REMOTE SENSING FOR MAPPING THE PLANETS

Dr. Yu.S. Tjuflin

Central Research Institute of
Geodesy, Airsurvey and Cartography

Moscow, USSR

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At present the main method of studying and mapping the planets and satellites is that of remote sensing from automatic interplanetary stations (AIS). Space photography was first performed by the Soviet automatic station "Luna-3". Then photography of the planets and satellites was included into a number of Soviet and American programs.

For the time being, photography method of studying the plantes from AIS has not yet become so conventional as, for example, aerophotography. Every space photo of the planet or the satellite gives much information concerning the object under study which justifies high costs spent to obtain it. Naturally, it is the case, in the first place, with the pioneer space experiments when the first pictures of the Moon far side, Mars, Mercury, Venus, Jupiter and Saturn have been obtained and when the first pictures of the Moon, Venusian and Martian surfaces have been transmitted to the Earth directly from the celestial body.

By January, 1984, photography information on the Moon, Mars and Venus has been obtained in the Soviet Union from 13 orbital and 9 descent vehicles.

To study the planets AIS were equipped with various cameras. Photo cameras with recoverable film were installed on spacecrafts "Zond-6, -7, -8". Photo and TV cameras were successfully operated on AIS "Luna-3", "Zond-3", "Luna-12", "Mars-4, -5". AIS "Mars-4, -5", "Luna-19, -22" and "Venera-9" carried TV scaners. Side-looking radars were used for mapping the Venusian surface from AIS "Venera-15, -16".

For detailed topographic studies of small landing areas of the planets scan TV cameras (telephotometers) were used in most cases. This equipment operated on automatic stations "Luna-9, -13, -20", automatic lunar vehicles "Lunokhod-1, -2", descent modules of AIS "Venera-9, -10, -13, -14". Besides telephotometers, small-frame TV cameras were used for remote control of "Lunokhod-1, -2" movement and for making topographic schemes along the route of the lunar vehicles.

Color photography of the Moon surface was performed from automatic station "Zond-7". Photography with red, blue and green filters enabled to obtain color synthesized pictures of the Martian ("Mars-5") and Venusian ("Venera-13, -14) surfaces.

To determine the altitudes of the Moon surface from automatic station "Luna-22" TV scanning and radar profiling were carried out simultaneously. To determine the altitudes of the Moon surface from automatic station "Luna-22" TV scanning and radar profiling were carried out simultaneously. To determine the altitudes of the Venus surface from AIS "Venera-15, -16" radar and radioprofiling systems were used.

The space experiments carried out and the planned ones and the experience gained in processing the pictures obtained raise new problems before photogrammetry. The necessity of receiving space pictures with various geometry from space stations, that are millions of kilometers away from the Earth, and making the control of these stations efficient required complicated complexes to receive and process visual information should be established. The conventional geodetic data used for map making was substituted by ballistic data; in this case the main information with exterior orientation of space pictures is provided by coordinates and angles of orientation of space stations that are determined when stations are in flight. The peculiarities of applying the photogrammetric method for mapping the planets are largely due to these and some other factors.

Consider some photogrammetric problems that have been solved in planet studies by using space photography. Begin with the theory, the equations connecting spatial coordinates of location points in reference coordinate system, and coordinates of their images. Space pictures obtained from AIS with the help of TV, photo and photo-TV equipment are close to central projections. Conventional collinear conditions can be used for them without any change; only connecting parameters will be new. They are angular elements of camera orientation relative AIS axes, angular elements of camera orientation and osculating elements of the station orbit at the time of taking pictures in the inertial coordinate system and angles at the same time - that determine the position of zero meridian and the north pole of the planet rotation. The latter parameters enable to transform the information from the inertial coordinate system at standard epoch into the planetocentric system.

