In this case, some procedures for optimizing the calculation process are proposed.

The Green function method, which is a special case of the radial functions method, is used for depth interpolation at grid-points. Let us note that this method is exact on linear functions. The essence of the method is in choosing one-dimensional radial functions $f(R)$. Then the linear combination

$$S(\vec{P}) = \sum_{i=1}^{k} \alpha(i) \cdot f\big(|\vec{P} - \vec{P}(i)|\big) + ax + by + c \tag{1}$$

represents a two-dimensional function. Here $\vec{P} = (x, y)$ is an arbitrary point of the area, $\vec{P}(i) = (x(i), y(i))$ are interpolating points from different sectors. The coefficients $\alpha(i)$, a, b, and c are to be defined from interpolating conditions (the coincidence of the function $S(\vec{P})$ and the sounding values $d(j)$ at the points $\vec{P}(i)$, used for the interpolation)

$$S\big(\vec{P}(j)\big) = \sum_{i=1}^{k} \alpha(i) \cdot f\big(|\vec{P}(j) - \vec{P}(i)|\big) + ax + by + c = d(j), \quad j = 1, \ldots, k, \tag{2}$$

and the orthogonality conditions

$$\sum_{i=1}^{k} \alpha(i) = 0, \qquad \sum_{i=1}^{k} \alpha(i)x(i) = 0, \qquad \sum_{i=1}^{k} \alpha(i)y(i) = 0. \tag{3}$$

From the system of equations (2) and (3) it is possible to find the coefficients $\alpha(i)$, a, b, and c and then to define from expression (1) the depth value at a new grid-point. Repeating this procedure for all grid-points of the area makes it possible to create the digital gridded bathymetry with arbitrary spatial grid-steps.

4. Example of application

Let us illustrate application of such a technology of constructing the gridded digital bathymetry on an example of obtaining an array of depths for a small region in the north Pacific around the Kodiak Island. In this 5×5 degrees area (between the 54th and the 59th degrees North latitude and from 156th to 151st degrees West longitude), a detailed gridded bathymetry with resolution of 30 arc seconds in both directions was created. Available

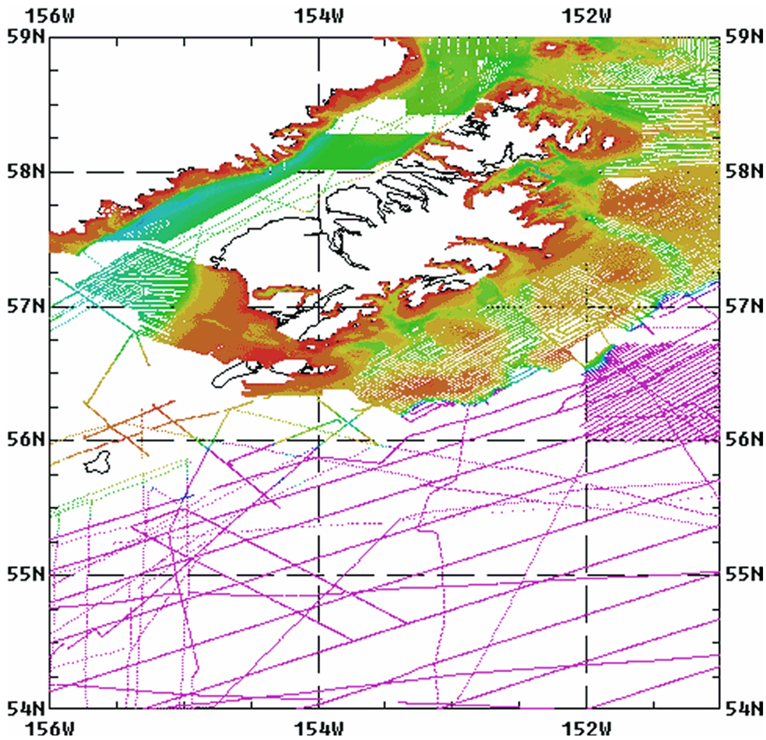

Figure 6. Marine Trackline Data for the area around Kodiak Island in the North Pacific

