Atlas Planetary Mapping: Phobos Case

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Abstract We present a general procedure of the Phobos Atlas creation. Main principles of mapping, mathematical, and geographical basics are described and justified. Data sources for mapping are listed. Approaches in the development of legends and design are considered, and some examples of the maps are shown.

Keywords Phobos Atlas · three-axial ellipsoid · Map design · Geomorphologic mapping

1 Introduction

The Phobos Atlas (MIIGAiK 2015) is based on images collected by different spacecraft, including the ongoing European Mars Express (launch 2003), NASA's Viking Orbiters (1976–1979), and the Soviet Phobos-2 (1988–1989) missions. The Atlas covers aspects of theoretical studies and practical data analysis for Phobos and integrates scientific results obtained by Russian researchers before and after Phobos-Grunt mission (2011). The Atlas was produced by MIIGAiK Extraterrestrial Laboratory (MExLab) under the support of the Russian Science Foundation (project №14-22-00197) and has broad objectives: firstly, to collect the results of the studies of the Martian satellite performed in different years (2009–2014); to present our modern knowledge about Phobos for educational and

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public outreach; and finally, to provide cartographic instrument for the preparation of the future international mission Bumerang[1] planned for launch with the same scientific tasks as the unsuccessful mission Phobos-Grunt: landing and sample return to understand the origin of Phobos and the Solar System.

Russia has a long-standing tradition in studying and mapping the Martian satellite. The first Russian map of Phobos was produced jointly at MIIGAiK and several institutions from the Russian Academy of Science as early as during preparation and planning of the Phobos-1 and -2 missions (1988). This map was created using airbrush technique and images from NASA missions Mariner 9 and Viking 1. To compile the map, special projections were developed, which represented the odd-shaped Phobos body in the form of triaxial ellipsoid (Bugaevsky 1987). Later, the map (1988) was used as a basis for a globe (Bugaevsky et al. 1992) and maps of Phobos in the *Atlas of the Terrestrial Planets and Their Satellites* (Shingareva et al. 1992) as well as in the multilingual map series on celestial bodies (Shingareva et al. 2005).

The Atlas of the Terrestrial Planets and Their Satellites (Shingareva et al. 1992) as a fundamental work, which combines comparative-planetographic descriptions, history of research, and various thematic maps, was used as a basic sample of the Phobos Atlas. Another example was the *International Atlas of Mars Exploration* (Stooke 2012) that contains not only maps, but multi-page text descriptions, accompanied by annotated images, and focuses on some aspects of the history of Mars research (including Phobos) that can be presented using cartographic methods.

2 Principles and Structure of the Atlas

2.1 Concept of the Phobos Atlas

An Atlas is a systematic collection of maps, drawn up according to the general procedure as a complete product (Salishev 1982). The Phobos Atlas was created as a comprehensive project, which represents miscellaneous characteristics of surface and physical properties of one of the Martian satellites. The main idea of our Atlas is to record the knowledge and experience of Phobos research, so besides maps, the issue includes descriptions of studies and their scientific results, methods, and techniques, as well as various catalogues (images, control points network, craters). The creation of the Atlas was based on the principles of integrality and complementarity of various sources integrated into an ArcGIS geodatabase (Karachevtseva et al. 2015).

[1]https://www.laspace.ru/projects/planets/expedition-m/.

2.2 Atlas Composition

Atlas materials are divided into four chapters:

I. History of Phobos studies and mapping;
II. Control point network, shape, and gravity field;
III. Spatial analysis of Phobos' surface;
IV. Geomorphology studies of Phobos.

The Atlas is structured sequentially, and each chapter is based on the results presented in the previous ones: e.g., the first chapter combines modern knowledge about main Phobos parameters and briefly describes the history of Phobos mapping, and then, the second chapter describes the photogrammetric technique and the results of modern image processing that provide coordinates basic for further analysis. The third section includes descriptions of the implementation of GIS technologies for semi-automatic measurements of Phobos features, whereas in the fourth part the results of spatial analysis and visual interpretation of the images are summarized.

The first part is an overview of Phobos studies indicating the level of our knowledge, illustrated with pictures that show early topographic schemes, historic Russian maps and globe mentioned above, modern cartographic products created using GIS and Internet technologies like the Geoportal (Karachevtseva et al. 2014), as well as maps produced recently (Wählisch et al. 2014). The complex and irregular shape of this celestial body always raises challenges for cartographers, so the section also includes detailed discussions on the usage of conformal and quasi-conformal projections, which have been developed for Phobos mapping over time (e.g., Snyder 1985; Stooke 2012).

This chapter is accompanied by three maps, which show Phobos in various views: (1) a surface representation based on modern images using Mercator and stereographic projections (for equatorial and polar parts, respectively), as well as a 3D view; (2) a historic map (1988) in normal conformal cylindrical projection for triaxial ellipsoid developed by Bugaevsky (1987) and in the original five-sheet layout proposed by Shingareva; (3) a new topographic map in Bugaevsky projection and Shingareva's layout to maintain the continuity of cartographic heritage with previous Russian mapping of Phobos.

The second chapter presents the photogrammetric methods used for the formation of the first three-dimensional geodetic control points network (CPN) of Phobos, a global orthomosaic and DEM, and separate high-resolution orthoimages and DEMs produced at MExLab (Zubarev et al. 2012). The new MExLab CPN mainly derived from Mars Express images provides the possibility to update the Phobos three-axial ellipsoid and to establish a coordinate system for mapping, to determine the fundamental Phobos parameters such as shape and libration (Nadezhdina and Zubarev 2014), as well as to characterize gravitational field (Uchaev et al. 2013). More than ten maps derived from these studies show various physical parameters of Phobos, including attractive potential, gravitational field, and dynamic heights. Besides the global maps of physical parameters, the chapter includes large-scale topographic maps demonstrating the surrounding area of Drunlo and Stickney craters with possible large scale (1: 60,000) based on photogrammetric processing of high-resolution stereo images (at 3–10 m/pixel resolution).