The available dependences for frame pictures are not suitable for processing space pictures received with the help of TV scan systems with various kinds of scanning, radar system, etc. However if every location point is determined in the camera coordinate system by its spherical coordinates and the distance from projection center to the location point, the same approach of obtaining dependences sought for can be used regardless of equipment types. Spherical coordinates of points should be expressed in terms of plane coordinates of picture points on the basis of the rules of image construction. To process TV and radar panoramic pictures it is necessary to distinguish parameters that are common for the whole image, that can be refined while solving photogrammetric problems. The parameters that locate space pictures, are osculating elements of the station orbit at a fixed moment, for example, at the time of passing station pericenter of the orbit from which the picture had been obtained. In the terms of photogrammetry these parameters are essentially the elements of outer orientation of space pictures. Their change during the image construction can be attributed to systematic errors of the image construction model. Such approach of obtaining initial equations is particularly reasonable to solve direct photogrammetric intersections, the problem of constructing photogrammetric network on planets and satellites, to refine orbital elements of space stations by using images, etc. Deflection angles of scanning beams in the coordinate system of optical-mechanical camera, time of scanning and station orbital elements are used to process TV panoramic images. While processing radar panoramic pictures, distances to location points and velocity components in the direction of radar beams are used instead of deflection angles of scanning beams.

While transforming space pictures into cartographic projections, various and complicated geometry of images forced to use computer-assisted analytical methods and input-output image systems. Various technological schemes are used to produce transformed images. The most commonly used technology is as follows: coordinates of initial image elements are precomputed by using those of the transformed image and then they are sought for in brightness matrix of the initial image and these brightnesses are transfered into the matrix of the transformed image. The regular network and interpolation methods within its closest junctions are used to construct most efficient algorithms and computer programs.

Altitude characteristics of the planet surface can be determined by using digital processing systems and represented as optical image convenient to visual perception and similar to maps with relief shading. Relief is represented as if it were on horizontal plane, with illumination being inclined. It can also be represented as an artificially created stereogram.

Space photogrammetry deals with the problems of refining rotation elements of planets and satellites and with those of accuracy estimation of photogrammetric networks of planets and satellites. In our opinion, three types of characteristics should be obtained to estimate accuracy of photogrammetric networks constructed. They are errors of interlocation of network points within the area of the network, errors of point locations in the accepted planetocentric coordinate system and external errors that characterize the orientation of the whole photogrammetric network in respect with the inertial coordinate system for the standard epoch. So far, accuracy characteristics are not available for all those celestial bodies that have photogrammetric networks.

Consider briefly some results of mapping the Moon and the planets obtained in the USSR.

The total map of the Moon at scale of 1:5 000 000 is the main result of the Moon mapping. For the latitude range of ± 60° the map is produced in orbitrary cylindrical projection and the maps of northern and southern Pole region are produced in azimuthal orthomorphic projection. Shading is used to represent relief on the map. This map was substantially supplemented and refined by using new data, and published in 1973 (3d edition).

Another series of the Moon maps at scale of 1:500 000 - 1:2 000 000 was produced on the basis of more recent data obtained from "Zond-6, -7, -8". The series includes four map versions of equatorial part of the Moon far-side in external perspective projection at scale of 1:2 000 000 (1971-1975, "Zond-6"); three map versions of far-side of the Moon at scale of 1:1 000 000 (1972); ten sheets of map of the far-side of the Moon in Mercator projection, at scale of 1:1 000 000 (1976, "Zond-8"); six map versions of the farside of the Moon for near equatorial region in Mercator projection at scale of 1:500 000 (1979); photomap of the Moon area with contour lines at scale of 1:1 000 000 (1971-1972).

39 large-scale plans of the Lunar surface at scale of

1:15 - 1:1000 were produced using photographic data received from lunar vehicles "Lunokhod-1, -2".

After photogrammetric processing and interpretation of the data received from AIS "Mars-4, -5" extension of photogrammetric control on Mars was performed and color maps with shaded relief were produced: one map at scale of 1:5 000 000, three insert maps at scale of 1:800 000 and four maps at scale of 1:500 000. Lambert-Gauss projection was used for all the maps.