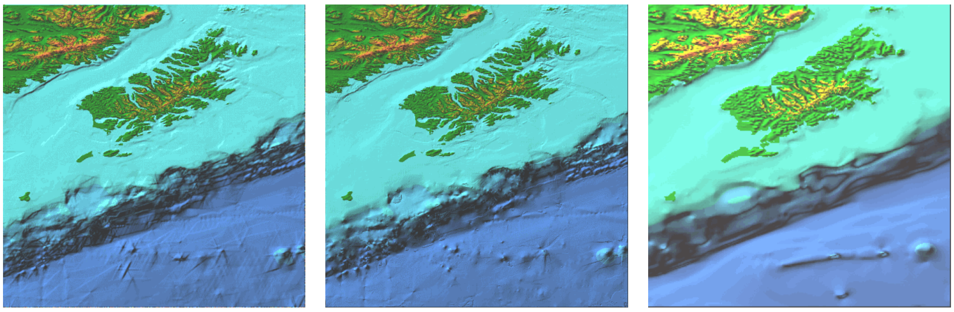

Figure 7. Tree-dimensional shaded images of the bottom relief (gridded bathymetry) that was created using linear interpolation (left) and spline interpolation (center) methods. The right drawing presents the GEBCO-2003 gridded bottom relief

depth sounding data with the coastline from "Marine Trackline Data" [1] and "Hydrographic Survey Data" [3] sources are presented in Figure 6. It is seen that in the shelf zone, the density of sounding measurements is significantly higher than in the deep ocean.

In this area, a 600×600 points array of depth values was created using linear and spline interpolation methods. Both digital arrays obtained are visualized in Figure 7 as a 3D shaded relief. This style of visualization [6] makes all small-size details of a bottom relief be very well visible. Here the illumination vector is directed from the upper left corner of the area. In the bottom part of the left picture corresponding to a linear interpolation algorithm, some "star" structures around local depth extrema are visible. In this part of the area, the depth soundings traces are located rather far from each other (see Figure 6). The quality of the bathymetry arrays obtained can be evaluated by comparison with the GEBCO-2003 gridded data [4] (see Figure 7).

5. The new Kuril-Kamchatka digital bathymetry

For some areas of interest, the information about depths from these global databases is insufficient for obtaining a high-quality gridded bathymetry. But if the BBC's are available, it is possible to apply technologies for digitizing the geographic information developed earlier [7], and methods proposed in this paper. For example, the information about depths for the Kuril–Kamchatka area contained in both global data sets is insufficient for our purposes. Therefore a set of four detailed bathymetry charts for this region were prepared in the Kamchatka Institute of Volcanology. Figure 8 shows the coverage of these charts. In Figures 9, the GEBCO isolines of depth (left) and a scanned image of one of these bathymetric charts (right) are shown. Using this data source (paper charts) make it possible to cre-

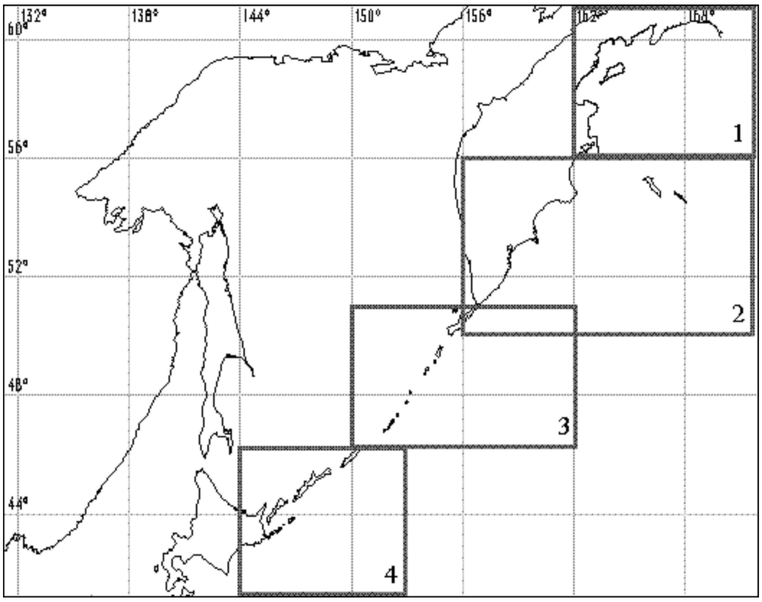

Figure 8. Geographic coverage of specially prepared bathymetric charts (segments 1–4)

