Detecting possible impact craters on the Earth's surface using the DEM data processing*

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Abstract. A new attempt to the detection of the impact craters and other morphologic structures on the Earth's surface was made using high-tech computational methods. For detection and allocation of such structures, the fast two-dimensional wavelet transformation and the fast nonlinear multiparameter regression analysis for the digital elevation (DEM) data subsets and 3D shaded images, which are drawn using these data should be applied in combination. The computing process for the solution of the indicated problem takes the form of a computational experiment and includes, in particular, the procedure of training on the known reliable impact structures, the procedure of testing of the constructed regression model and detection and identification of the required shapes on the Earth's surface with their subsequent contrast improvement. This technology was used for the detection of the big circle structures on the territory of North America and Central Siberia. In this case, the GTOPO 30 data were used. The results obtained seem to be promising. The known circle structures are effectively detected and clearly distinguished on the surface area under study. The quantitative information is represented in convenient form for subsequent processing and analysis.

1. Introduction

Analysis of the available data on impact structures on the Earth's surface shows that, on average, once in 50–100 years celestial body of a size compatible to that of the Tungusska space event (50–100 m in diameter) falls down on the Earth. Events like the Revelstoke bolide (1965) of 10–20 m diameter can annually occur. The estimated frequency of meteorite impacts into the oceans for scaled asteroids is 1 in 10^4 years for 0.5–1 km-sized objects, 1 in 10^5 years for celestial bodies of 5 km diameter and 1 in 50 million years for an asteroid of 20 km diameter. The probability of a kilometer-sized object colliding with the Earth within the next 100 years is 10^{-4} [1]. If there are no erosive forces, some 2000 craters having sizes of 10 km (or > 10 km) should be recorded during the period of 200 million years (the age of the current system of the oceans). Figure 1 shows the location of some reliable significant impact structures discovered on the Earth's surface. It is conditionally taken that about 70 percent of all meteorites are falling down into the oceans. But only one crater was detected on the ocean bottom (the Montagnais structure). Analysis of the structure of a substance makes it possible to estimate the age of a crater and the frequency of celestial
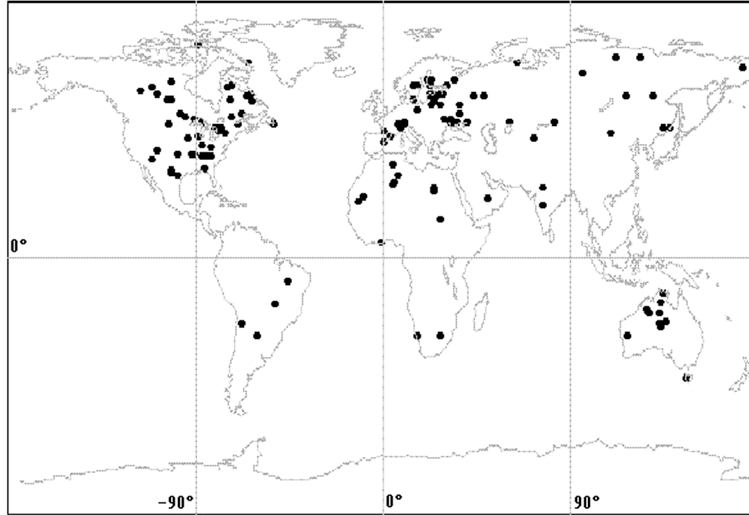
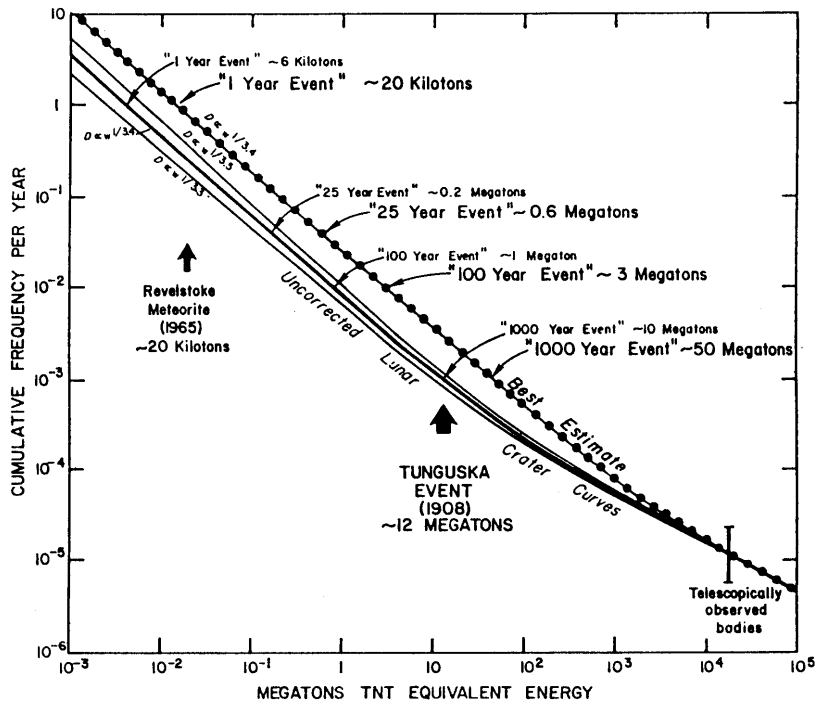**Figure 1.** Reliable impact structures of the Earth's surface