Topographic study of planet surfaces is not restricted to photography from AIS orbits. Photo and TV data from descent modules are used to compile large-scale topographic maps intended for studies of surface microstructures. After the photogrammetric processing of the data obtained from descent modules of AIS "Venera-9, -10" superlargescale plans of landing sites at scale of 1:10 were produced. For this purpose pencil retouching was used that reflects photometric features of the Venus surface.

In 1983 the photogrammetric and cartographic processing of TV panoramic pictures received from descent modules of AIS "Venera-13, -14" was completed. Topographic photoplans of landing sites were produced at scale of 1:20. To produce them computer-assisted digital method was used along with an input-output image system. The plane of landing ring of descent modules served as horizontal control for topographic photoplans.

Large-scale topographic plans of the Venus surface are intended for detailed geological-morphological studies and for determination of dimensions and interlocation of relief elements. They can also be used as a basis for subsequent compilation of superlarge-scale thematic plans. These plans are essentially photo-keys to interpret radar images of Venus obtained from orbiters.

In 1983-1984 the main attention in the Soviet Union was focused on mapping the Venus surface from AIS "Venera-15, -16". Radar mapping of Venus from AIS "Venera-15, -16" is a new step of mapping this planet. The Venus atmosphere is not transparent in visual, infrared and ultraviolet parts of the spectrum and therefore only the radar method enables to perform surface surveying, to construct control network and to produce topographic and thematic maps on the regions studied.

Since November 1983 successive mapping of Northern parts of Venus has been performed with the resolution of 1.5-2 km.

The equipment for radar mapping includes a side-looking radar and radioaltimeter. The radar equipment mounted on the stations operates under two modes being in turn a radioaltimeter and a side-looking radar with antenna deflection of 10° in the plane perpendicular to the plane of the station orbit. The main mode for radar mapping is to the right in the direction of the station motion. The axis of the radio altimeter tracks mass center of the planet. The wave length of the radar equipment is 8 cm. The beam pattern of the radio altimeter is 4° and that of the side-looking radar is 0.8 - 1° in the direction of the station motion and 5-6° in the direction of mapping. Radar mapping and radioprofiling of the surface are performed near orbit pericenter at altitudes of 1000-2000 km. The orbit inclination is close to 90°, the orbit is elongated, elliptical, the revolution period of the stations is 24 hours.

Pericenter tracks of the stations on the Venus surface in Venusian coordinate system is at the latitude of about 60°. Period of radar mapping and radioprofiling takes 15-16 min. The results include radar panorama covering the area of about 100x7000 km^2 and altitude profile along the station track.

The system recommended by the International Astronomical Union (IAU) was accepted as Venusian coordinate system for radar mapping of Venus from AIS "Venera-15, -16". The angles α_0, δ_0, W determining the position of the system with respect to Venusian geoequatorial coordinate system of the epoch B1950 and reference-surface of the planet assumed to be a sphere with radius of 6051.0 km, were also recommended by IAU.

Proceeding from the resolution and interpretability of the radar pictures obtained scale of 1:5 000 000 was chosen for mapping the Venus surface. The results of radar mapping enable for the first time to represent separate small morphological forms along with the macroforms of the surface on Venus maps. To produce photoplans and maps of Venus surface at this scale the planet surface is divided into trapeziums that are in different latitude belts. To reduce distortions different cartographic projections will be used for every latitude belt. The method used to divide the Venus surface into trapeziums and to choose cartographic projections was the same as the one used in producing the maps of Mercury and Mars. The maps of Polar regions will be produced in normal azimuthal orthomorphic projection and those of medium latitude will be produced in Lambert-Gauss normal orthomophic conical projection and equatorial regions will be produced in Mercator normal cylinder projection.

Radar panorama of the surface swath is the main initial material for photogrammetric processing and interpretation. Like an airphoto picture, a radar panorama contains complete information about the surface. Every panorama element is determined by spherical coordinates B and ϑ_n in Venusian orbital coordinate system at the time of station passing the pericenter of the orbit revolution. Here ϑ_n is the true station anomaly at a current moment referred to Keplerian orbit at the time moment of station passing the orbit pericenter, B is the angle between the orbit plane and the line connecting Venus mass center with a point on the surface. The origin of Venusian orbital coordinate system coincides with mass center of the planet, the plane OX_nZ_n coincides with the plane of osculating orbit at the time moment of station's passing the orbit pericenter, axis OZ_n coincides with direction of vector radius of the station at the time moment of station's passing the orbit pericenter, axis OX_n is in the direction of the station motion, the direction of axis OY_n forms the right-hand system.