The third chapter describes the results of spatial analysis of Phobos' surface, carried out using modern GIS technology. It includes the description of object catalogues (of craters, rocks, and grooves) and their application for various studies, e.g., Phobos meteoroid bombardment modeling (Dmitriev et al. 2013) that was verified using crater spatial distribution. The studies described at this section are based on Phobos information system (Karachevtseva et al. 2014) that integrates different GIS layers and provides assessment of size and spatial distribution of craters and rocks presented on the maps as well as cumulative density plots and size-frequency diagrams. Processing of multi-spectral images obtained by Mars Express HRSC camera (Jaumann et al. 2007) and their careful co-registration in GIS gives the assessment of Phobos albedo properties. Albedo parameters obtained in various spectral channels showed on the maps demonstrate the possibility to judge with sufficient confidence the presence of at least three materials with different reflecting properties on the surface of Phobos (Patsyn et al. 2012). Besides 12 single maps, the chapter includes two multi-page maps that show the spatial distribution of Phobos features and surface properties with various scales.

The fourth chapter presents the current understanding of geological composition and surface processes on Phobos. It includes the description of crater morphology (Basilevsky et al. 2014) illustrated by high-resolution images that were used for visual analysis and interpretation. Particular attention is paid to the morphology of Phobos grooves; a consequence of grooves analysis is the special zoning of the Phobos surface into some individual sections that have a different geological history (Lorenz et al. 2016). The morphometric analysis of Phobos craters is illustrated by plots showing comparison with craters on other Solar System bodies (Kokhanov et al. 2014). Estimation of the degrees of crater degradation, assessment of ejecta, and analysis of deposit distribution associated with slope processes derived from the research are presented on five geomorphologic maps.

3 Coordinate System

3.1 Geographic Basis

For Earth mapping as usual some cartographic objects such as coastline and rivers can be applied to show thematic content on the maps. In extraterrestrial cartography, orthomosaics and digital elevation models (DEM) are used as geographical basis. Our studies of Phobos are based on data produced in MExLab: orthomosaic as well as separate orthoimages with the highest resolution, and DEMs with different resolution derived from three-dimensional control point network created at the first time for Phobos (Zubarev et al. 2012). It provides the geographic basis for mapping at various levels of detail. Names of Phobos relief features are taken from the Gazetteer of Planetary Nomenclature.[2] Global mosaic and names allow navigating and matching of the cartographic images and spatial distribution of the thematic content.

As Phobos has a very irregular shape that resembles a potato (see image on Fig. 4), a three-axial ellipsoid is the most suitable for the representation of its surface. Because modern GISs do not support a reference system for irregular surfaces, only some maps were produced based on the three-axial ellipsoid. These maps (see Fig. 6) were compiled using the special tool, developed by the GIS Research Centre of the Institute of Geography of the Russian Academy of Sciences[3] (Nyrtsov et al. 2012), for transformation to Bugaevsky projection for three-axial ellipsoid (Bugaevsky 1987). Parameters of ellipsoid are derived from the Phobos control point network, created in MExLab, with axis a = 13.24 km, b = 11.49 km, c = 9.48 km (Nadezhdina and Zubarev 2014).

For all other maps, the unified planetocentric coordinate system was implemented with east positive longitude from 0° to 360° based on the sphere with radius 11.1 km as recommended by the International Astronomical Union (Archinal et al. 2011).

3.2 *Scales and Cartographic Projections*

All maps in the Phobos Atlas are divided into three levels of detail that are determined by their scales: global (1:200,000–1:250,000), regional (1:120,000–1:150,000), and local (1:45,000–1:75,000).

According to the scale for global maps and typographical requirements, the Atlas was printed in the size of 35 × 25 cm. This format is also convenient for the presentation of individual Phobos sites at scales selected for multi-sheeted maps (1:75,000 and 150,000).

For global maps, a set of cartographic projections was defined according to features of the mapping area and acceptable distortions. For the characterization of image resolution and control point errors, as well as for maps showing distribution of surface parameters for entire body, the simple cylindrical projection was used (Fig. 1). This projection is often applied to represent the results of processing the of initial data, so it is also most often used for mapping of planetary bodies, for example, in the Astrogeology Science Center,[4] since it does not require to re-arrange maps into other projections.

For topographic maps and maps of relief features, conformal Mercator and polar stereographic projections (Fig. 2) were selected to show the objects in both equatorial and polar areas with the same details.

[2]http://planetarynames.wr.usgs.gov/Page/PHOBOS/target.

[3]http://geocnt.geonet.ru/en/3_axial.

[4]https://astrogeology.usgs.gov/maps.

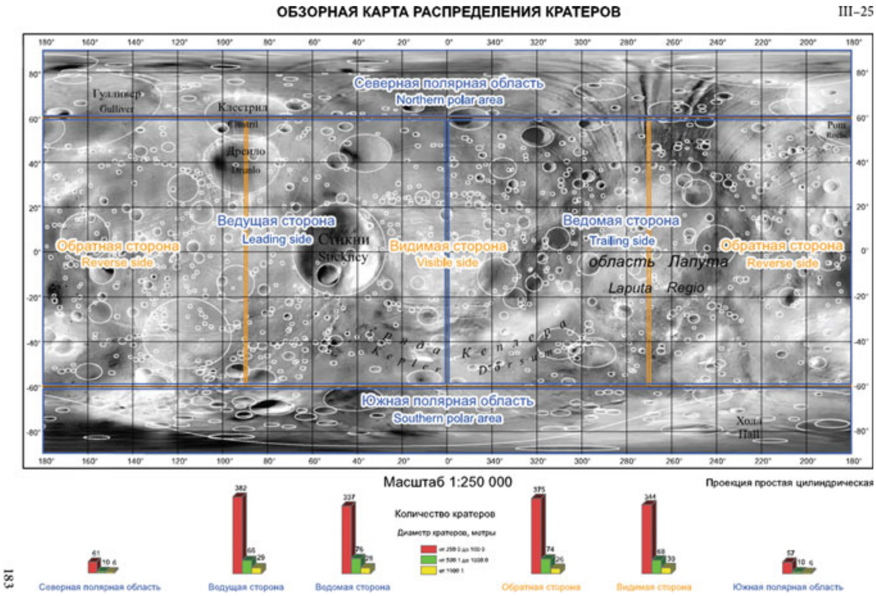

Fig. 1 Index of fifth sheet map of crater distribution (Phobos Atlas, MIIGAiK, 2015)

