RADAR SURVEYING OF VENUS'S SURFACE AND ITS CONTRIBUTION TO DEVELOPMENT OF PHOTOGRAMMETRY

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ABSTRACT

Introduction of each new type of surveying with unconventional geometry of image formation contributes to further development of photogrammetry. Radar surveying of Venus's surface by "Venera-15" and "Venera-16" probes is an example of such development. The equipment used for radar surveying as well as its parameters are discussed, geometry of radar panoramas formation, basic equations and methods of photogrammetric problems solution are presented, problems of stereophotogrammetric method employment, cartographic output of Venus's surface surveying are described. The radar images acquired for the area of 115 million sq.km were used to prepare 27 photomaps with contours at 1:5,000,000 scale. The conformal projections were chosen for the photomaps. Conversion of radar imagery into cartographic projections was made by means of digital techniques using a computer and an image processing system.

Introduction of each new type of surveying with unconventional geometry of image formation contributes to further development of photogrammetry. Radar surveying of Venus's surface by "Venera-15" and "Venera-16" probes is an example of recent development [1,2].

The surveying equipment comprised a side-looking radar and a radar altimeter. The equipment operated in two modes, i.e. by turns, first as altimeter and then as side-looking radar with 10° deflection of antenna from orbital plane of the probes. Axis of the altimeter tracked the planet's center of mass. The wave-length of the radar equipment was 8 cm. Surveying was carried out in the area of orbital circuit pericenter at an altitude ranging from 1000 to 2000 km. A surveying session lasted 15 or 16 minutes. All surveying information was recorded by long-term memory device and transmitted to the Earth during communication sessions. The output of surveying and radar profiling for each circuit was a radar panorama covering area of approximately 100x7000 sq.km and profiles of heights along probes' orbits.

The radar panorama of a terrain strip is the main source material for interpretation, map compilation and establishment of geodetic control. The radar panorama, just like an aerial photograph, comprises geometrical and interpretational information about terrain surface. However one must know geometric laws of the panorama formation to use it for mapping purposes.

The radar panoramas were synthesized from arrays of surface radio brightness data. The terrain elements located within a scattering spot illuminated by radio waves at a current instant of time belong to a certain data array. Overlaps in the arrays of radio brightness made it possible to obtain an integral image of the planet's surface along a surveying circuit. To form this image it was necessary to know elements of probe's orbit at a current instant of time with respect to every terrain point (α, e, τ), the length of venerocentric radius vector of this point, the distance between the radiation center of radar antenna and the terrain point as well as probe velocity component on range vector. The above distance and the velocity component were determined from time lag of a signal and Doppler frequency shift with respect to a given terrain element; as for the length of venerocentric radius vector of a terrain point, the average radius of Venus was used for panorama formation [5]. Every element of the radar panorama is defined by spherical coordinates of venerocentric orbital coordinates system. The cartographic projection employed for radar panoramas is called cylindrical equirectangular equal-space projection. Thus in each panorama the trace of probe's orbital plane on the sphere of Venus (its radius is equal to 6051.0 km) corresponds in this projection to conventional equator, the latitudes and longitudes correspond to spherical coordinates [5].

Geometrically each point in radar panorama is determined from intersections of three second-order surfaces, namely two spheres and a conical surface. Center of one sphere coinsides with the planet's center of mass and the sphere's radius is equal to average radius of Venus. The center of another sphere and vertex of the conical surface coincide with position of probe at a given instant of time. Radius of the sphere is equal to distance along radar beam from the probe to a terrain point. Axis of symmetry of conical surface coincides with velocity vector of the probe and makes permanent angle with projection of velocity vector on radar beam direction (conical surface generator).

Elements of probe's orbit referenced to the instant the probe passes orbital circuit pericenter are permanent parameters for each panorama. Changes in these elements that occur during surveying session are assumed to be systematic errors of images.

To establish relation between coordinates of terrain points and radar panoramas the geodetic principle of measuring angles from the center of projection was used for each point. The position of this center in space corresponds to only one given point on the surface of the planet. Angular elements of probe's orbit and the angles that define position of North pole of Venus's rotation and direction of Venus's zero meridian in geocentric coordinate system of standard epoch were employed as transformational parameters to convert spherical coordinates of radar panoramas into venerocentric coordinates [6, 9].

These planetodetic parameters and the venerocentric coordinate system rigidly tied to the planet were adopted in accordance with recommendations of IAU/IAG/COSPAR Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites [11] .

If semi-major axis a , excentricity e and an instant of time probe passes orbital pericenter τ ,were used for panorama formation as elements of probes orbit, then coordinates of terrain points in venerographic coordinate system can be calculated from

$$tg\lambda = \frac{b_1 \cos B_n \cos L_n + b_2 \cos B_n \sin L_n + b_3 \sin B_n}{a_1 \cos B_n \cos L_n + a_2 \cos B_n \sin L_n + a_3 \sin B_n}$$

$$tg\varphi = \frac{c_1 \cos B_n \cos L_n + c_2 \cos B_n \sin L_n + c_3 \sin B_n}{a_1 \cos B_n \cos L_n + a_2 \cos B_n \sin L_n + a_3 \sin B_n} \cos\lambda \tag{1}$$