The methods of solving direct photogrammetric problems, of refining the elements of outer orientation of radar panoramas, of image transformation into cartographic projections and of constructing the photogrammetric control on the planet surface will be used in processing Venus radar data from AIS "Venera-15, -16".

Initial equations in processing the radar data and for solving photogrammetric problems are:

$$\mathcal{F}' = R_{ni}^2 + R^2 - z^2 - 2RR_{ni}(A\cos\vartheta_n + B\sin\vartheta_n) = 0\ ,$$

$$\mathcal{F}'' = zV_z - V_u R_{ni}(B\cos\vartheta_n - A\sin\vartheta_n) - V_R R_{ni}(A\cos\vartheta_n + B\sin\vartheta_n) + RV_R = 0\ ,$$

$$\mathcal{F}''' = tg\,\vartheta_n + \frac{(R^2 + z^2 - R_{ni}^2)(AV_R + BV_u) - 2R(BRV_u - AV_z z)}{(R^2 + z^2 - R_{ni}^2)(BV_R - AV_u) + 2R(ARV_u - BV_z z)} = 0\ ,$$

where
$$A = a_{1n}\cos\varphi\cos\lambda + b_{1n}\cos\varphi\sin\lambda + c_{1n}\sin\varphi\ ,$$
$$B = a_{2n}\cos\varphi\cos\lambda + b_{2n}\cos\varphi\sin\lambda + c_{2n}\sin\varphi\ ,$$

$$R = \frac{a_n(1 - e_n^2)}{1 + e_n\cos\vartheta_n}\ ,\quad V_R = \sqrt{\frac{\mu}{a_n(1 - e_n^2)}}\, e_n\sin\vartheta_n\ ,\quad V_u = \sqrt{\frac{\mu}{a_n(1 - e_n^2)}}\,(1 + e_n\cos\vartheta_n)\ ,$$

$$t = \tau_n + \frac{E_n - e_n\sin E_n}{\sqrt{\mu/a_n^3}}\ ,\quad tg\,\frac{E_n}{2} = \sqrt{\frac{1 - e_n}{1 + e_n}}\, tg\,\frac{\vartheta_n}{2}\ ,$$

t, z, V_z are the time moment, the distance from station to the surface point, the component of the station velocity in the direction to the surface point; φ, λ, R_{ni} are Venusian latitude and longitude of the surface points and the length of the Venusian radius-vector of the surface point; R, V_R, V_u are the length of the station radius-vector, the radial and transversal components of the station velocity; ϑ_n is the true anomaly of the station referred to Keplerian orbit of the time moment of station passing the orbit pericenter; $a_{1n}, \dots, c_{3n}$ are the matrix elements for transformation of the Venusian orbital central coordinate system into the Venusian coordinate system; a_n, e_n, τ_n are the major semiaxis of the station orbit, the excentricity and the time moment of station passing the orbit pericenter.

Matrix elements $a_{1n}, \dots, c_{3n}$ are calculated using angles α_0, δ_0 and W which are known at time moment in the Venusian central geoequatorial coordinate system for standard epoch B1950 and which determine the North Pole of Venus rotation and direction of the zero meridian; precession orbital elements ζ, θ, z which are used for transformation from standard epoch B1950 into epoch T_1; osculating orbital elements Ω_n, i_n, ω_n at the time moment of station passing the orbit pericenter which are known for epoch T_1 in the Venusian central geoequatorial coordinate system.

Strictly, osculating elements of Keplerian orbit would not coincide at an arbitrary time moment and at the time moment of station passing the orbit pericenter. This fact can be accounted for in processing.