Figure 2. Cumulative frequency distribution of kinetic energy
of falling celestial bodies

body impacts of different size (energy). Most of the land impact structures have been identified by a combination of criteria, including observations of the circular topographic and geological formations and finding high pressure polymorphs and other shock debris [2]. The cumulative frequency distribution of the kinetic energy of such celestial bodies is given by Shoemaker [3] and shown in Figure 2.

In order to correctly estimate the frequency of falling of big celestial bodies, it is necessary to reveal as many as possible traces from such falls and to determine their age [4]. In order to adjust the appearance law of celestial bodies impact, it is necessary to discover other craters (in addition to the existing catalog of reliable impact structures). These traces (impact structures) have some special features in comparison with other circle structures on the Earth's surface. There are some geological, geophysical and geomorphologic criteria for a structure being an impact crater. Usually, such structures are sought for using the Earth's surface photos, made from satellites. But sometimes it is easier to do this using the global geophysical databases.

## 2. Detection of impact craters on the Earth's surface

A wide-spread way for the detection of impact craters is analyzing satellite images of the Earth. But it is often very difficult to recognize an impact crater among other kinds of surface roughness. As an example, Figure 3 shows a snapshot of the Zhamanshin crater, taken from the "Saljut" space-lab. So, there is an idea to seek for the possible impact structures using the digital models of the Earth's relief.
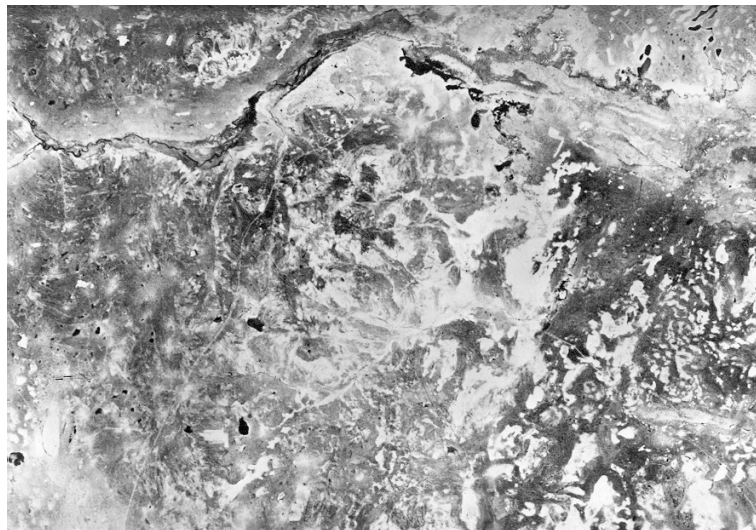