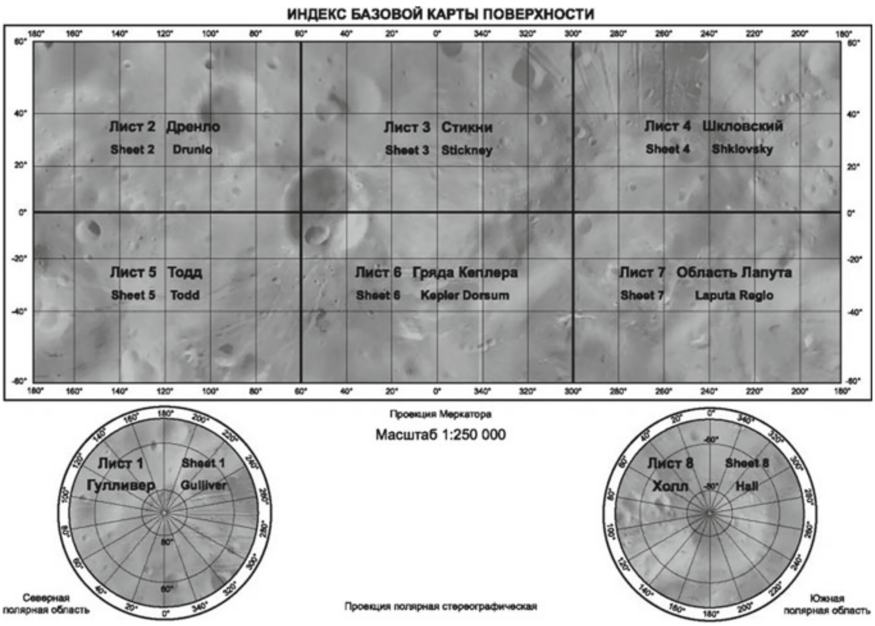

Fig. 2 Index of Phobos base map sheets

Fig. 3 Map of crater distribution, fourth sheet, trailing side of Phobos (see also Fig. 1)

Mollweide projection was chosen to demonstrate albedo properties (central meridian 90°) as well as crater density (central meridian 0°). In the first case, the choice is due to the fact that the multi-spectral data was available only for a certain Phobos area, whereas in the second case a *density* map requires an *equal area* projection.

A base map as usual depicts background reference information such as landforms and landmarks. The Phobos base map is a map derived from an orthomosaic to show relief features with possible large scale (1:75,000) for the entire body; it also includes contour lines and elevation marks added for outstanding landforms and locational reference. This map follows the eight-sheet layout of Greeley and Batson (1990) (Fig. 2).

Each of the sheets between −60° and 60° parallels was transformed into Mercator projection with the main parallel and main meridian in the center of the map. For polar areas, a stereographic projection was used.

To show crater distribution derived from manual crater detection, a five-sheet map (1:150,000) was prepared. Four sheets represent an area between −60 and 60 parallels in Mercator projection with the main parallel and main meridian in the center of each sheet. The fifth sheet shows the polar areas, for which the same stereographic projection, as described for global maps, is used. Craters outlined on the map (Fig. 3) were digitized semi-automatically using Crater Tools (Kneissl et al. 2011). Our crater catalogue that includes about 5500 objects was produced using the MExLab global mosaic and refined by available images of high resolution (4–10 m/pixel) obtained under various solar illumination conditions (Karachevtseva et al. 2012).

The most detailed map (1:45,000) shows the distribution of boulders, which is presented on a high-resolution image (1.5 m/pixel), obtained by Mars Orbiter Camera onboard Mars Global Surveyor (Malin et al. 2010). Boulders were outlined as circle objects with Crater Tools. The smallest boulder has diameter of 1.7 m.

4 Data Source and GIS

The stand-alone geodatabase has been developed with the proprietary software ArcGIS (ESRI™) for data storage, data analysis, production of derived data and mapping (Karachevtseva et al. 2014).

Various data sets—the Super Resolution Channel (SRC) of the High Resolution Stereo Camera (HRSC) images (Oberst et al. 2008) onboard the European Mars Express, as well as NASA Viking Orbiter-1 data, and images from Soviet mission Phobos 2—were used for photogrammetric image processing, performed in MExLab (Zubarev et al. 2012). They provided the basic layers: a geodetic control point network (CPN), a global orthomosaic, and a DEM. Our technique is based on proprietary photogrammetric software PHOTOMOD (Rakurs™) that was specially adopted in MExLab for planetary data processing.

The MExLab CPN includes 813 points measured 9738 times. This means that the coordinates of each point were measured accurately, in average on 12 images. Altogether, 191 images were used: 165 SRC images, and additional 16 Viking Orbiter 1 images and 10 Phobos 2 images to fill gaps in Mars Express coverage. The SRC images with a resolution ranging from 2.5 to 20 m per pixel cover 91% of the Phobos surface; the remaining 9% are covered with Viking Orbiter 1 images with an analogous resolution. The Phobos 2 images made it possible to supplement the network with new measurements, enhancing its rigidity, since the Phobos 2 orbit was different from orbits of other missions. Thus, frame images of three Phobos missions with a resolution up to 80 m/pixel were jointly processed. The accuracy of the CPN ranges from 4.5 to 67.0 m, and the mean uncertainty of three-dimensional point location is 13.7 m (Nadezhdina and Zubarev 2014).