To conclude it should be pointed out that mapping the Moon and the planets helps us to know better and to study our own planet and to give the humanity new knowledge about Nature.

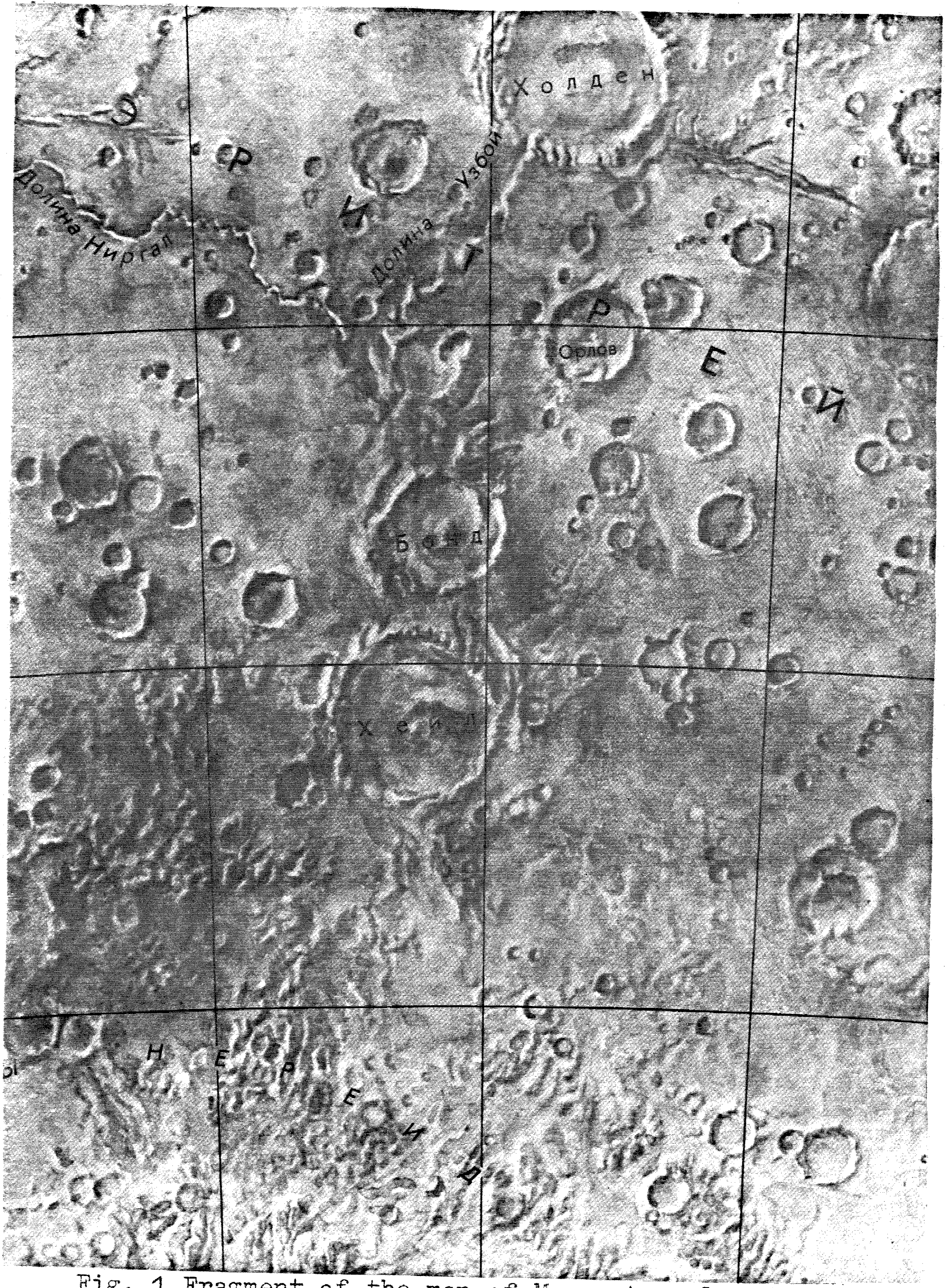

Fig. 1 Fragment of the map of Mars at scale of 1:5 000 000 produced using AIS "Mars-4,-5" data