Figure 3. Space photo of the Zhamanshin impact crater

At the present time, there are some global data banks, which contain the Earth's relief with a different degree of detailization. The most well known among them are ETOPO-5 and GTOPO-30. The data bank ETOPO-5 represents a relief of the Earth's surface and the ocean bottom in linking to a geographical coordinate grid with a spatial step of 5 geographical minutes, that is approximately about ten kilometers on latitude and from 10 km on a longitude on the equator up to zero on the poles (according to approaching each other). It is clear that on such a grid only a large-scale roughness of a relief can be detected, therefore for discovering the impact structures on the surface of the Earth it is necessary to use the relief data with a spatial step not exceeding one kilometer.

Those is a database GTOPO-30 representing an earthly relief also in linking to a geographical coordinate grid, but already with 30 geographical seconds spatial resolution, that is ten times more detailed, than the database ETOPO-5. This data bank contains the elevation data only for land. The surface of the sea is designated there by the value -9999. The data bank in question allows us to find on the Earth's surface various structures having the size from 5 km and more. There is also 1-arcsecond resolution data bank, which is 30 times more detailed than the GTOPO-30 data. The spatial resolution here is about 30 meters. Now the authors have access to this data only for the USA territory (including Alaska and Hawaiian islands). The whole territory of the USA is divided into segments of the size of 1x1 degree. This digital elevation data can help to discover rather small impact craters. As examples, Figures 4 and 5 show the 3D and shaded pseudo 3D visualization of "Upheaval" (Figure 4) and the famous "Meteor" (Figure 5) craters.
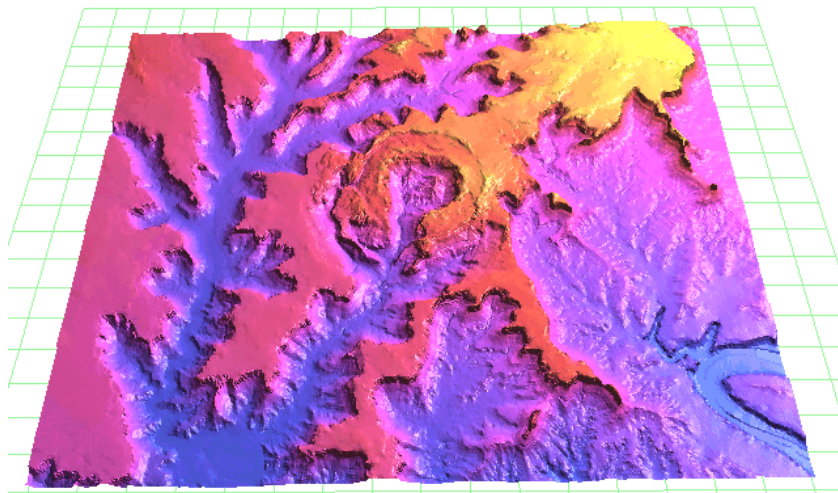
Figure 4. 3D visualization of the Upheaval impact structure
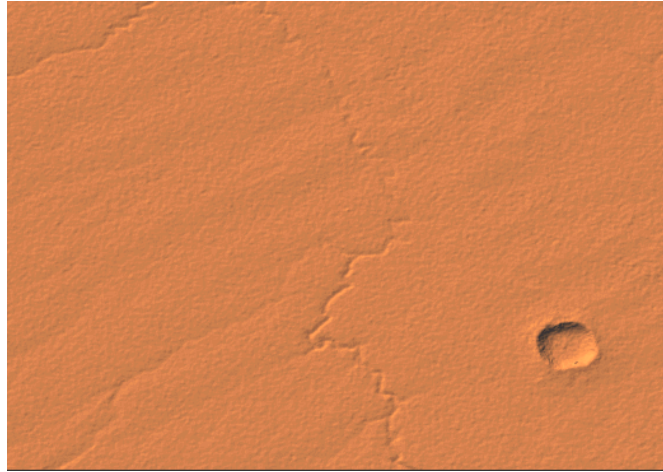
Figure 5. A shaded pseudo-3D image of the Meteor crater in the Arizona desert

3. Wavelet-transformation of bi-variable function

The algorithm for the fast obtaining a wavelet-diagram of bi-variable function and examples of its usage will be represented in this section. Such a type of the wavelet filtering is able to discover the circle structures (depression or uplifting of the Earth's surface) of a specified size. If an impact crater has some level depression as compared to the surrounding relief, then the location of this crater can be effectively defined using the proposed algorithm.