Global Phobos orthomosaic and DEM (with resolution 20 and 200 m/pixel, respectively) were referenced to the CPN, whose coordinates have been re-analyzed recently (Oberst et al. 2014) due to new SRC images obtained by ongoing Mars Express mission since the first release of our CPN (2012). The DEM derived from automatic stereo measurements of elevation points on image pairs was augmented manually by including 3D shape structural lines along terrain features (rims of craters and grooves). As a result, a digital terrain model (DTM) was created that accurately reflects the position of relief objects. It is very important for further analysis, for example, for morphometric measurements such as crater form or depth, because sometimes the position of objects picked on orthomosaic and then measured on DEM diverges due to different processing techniques.

Based on the DTM, a number of secondary products (slope, shaded relief) were generated using the standard spatial tools of ArcGIS. Phobos roughness that shows variations of heights was calculated in many ways (Karachevtseva et al. 2012). Topographic roughness is an important geomorphological index that depends on the scale of the territory and studied forms of relief, as well as the type and resolution of input data (Florinsky 2016). To define roughness parameters of Phobos, we applied various statistical methods: area ratio, standard deviations of elevation, slope, and profile curvature (Grohmann et al. 2010) as well as Laplacian as interquartile range of the second derivative of heights (Kokhanov et al. 2013). It should be noted that none of the considered roughness indexes gives a satisfactory result using the existing global Phobos DEM. There are two reasons for this. Firstly, the actual amount of topographic information is still too small, and the ratio of body size to the resolution of the Phobos DEM is not large enough. Secondly, the quality of the original image set (resolution and accuracy) that was used for DEM formation is too heterogeneous because it is derived from various missions at different times. Therefore, a reliable computation of surface roughness will be possible in the future, when homogeneous, high-resolution topographic data will be available. However, the method of area ratios is independent of scale (Grohmann et al. 2010) and shows stable results regardless of the resolution of the original DEM, so a map of Phobos roughness was created based on this topographic index. Various roughness parameters have been calculated using specially developed tools embedded in ArcGIS (Kokhanov et al. 2013).

Efforts were made to develop the morphometric catalogue of Phobos craters—5485 features in total—(Karachevtseva et al. 2012) and inventory of grooves—862 features in total (Lorenz et al. 2016). Features included in these catalogues were measured with special morphometric tools integrated into ArcGIS (Kokhanov et al. 2016b) and used for compiling the geomorphologic maps in the Atlas (Kokhanov et al. 2016a).

5 Legends

The *Digital Cartographic Standard for Geologic Map Symbolization of Federal Geographic Data Committee* (FGDC 2006, Chapter 25: Planetary Geology Features) describes the cartographic symbols for planetary mapping.[5] A set of the symbols adopted for implementation in ArcGIS is presented in Nass et al. (2010). Since a common basis for the symbolization is offered, for the Atlas maps we proposed our own legend, which, although is based on the standard in general, includes original symbols to reflect the distinctive features of Phobos (Fig. 4).

[5]https://ngmdb.usgs.gov/fgdc_gds/geolsymstd/fgdc-geolsym-sec25.pdf.

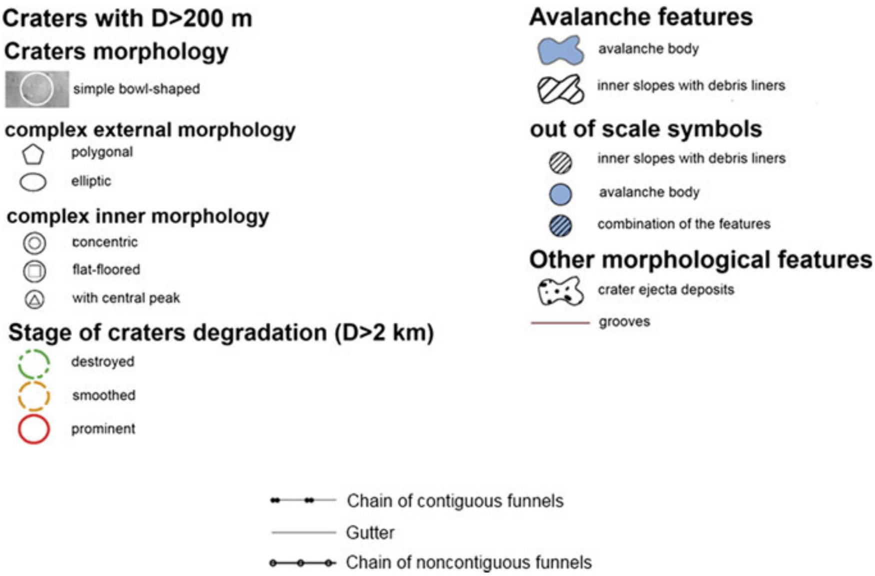

Fig. 4 Legends developed for geomorphological maps of Phobos

Although Phobos, similarly to other rocky bodies of the Solar System, is intensively cratered, a presence of several sets of grooves, crossing each other and forming a dense network, is a unique feature of the Martian satellite. Objects like Phobos are not known elsewhere among the small rocky worlds. The origin of the grooves remains unclear, and their detailed measurements and analysis carried out in our research contribute to understanding of their nature.