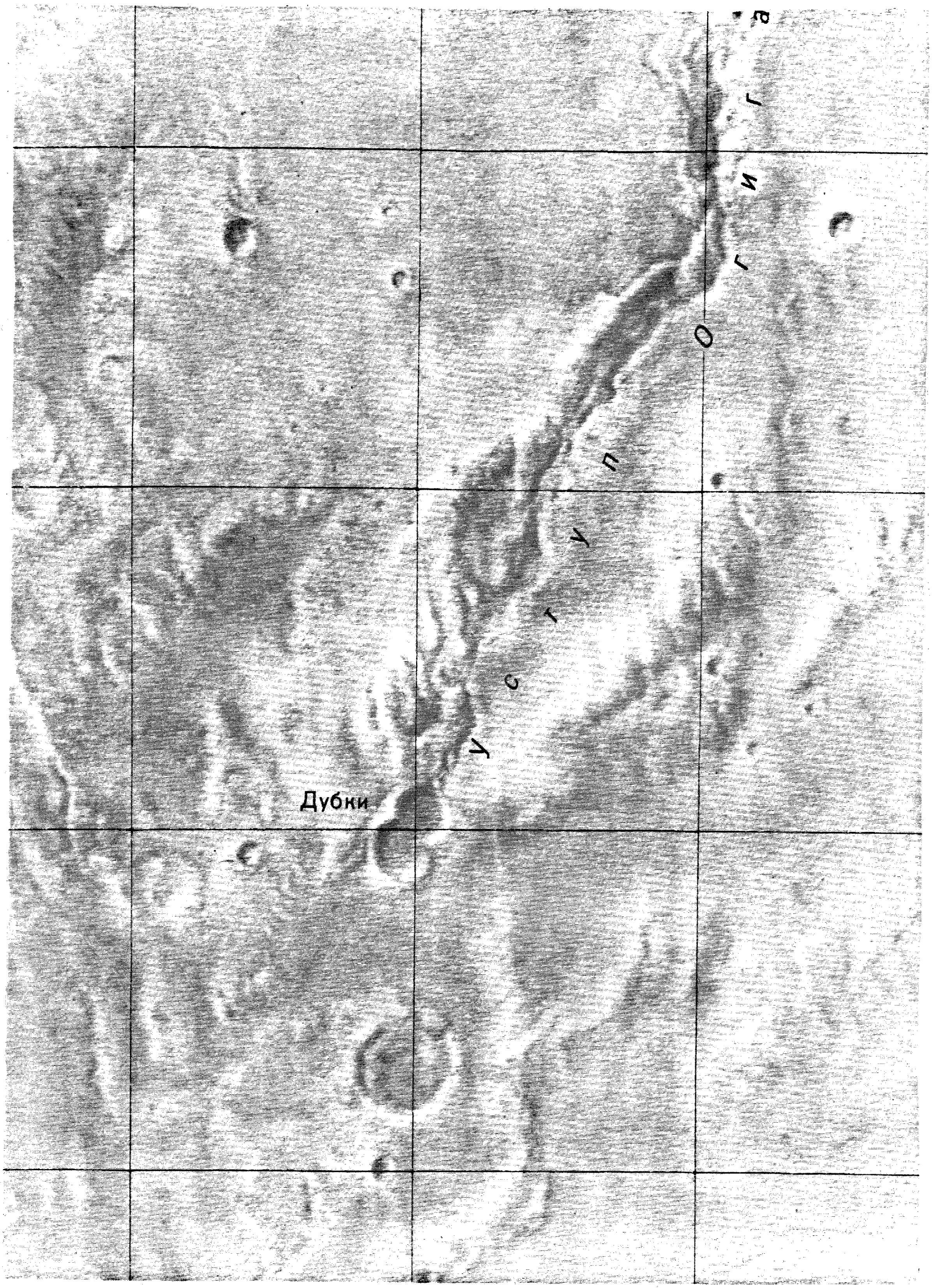

Fig. 2 Fragment of map of Mars at scale of 1:500 000 produced using AIS "Mars-5" data