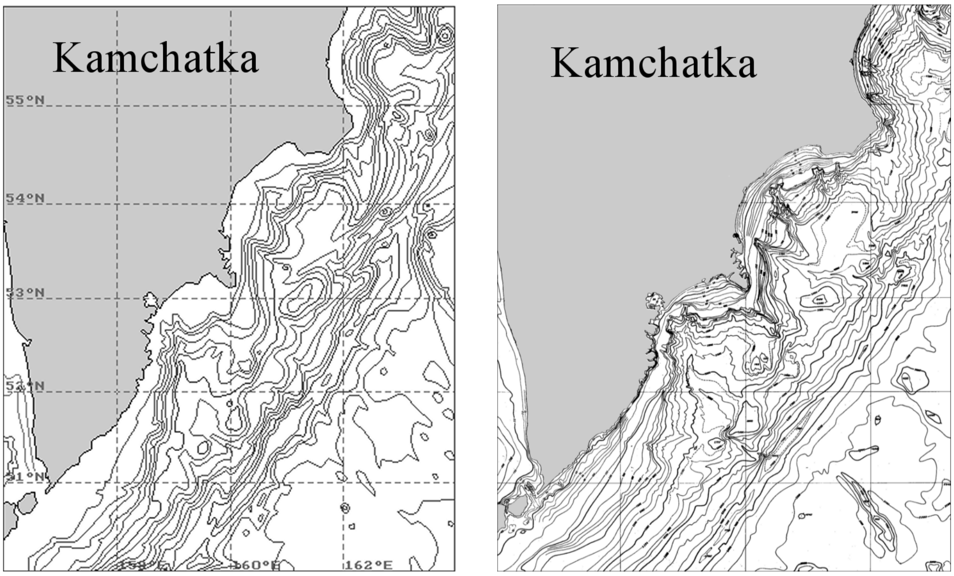

Figure 9. Comparison of the depth isoline sets from the GEBCO database and the specially prepared bathymetric chart

ate a new gridded digital bathymetry for this region. One arc-minute and 0.5-min gridded bathymetry arrays were produced for areas 1–4 using the linear interpolation and the spline interpolation method. As an example, a 3D shaded relief of segments 1 and 2 is shown in Figures 10 and 11. Further in this paper, we will call this digital bathymetry set as the "New Kuril–Kamchatka bathymetry".

As expected, the matching of Sandwell's data with more reliable bathymetric data (created by the method proposed here) in the north Kamchatka region has revealed a significant (in some places) mismatch of these data with actual depth measurements. As an example, Figures 12 and 13 show a difference between the new bathymetry depth values against Smith–Sandwell

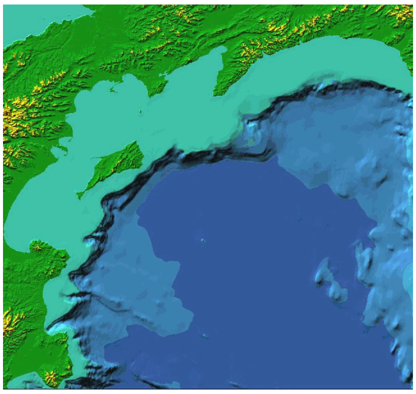

Figure 10. Bottom relief near the North Kamchatka (segment 1)

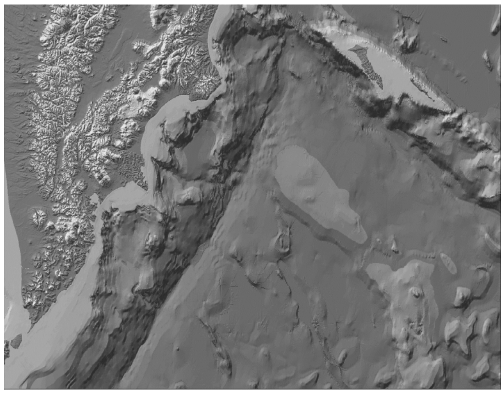

Figure 11. Bottom relief near the South Kamchatka (segment 2)