The uniqueness of Phobos was the main motivation for the creation of the new symbols as well as the lack of point-located cartographic symbols for morphologic objects. The developed symbols are derived from the suggested geologic classification of grooves: *gutters* (simple line depressions), *chains of contiguous funnels*, and *chains of noncontiguous funnels* (Lorenz et al. 2016). Specialty of presentation of morphological types of impact craters is chosen considering the Atlas as *an instrument for planning future missions*, including selection of landing sites, where fresh craters are of great danger.

Since symbols of craters morphology represent inner and outer geometric peculiarities, we use simple geometric off-scale signs for their classification. Areal signs are used for color-coded visualization of crater degradation stages, as well as for avalanche features and ejecta deposits visible at defined scale. Grooves are shown in linear signs.

Fonts were used to code the types of relief features: craters (normal serif), dorsae (ridges) (italic serif), regions (italic sans serif), and planitiae (plains) (normal sans serif) (Fig. 5).

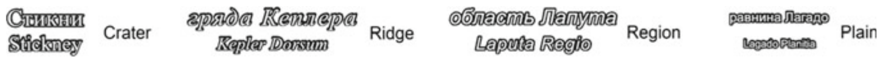

Fig. 5 Implementation of fonts for coding of relief feature types

While the text descriptions and map legends in the Atlas are prepared in Russian, feature names on the maps are presented in bilingual form (Cyrillic and Latin), because the Atlas is intended to be used by the international community, including scientists, students, and anyone interested in astronomy and planetary sciences.

6 Design

The color ramps in the Phobos hypsometric and topographic maps have been created specifically for the Atlas (Fig. 6). In accordance with the traditions of Russian cartography, various color hypsometric ramps based on perceptual approach should be chosen for different celestial bodies as it presented in the *Atlas of the Terrestrial Planets and Their Satellites* (Shingareva et al. 1992). It is taking into account the laws of perception of graphic information, for planets—these are images obtained by space missions. For the Phobos Atlas, we created the design of hypsometric ramps using an integrated perceptual analytical approach suggested by Vereshchaka and Kovaleva (2016). The analytical approach is based on the use of quantitative color parameters of ramp steps and patterns of their variation in different color models. Its advantage is the objectivity, mathematically conditioned by the characteristics of color, and the possibility for use in computer technologies.

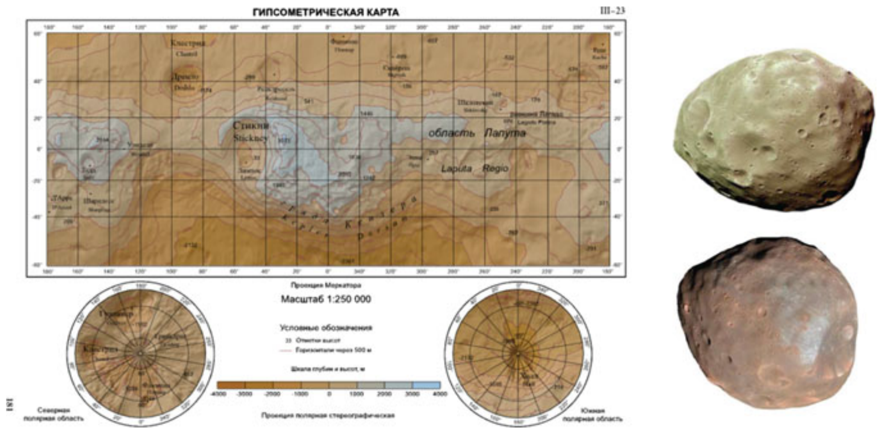

Fig. 6 Hypsometric color-coded map from Phobos Atlas (left) and color-synthesized images of Phobos obtained by Mars Express HRSC camera (right, top), credit (ESA/DLR/FU Berlin, HRSC, G. Neukum) and Mars Reconnaissance Orbiter HiRISE camera (right, bottom), credit (NASA/JPL-Caltech/University of Arizona)

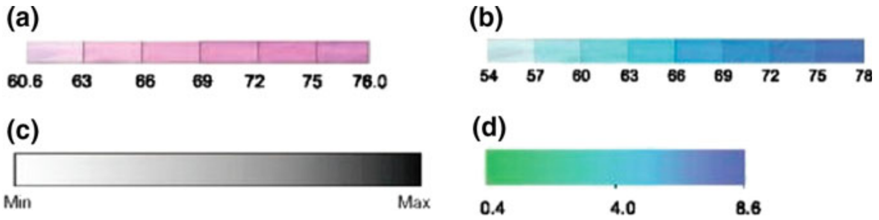

Fig. 7 Types of color scales: **a** stepped, changing in lightness for map of gravitational potential, **b** stepped, changing in lightness for map of attractive potential, **c** gradient grayscale for map of roughness, **d** gradient spectral for map of crater density

Having applied the perceptual analytical method, the boundaries of the color ramp of the Phobos hypsometric map (Fig. 6, left) are chosen in accordance with the visual perception of the Martian satellite surface on color-synthesized images (Fig. 6, right). Then, within the specified color gradient, the quantitative color parameters of the chosen ramp steps are programmed analytically using the ArcMap coloring tools.

For the other maps, we developed color ramps according to various types of data (qualitative/quantitative, absolute/relative) and different surface parameters: stepped, changing in lightness for gravitational characteristics (Fig. 7a, b), gradient grayscale for roughness, and gradient spectral scale for crater density (Fig. 7c, d). The choice of colors was determined both by cartographic traditions (e.g., for topographic maps usually red-brown ramp is used) as well as according to the color solutions implemented earlier in the *Atlas of the Terrestrial Planets and Their Satellites* (Shingareva et al. 1992), e.g., purple color for geophysical maps.

Preparation, layout compiling, design, and correction of maps were carried out by ArcMap tools. Then maps were converted into PDF format for pre-press and further publication in printing house.