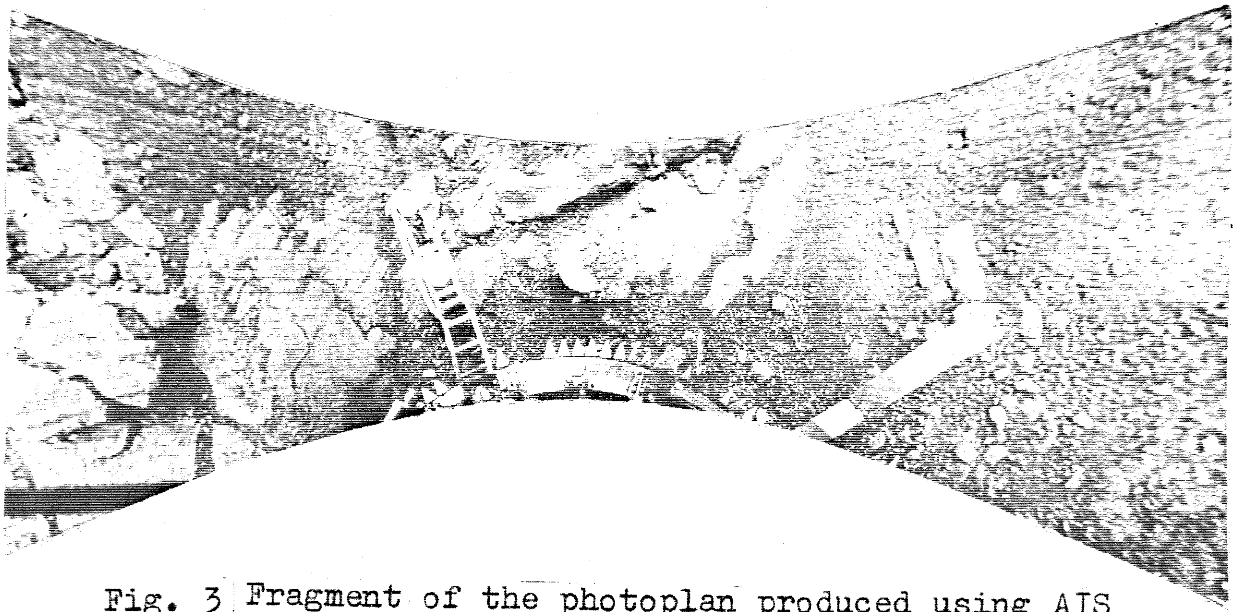

Fig. 3 Fragment of the photoplan produced using AIS "Venera-13" descend module data