The program implementation of this algorithm is a part of a package of programs for the space geomorphological and topographical data processing, that is being developed for solution of a wide range of problems, including the task of searching the impact craters on the Earth's surface.

Note that the wavelet-transformation of a one-dimensional signal is its decomposition on the basis constructed from the soliton-type function (wavelet). A well-localized function is one of elements of the wavelet transformation basis, rapidly approaching zero out of a small interval. Therefore each function of this basis characterizes both a particular space (temporary) frequency, and its localization in the physical space (time). In the case of two-dimensional data, the "mother" wavelet is a surface with a central symmetry corresponding to the same set of requirements, as in the one-dimensional case.

Let us present the following algorithm of construction of the bi-variable wavelet-diagram, which was developed for the concrete task—the search for the ring structures on the Earth's surface.

The initial data D are $N \times M$ matrix units, which contain values with some properties in clusters of a rectangular coordinate grid. It is necessary

to find structures of a given form weakly expressed against the background of an inhomogeneous medium.

The following algorithm of the bi-variable wavelet-transformation is proposed.

1. Setting up the "mother" wavelet. For practical application, it is important to know indications, to the function which necessarily will be a wavelet:

- localization in space (time) and in frequency;

- zero mean

$$\int\limits_{-\infty}^{\infty} \int\limits_{-\infty}^{\infty} \varphi(x,y)\, dx\, dy = 0; \tag{1}$$

- limitation

$$\int\limits_{-\infty}^{\infty} \int\limits_{-\infty}^{\infty} |\varphi(x,y)|^2 dx\, dy < \infty; \tag{2}$$
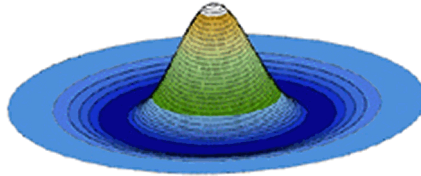
- an auto-model of the basis, all elements of the given set $\phi_{a,b}(x)$ having the same number of oscillations, as the basic wavelet.

2. Further, let us assume:

$$\Phi_{x+M,y+M} = \varphi\left(\frac{10((x-M)^2 + (y-M)^2)}{M}\right), \quad x,y \in (-M, M); \tag{3}$$
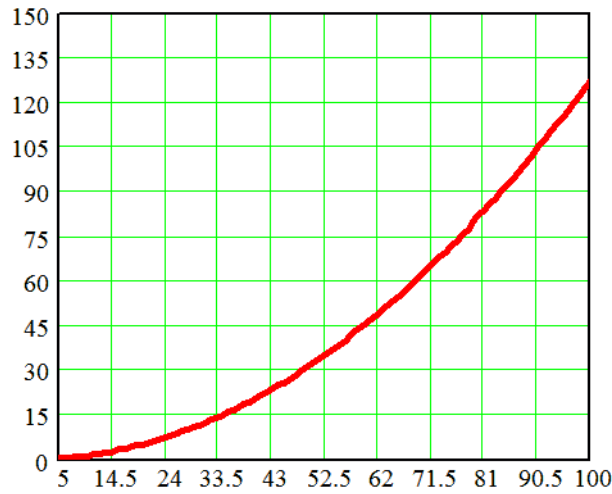$$\varphi(t) = -(1-t)e^{-t};$$

where M is a scale of wavelet-transformation, $\Phi_{x+M,y+M}$ are matrices of the basic wavelet. Figure 6 represents the selected mother wavelet.