7 Conclusion

The production of the Phobos Atlas—such a versatile cartographic product—requires the involvement of specialists and consultants of different specialties, whose work had to be coordinated by an editorial board. Being a comprehensive monograph, the Atlas attracted a large group of researchers from various organizations—geodesists, celestial mechanicians, geomorphologists, geologists, and cartographers. They were united by various projects: *"Geodesy, cartography and study of planets and satellites"* (Ministry of Education of Russian Federation, № 11. G34.31.0021, 2010–2012), *"Geodesy, cartography and study of Phobos and Deimos"* (Russian Foundation for Basic research, №11-05-91323, 2011–2013), *"Research of fundamental geodetic parameters and relief of planets and satellites"* (Russian Science Foundation, № 14-22-00197, 2014–2016).

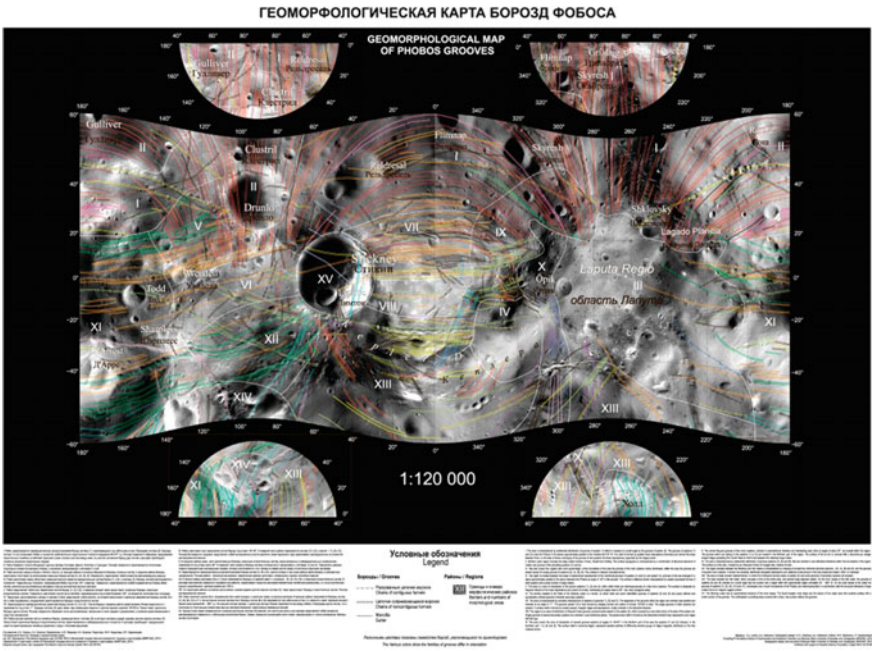

Fig. 8 Geomorphological wall map of Phobos grooves (MIIGAiK, 2016). Projections for three-axial ellipsoid developed by Bugaevsky (1987): normal conformal cylindrical (for central belt); azimuthal equidistant (for sub-polar areas)

The main results from these recent projects, which provided a coordinate-cartographic basis, were published in various scientific journals. Therefore, the Phobos Atlas was developed accumulating intensive research on the Martian satellite, such as the creation of a geodetic control point network (Zubarev et al. 2012) and the determination of shape parameters (Nadezhdina and Zubarev 2014), modeling and study of gravity field (Uchaev et al. 2013), surface compositional studies using HRSC color-channel data (Patsyn et al. 2012), the preparation of craters and grooves catalogues, the creation of a Phobos Information System (Karachevtseva et al. 2012, 2014), statistics of crater size-frequency distributions based on multi-fractal approach (Uchaev et al. 2012), and visual geologic analysis of Phobos features (Basilevsky et al. 2014). The geomorphological study of the grooves was extended (Lorenz et al. 2016) and mapped in three-axial ellipsoid that better demonstrates the irregular Phobos shape (Fig. 8).

As a collective work, students also contributed to the Atlas. Mainly geodesists and cartographers, at least ten MIIGAiK students took part at various stages of the work (collecting and pre-processing images, data co-registration, digitizing of craters and grooves, crater measurements using GIS). Having joined at the very

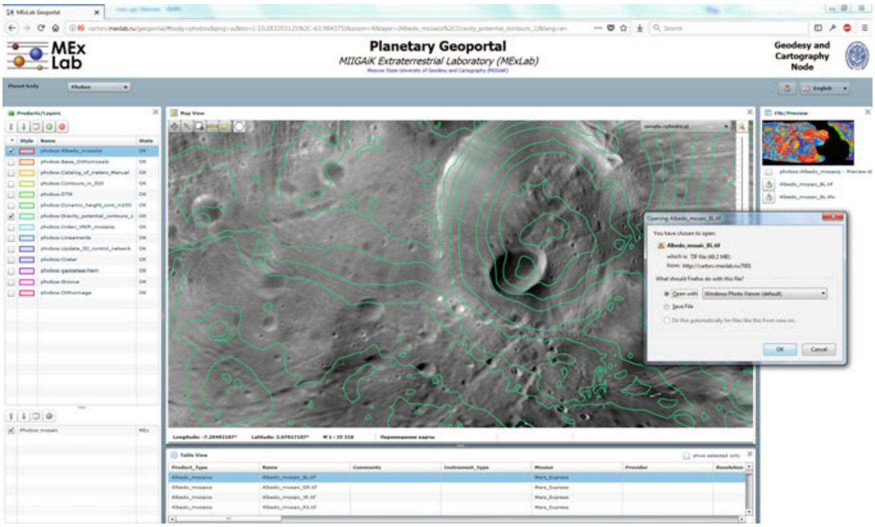

Fig. 9 Phobos layers in MExLab Geoportal: User interface for data set uploading

beginning of Phobos studies during educational practice, some of the students continued the research and defended their diploma theses in the frame of the projects and research mentioned above. Finally, maps created especially for the Atlas became a part of Ph.D. dissertation related to the cartographic support for the planning of future missions.