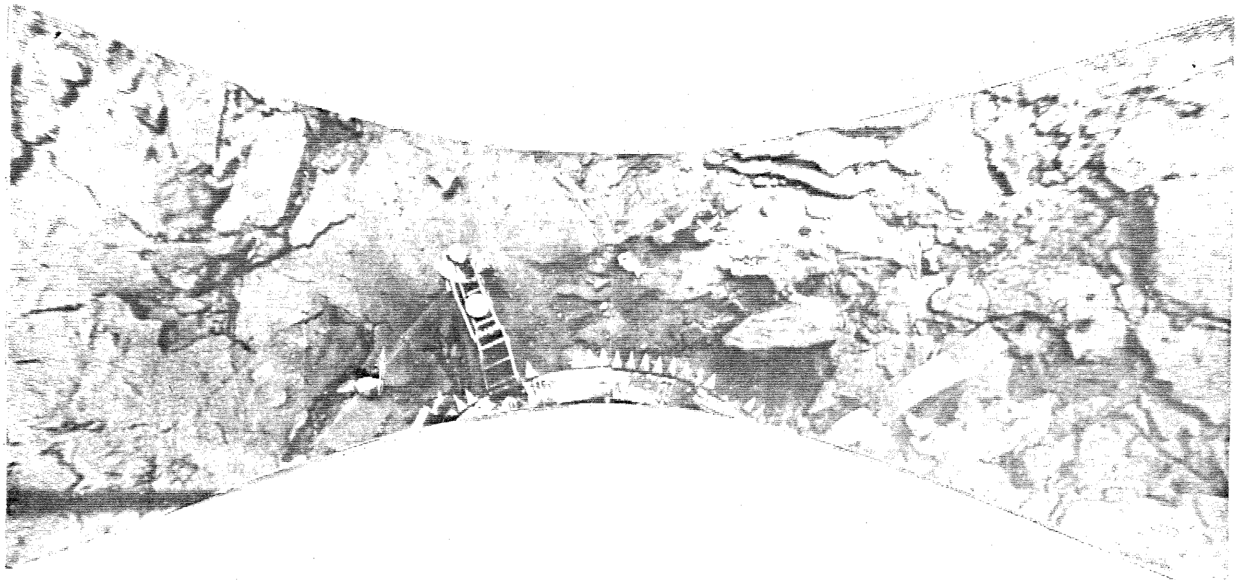

Fig. 4 Fragment of the photoplan produced using AIS "Venera-14" descend module data

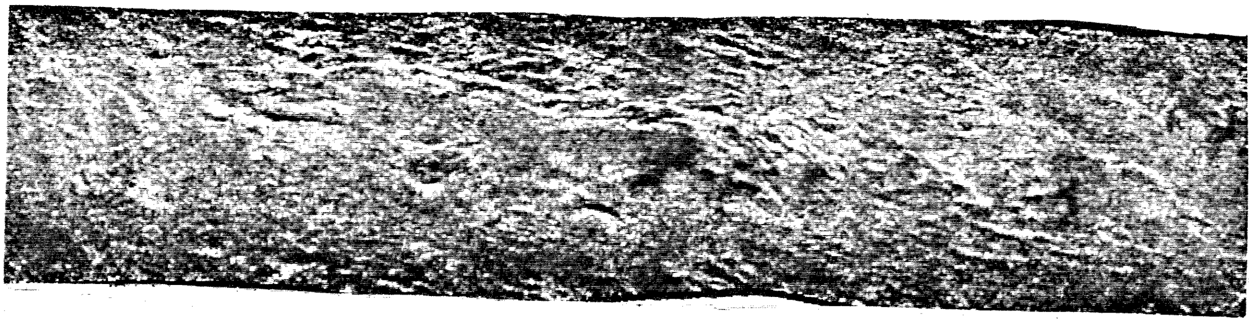

Fig. 5 Fragment of radar panorama of the Venus surface produced using AIS "Venera-15" data

Fig. 6 Fragment of radar panorama of the Venus surface produced using AIS "Venera-15" data

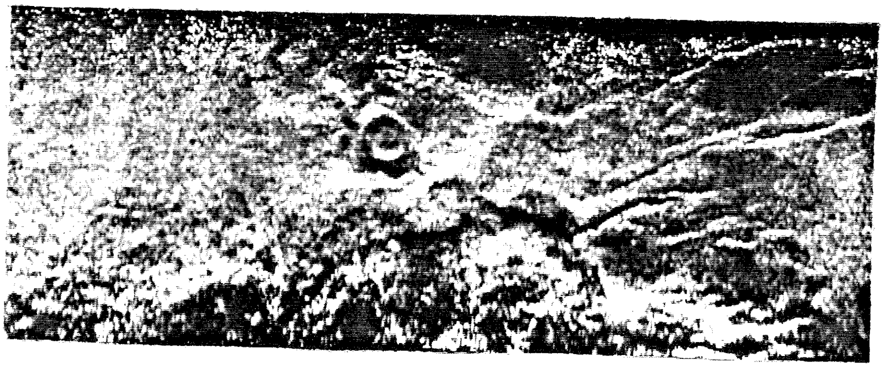

Fig. 7 Fragment of radar panorama of the Venus surface produced using AIS "Venera-16" data