Figure 6. An example of the mother wavelet

Now the wavelet-transformation can be rewritten as integral sum:

$$W_{x,y} = \frac{\Delta x \Delta y}{\sqrt{M_i}} \left(\sum_{k=1}^{M} \sum_{l=1}^{M} \Phi_{M-k,M-l}(D_{x-k,y-l} + D_{x-k,y+l} + D_{i+k,j-1} + D_{i+k,j+1}) + \right.$$
$$\left. \sum_{k=1}^{M} \Phi_{M-k,M}(D_{x-k,y} + D_{x,y-l} + D_{i+k,j} + D_{i,j+1}) + \Phi_{M,M} D_{x,y} \right). \tag{4}$$

Figure 7. The time expenditures for calculation of
the wavelet-diagram for 200×200 matrix

As entries of both matrices are constants, the procedure of wavelet-transformation consists in multiplication and addition of a certain set of constants. The matrices are organized in the way that the amount of operations of calculation of coefficients of the entries be minimal. This substantially reduces the machine calculation time.

The relative time expenditures for calculation of a wavelet diagram for 200×200 matrix are represented in the graph (Figure 7), the calculations were carried out on P III-800. The digits along the vertical axis give the processor time and the numbers along the horizontal axis give the "mother" wavelet effective diameter.

After the circle structure have been found, some criteria for it identification as the impact crater can be applied. For example, the ratio between the crater's depth and the diameter must be from 0.1 to 0.25. Thus, the effective software for the DEM data processing, in particular, for detection the round structures (as the possible impact craters) on the Earth's surface were developed.

4. Determination of the Popigai crater location

The location of the Popigai crater on the Earth' surface is estimated in the following coordinates: $71.35°\,$N, $111.00°\,$E; diameter being approximately estimated as 100 km, the age — about 39 million years [2].

In this paper, the simulation of topographical data (the size of the area is 1500×1300 km) for identification of the Popigai crater; the time of data array processing on Pentium IV is 15 min.
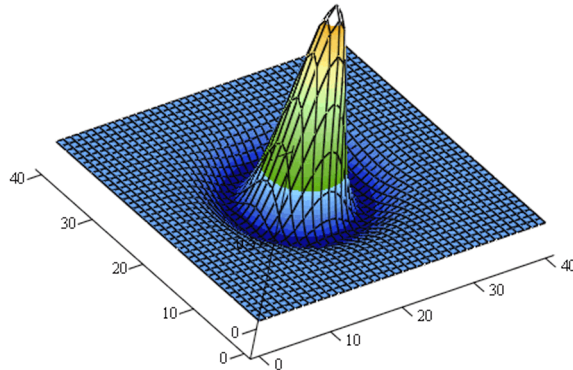
Figure 8. The "mother" wavelet used for the Popigai crater detection

a   b   c   d
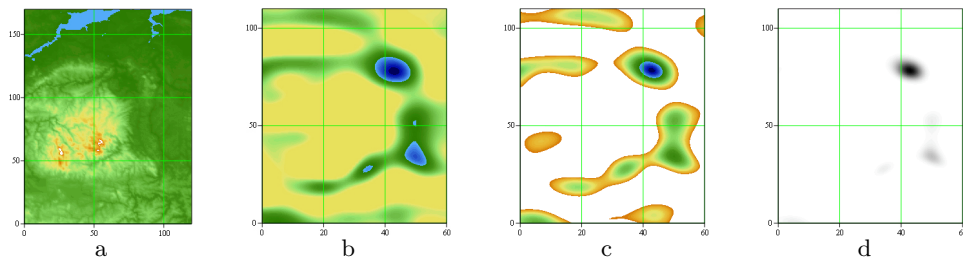
Figure 9. Step-by-step wavelet–filter of the Earth's surface topography: (a) input data; (b) filter $M30$ (effective diameter of the "top" of wavelet is 30 km); (c) filter $|M30| - M25$; (d) results of filtering

The basic wavelet is shown in Figure 8 and the results of processing of the indicated data are presented in Figure 9.

Thus, the developed algorithm and the software have shown its high efficiency in solving the task of the search for a craters on the Earth's surface.

References

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