The Phobos Atlas is a practical instrument for landing site selection and planning mission operation at the surface, useful for the International Phobos/Deimos Landing Site Working Group,[6] organized to maintain focus on future international projects such as *Bumerang* and *Martian Moons Exploration* (MMX) missions (Kuramoto et al. 2017) to provide Phobos sample return.

Spatial data products that were applied for Phobos cartography are integrated into a stand-alone ArcGIS geodatabase, and freely accessible via the MExLab Geoportal[7] in GIS-ready format: vector layers can be downloaded as shape files, and raster data sets as georeferenced images (geotiff) (Fig. 9).

[6]https://www.lpi.usra.edu/sbag/meetings/jan2017/presentations/Duxbury.pdf.

[7]http://cartsrv.mexlab.ru/geoportal/.

References

Archinal BA, A'Hearn MF, Bowell E, Conrad A, Consolmagno GJ, Courtin R, Fukushima T, Hestroffer D, Hilton JL, Krasinsky GA, Neumann G, Oberst J, Seidelmann PK, Stooke P, Tholen DJ, Thomas PC, Williams IP (2011) Report of the IAU working group on cartographic coordinates and rotational elements: 2009. Celest Mech Dyn Astron 109:101–135

Astrogeology Science Center. https://astrogeology.usgs.gov/maps. Accessed 08 Dec 2017

Basilevsky AT, Lorenz CA, Shingareva TV, Head JW, Ramsley KR, Zubarev AE (2014) Surface geology and geomorphology of Phobos. Planet Space Sci 102:95–118. https://doi.org/10.1016/j.pss.2014.04.013

Bugaevsky LM (1987) On the problem of elaborating of isometric coordinates and equiangular cylindric projection of the triaxial ellipsoid. Izvestiya vuzov «Geodeziya i aerofotosyemka» («Geodesy and Aerophotosurveying») 4:79–90 (in Russian)

Bugaevsky LM, Krasnopevtseva BV, Shingareva KB (1992) Phobos map and Phobos globe. Adv Space Res 12(9):17–21. https://doi.org/10.1016/0273-1177(92)90314-N

Cartographical Projections of Triaxial Ellipsoid. http://geocnt.geonet.ru/en/3_axial. Accessed 25 May 2017

Dmitriev V, Lupovka V, Christou A, Oberst J (2013) Meteoroid population near Mars. In: 2013, European planetary science congress, London, EPSC 2013-629-1

FGDC (2006) Digital cartographic standard for geologic map symbolization. Federal Geographic Data Committee prepared by the U.S. Geological Survey (FGDC-STD-013-2006)

Florinsky IV (2016) Digital terrain analysis in soil science and geology, 2nd edn. Academic Press, Amsterdam

Gazetteer of nomenclature. http://planetarynames.wr.usgs.gov/Page/PHOBOS/target. Accessed 15 May 2017

Geoportal of Planetary data. Geodezy and Cartography Node. http://cartsrv.mexlab.ru/geoportal/

Greeley R, Batson G (1990) Planetary mapping. Cambridge University Press, Cambridge

Grohmann CH, Smith MJ, Riccomini C (2010) Multiscale analysis of topographic surface roughness in the Midland Valley, Scotland. IEEE Trans Geosci Remote Sens. PP(99):1–14

International Phobos/Deimos Landing Site Working Group. https://www.lpi.usra.edu/sbag/meetings/jan2017/presentations/Duxbury.pdf. Accessed 08 Dec 2017

Jaumann R, Neukum G, Behnke T, Duxbury TC, Eichentopf K, Flohrer J, Gasselt SV, Giese B, Gwinner K, Hauber E, Hoffmann H, Hoffmeister A, Kohler U, Matz K-D, McCord TB, Mertens V, Oberst J, Pischel R, Reiss D, Ress E, Roatsch T, Saiger P, Scholten F, Schwarz G, Stephan K, Wahlisch M, the HRSC Co-Investigator Team (2007) The high-resolution stereo camera (HRSC) experiment on Mars Express: instrument aspects and experiment conduct from interplanetary cruise through the nominal mission. Planet Space Sci 55:928–952

Karachevtseva IP, Shingareva KB, Konopikhin AA, Mukabenova BV, Nadezhdina IE, Zubarev AE (2012) GIS mapping of Phobos on the results of data processing of remote sensing satellite Mars Express. Mod Prob Remote Sens Earth Space 9(4):304–311 (in Russian)

Karachevtseva IP, Oberst J, Zubarev AE, Nadezhdina IE, Kokhanov AA, Garov AS, Uchaev DV, Uchaev DV, Malinnikov VA, Klimkin ND (2014) The Phobos information system. Planet Space Sci 102:74–85. https://doi.org/10.1016/j.pss.2014.11.024

Karachevtseva I, Kokhanov A, Rodionova J, Konopikhin A, Zubarev A, Nadezhdina I, Mitrokhina L, Patratiy V, Oberst J (2015) Development of a new Phobos atlas based on Mars Express image data. Planet Space Sci 108:24–30. https://doi.org/10.1016/j.pss.2014.11.024

Kneissl T, Gasselt S, Neukum G (2011) Map-projection-independent crater size-frequency determination in GIS environments—New software tool for ArcGIS. Planet Space Sci 59: 1243–1254. https://doi.org/10.1016/j.pss.2010.03.015

Kokhanov A, Lorenz C, Karachevtseva I (2016a) GIS-study and new Geomorphologic Mapping of Phobos. In: Geophysical research abstracts, vol. 18. EGU2016-1726, European Geosciences Union General Assembly, Vienna, 17–22 April 2016