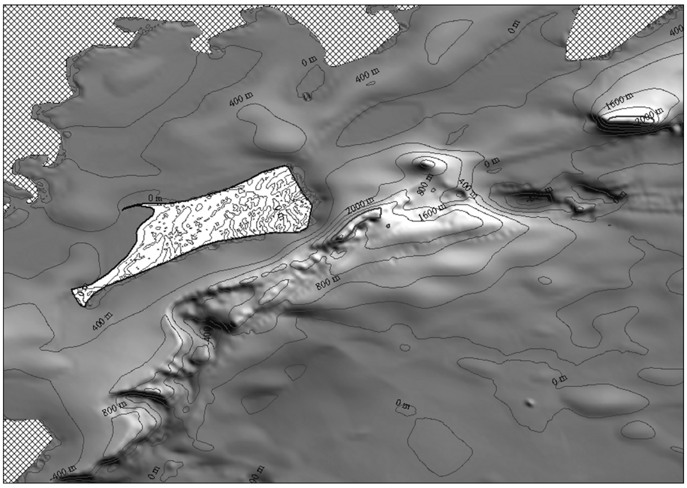

Figure 12. A difference between the New Kuril–Kamchatka and the Smith–Sandwell gridded bathymetric data in segment 1

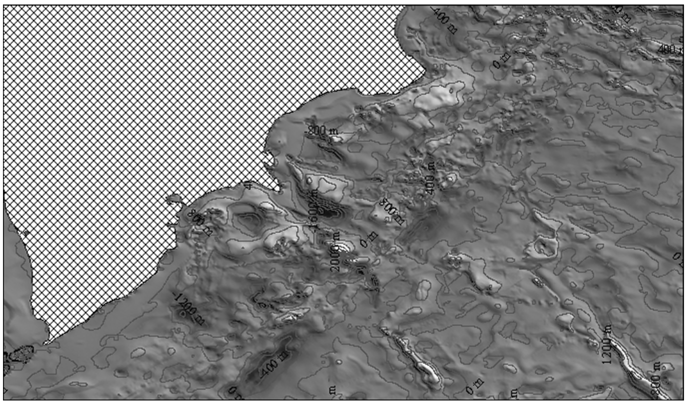

Figure 13. A difference between the New Kuril–Kamchatka and the Smith–Sandwell gridded bathymetric data in segment 2

gridded data [5] in segments 1 and 2. Here the color of drawing indicates the value of depth difference in the range from −1,500 m (black color) up to 1,600 m (white color). Some isolines of depth are also drawn and marked.

It is seen that the most significant depth difference is located at the shelf edge and around some local bottom structures. We consider the "New Bathymetry" to be a more reliable (than that of Smith–Sandwell) digital bathymetry, because we use a variety of depth soundings around Kurils and Kamchatka which were unavailable for Smith and Sandwell [5].

The user interface for the comparative analysis of the gridded bathymetry, the RNC and the ENC was developed. This can help the user to

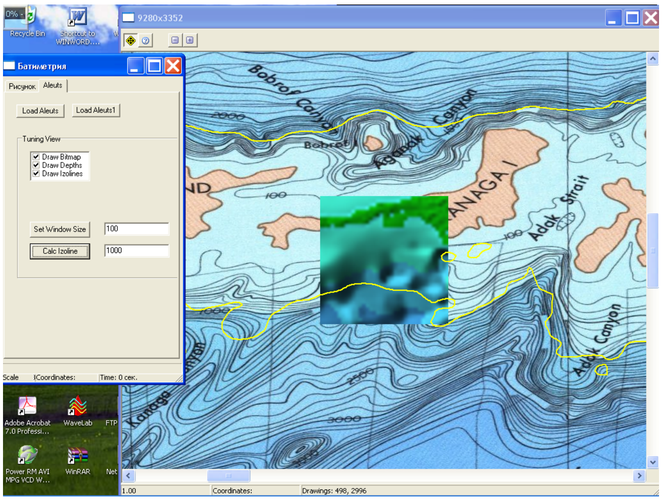

Figure 14. The user interface of the Bathymetry Comparison System. A raster chart is compared to the Smith–Sandwell gridded data

easily find bottom relief mismatches between various bathymetric data sets. As an example, Figure 14 presents a screenshot of this interface, where the routine of comparison of the RBC depth values against the Smith–Sandwell gridded data for the Aleutian Islands is shown.

Conclusion

For some regions of the World ocean, the quality of bathymetric data (on a random grid) that is contained in global databases allows one to create rather a detailed gridded digital bathymetry using the methods proposed. If the number of depth measurements is insufficient, then additional sources of bathymetric information can be used. New digital bathymetry on a regular grid for the Kuril-Kamchatka region was created using the described in this paper technology and numerical experiments of tsunami propagation were carried out. The user interface for comparative analysis of a gridded bathymetry, the RNC and the ENC has been developed.

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