Kokhanov AA, Bystrov AY, Kreslavsky MA, Matveev EV, Karachevtseva IP (2016b) Automation of morphometric measurements for planetary surface analysis and cartography. Int. Arch. Photogramm. Remote Sens Spatial Inf Sci XLI-B4:431–433. https://doi.org/10.5194/isprs-archives-xli-b4-431-2016
Kokhanov AA, Kreslavsky MA, Basilevsky AT, Karachevtseva IP, Zubarev AE (2014) Morphometry of large craters on Phobos and comparison with other bodies. In: 45th LPSC, abs. #1084
Kokhanov AA, Kreslavskiy MA, Karachevtseva IP, Matveev EN (2013) Mapping of the statistical characteristics of the lunar relief on the basis of the global digital elevation model GLD-100. Mod Probl Remote Sens Earth Space 10(4):136–153 (in Russian)
Kuramoto K, Kawakatsu Y, Fujimoto M, MMX Study Team (2017) Martian moons exploration (MMX) conceptual study results. In: XLVIII lunar and planetary science conference (LPSC), Abstract #2086
Lavochkina Association, POSKOCMOS. Bumerang project. https://www.laspace.ru/projects/planets/expedition-m/. Accessed 08 Dec 2017 (in Russian)
Lorenz CA, Kokhanov AA, Karachevtseva IP (2016) Morphological study of Phobos surface and mapping of the grooves. In: 47th LPSC, abs. #1831
Malin MC, Edgett KS, Cantor BA, Caplinger MA, Danielson GE, Jensen EH, Ravine MA, Sandoval JL, Supulver (2010) An overview of the 1985–2006 Mars Orbiter Camera science investigation. Mars—Int J Mars Sci Explor 5:1–60 Mars Informatics Inc.
Nadezhdina IE, Zubarev AE (2014) Formation of a reference coordinate network as a basis for studying the physical parameters of Phobos. Sol Syst Res 48(4):269–278. https://doi.org/10.1134/S003809461404008X
Nass A, van Gasselt S, Jaumann R, Asche H (2010) Implementation of cartographic symbols for planetary mapping in geographic information systems. Planet Space Sci 59(11–12):1255–1264. https://doi.org/10.1016/j.pss.2010.08.022
Nyrtsov MV, Fleis ME, Borisov MM (2012) Mapping asteroid 433 Eros with equidistant along meridians cylindrical and azimuthal projections of triaxial ellipsoid. Izvestiya vuzov «Geodeziya i aerofotosyemka» («Geodesy and Aerophotosurveying») 1:54–56 (in Russian)
Oberst J, Schwarz G, Behnke T, Hoffmann H, Matz K-D, Flohrer J, Hirsch H, Roatsch T, Scholten F, Hauber E, Brinkmann B, Jaumann R, Williams D, Kirk R, Duxbury T, Leu C, Neukum G (2008) The imaging performance of the SRC on Mars Express. Planet Space Sci 56 (3–4):473–491
Oberst J, Zubarev A, Nadezhdina I, Shishkina L, Rambaux N (2014) The Phobos geodetic control point network and rotation model. Planet Space Sci 102:45–50. https://doi.org/10.1016/j.pss.2014.03.006
Patsyn VS, Malinnikov VA, Grechishev AV (2012) Research of spectrometric characteristics of the surface of Phobos on the HRSC data from the Mars Express spacecraft. Mod Probl Remote Earth Sens Space 9(4):312–318 Space Research Institute, Moscow (in Russian)
Phobos from 6,800 Kilometers (Color): NASA/JPL-Caltech/University of Arizona/PIA10368. https://photojournal.jpl.nasa.gov/catalog/PIA10368/. Accessed 08 Dec 2017
Phobos: a colored view made from images taken from two different flybys in March 2010: ESA/DLR/FU Berlin (G. Neukum). https://www.universetoday.com/82302/mars-express-set-for-phobos-flyby/. Accessed 08 Dec 2017
Salishev KA (1982) Kartovedeniye (Cartography). 3rd edn, 400 p (in Russian)
Shingareva KB, Krasnopevtseva BV, Leonenko SM, Fleis ME, Buchroithner MF, Waelder O, Stooke P (2005) Phobos and Deimos—a new map in the series of multilingual relief maps of terrestrial planets and their moons. In: Proceedings of 22nd international cartographic conference, A Coruña, Spain, 9–16 July 2005
Shingareva KB, Krasnopevtseva BV, Rodionova JF et al (1992) Atlas of the terrestrial planets and their satellites. MIIGAiK, Moscow, p 208 (in Russian)
Snyder JP (1985) Conformal mapping of the triaxial ellipsoid. Survey Rev 28(217):130–148
Stooke PJ (2012) The international atlas of mars exploration. the first five decades, volume 1, 1953 to 2003. Cambridge University Press, Cambridge, p 376

Uchaev DV, Uchaev DmV, Malinnikov VA, Oberst J (2012) Multifractal model for Phobos crater size-frequency distribution. In: EPSC abstracts 7, EPSC2012-705-3

Uchaev DmV, Uchaev DV, Prutov I (2013) Multiscale representation of gravitational fields of small celestial bodies. Izvestiya vuzov «Geodeziya i aerofotosyemka» («Geodesy and Aerophotosurveying») 4:3–8 (in Russian)

Vereshchaka TV, Kovaleva OV (2016) Presentation of the relief on the maps: theory and methods (design aspect). The Scientific World, Moscow, 181 p. ISBN 978-5-91522-427-7 (in Russian)

Wählisch M, Stooke PJ, Karachevtseva IP, Kirk R, Oberst J, Willner K, Nadejdina IA, Zubarev AE, Konopikhin AA, Shingareva KB (2014) Phobos and Deimos cartography. Planet Space Sci 102:60–73. https://doi.org/10.1016/j.pss.2013.05.012

Zubarev AE, Nadezhdina IE, Konopikhin AA (2012) Problems of processing of remote sensing data for modeling shapes of small bodies in the Solar system. Mod Probl Remote Sens Earth Space 9(4):277–285 (in Russian)