where a_1, ... c_3 are matrix coefficients of transition from venerocentric orbital coordinates system to venerographic coordinates; B_n , L_n are spherical coordinates of terrain points in venerocentric orbital coordinates system. Under the accepted model of panorama formation, the measured spherical coordinates of radar panorama points B and L were corrected for terrain relief to obtain true values of spherical coordinates B_n and L_n that appear in (1)

$$L_n = L + arctg \frac{e \sin L \,(R_n^2 - R_{ni}^2)}{(1 + e\cos L)(R_{ni}^2 - R_n^2 + 2RR_n \cos B)}$$

$$B_n = arccos \frac{R_{ni}^2 - R_n^2 + 2RR_n \cos B}{2RR_{ni} \cos (L_n - L)} \tag{2}$$

where e is probe's orbit excentricity, R is length of probe's venerocentric radius vector; R_{ni} is length of terrain point's venerocentric radius vector, R_n is radius of Venus adopted for radar panorama formation.

Special-purpose software to collect and process data was developed for referencing purpose. Referencing of all radar panoramas was completed within a short period of time, besides venerocentric latitudes and longitudes for those points in the panoramas where conventional parallels and meridians intersected were calculated. Later venerocentric latitudes and longitudes were calculated for rather large set of points that belonged to several distinctly outlined relief formations; the points were arranged by quadrangles in a catalogue. These characteristic terrain points were selected preferably in those areas where two or more adjucent radar panoramas overlapped. Selection and punching of the points were made with a stereoscope, as for the measurement of the points, it was carried out with a monocomparator. Affine and bilinear transformations were used to allow for deformations of photographic material, the coefficients of the transformations were determined from coordinates of panorama grid crosses.

Digital methods were employed for photomaps preparation, i.e. transformation algorithms realized in the form of computer program package were used.

Data of radar profiling were used in the process of photomaps compilation to allow for the planet's relief. To allow for the relief as well as to obtain contours, digital terrain models were derived from the data of radar profiling [4] . Linear interpretation of elevation data obtained along the probe's paths was carried out to derive elevations of the points aside from the paths. After completion of all the necessary computer transformations the cartographic information recorded on magnetic tape was visualized by means of image output systems. Since resolution of the panoramas was 1.5 km an element of discretization during output was taken equal to 50 micrometers which correspond to approximately 0.8 kilometers on the planet's surface [4] .

Resolution in the image field of radar panoramas varies. To precompute resolution values in various points of a radar panorama the following formulas were derived [8] .

$$\Delta X = -\frac{\lambda \tau}{2 V_{H} \cos B} \Delta \nu \quad , \quad \Delta Y = \frac{c \tau}{2 R \sin B} \Delta \tau \qquad (3)$$

where ΔX , ΔY are resolution values correspondingly in the direction of the probe's movement and in the direction which is perpendicular to the movement $\Delta \nu$ = 260 Hz is frequency resolution, $\Delta \tau$ = 1.5 microseconds is delay time resolution; λ = 8 cm is wave length of radar equipment, $C = 2.998 \cdot 10^5$ kilometers per second is electromagnetic wave velocity, R is length of probe's venerocentric radius vector at a current instant of time, τ is slant range between probe and a point on the surface at a current instant of time, V_H is horizontal component of probe's velocity at a current instant of time.

After analytical contouring on the photomaps was completed, their manual finishing was carried out to insert those contours that were generated from digital terrain models only. Stereoscopic viewing of overlapping radar panoramas and study of patterns of surface relief was used to insert the contours. It gave us opportunity not only to make contours within a map sheet more accurate but to match contours of adjucent quadrangles.

Proceeding from the fact that the same points in overlapping panoramas are obtained with an observational basis, we had an opportunity to employ stereoscopic method. The program of surveying with "Venera-15" and "Venera-16" probes was set up in such a way that serial radar panoramas overlapped approximately up to 55° latitude. However the laws that govern perception of stereomodels made up of radar panoramas differ from the laws of perception of stereomodels made up of aerial photographs.

If radar panoramas are viewed stereoscopically, relief elements will be seen as if located on some complex surface [7].

Such a deformation of stereoscopic model depends on the method of image formation and geometry of surveying; as for degree of stereoscopicity of a model, it depends on magnitude of parallax differences in the space of the model. Stereoscopic effect in this case is weak due to acute angle of intersection, however it is sufficient to single out positive and negative forms of relief and carry out morphological laying of contours. Deformations of stereoscopic terrain models calculated with respect to actual conditions of surveying were taken into account and used to increase accuracy of contours in the photomaps [7]. The form of the deformations depended on lengths of terrain radius vectors and on location of terrain areas in radar panoramas.

The employment of the new type of surveying with unconventional geometry of image formation contributed to further development of traditional methods of photogrammetric problems solution, e.g. photogrammetric intersection, establishment of control points on planets, etc. The basic photogrammetric equations that can be used to solve these problems were presented at the 15-th ISPRS Congress in 1984 [10], as well as published in [9]. The equations include the following main types of surveying information: distance from radiation center of radar antenna to a terrain point (τ), probe velocity component along this distance (V_{τ}), current instant of time with respect to probe's orbital position (t). In the process of actual solution of the photogrammetric problems on the basis of equations obtained for radar panoramas, the most general mathematical model of adjustment was employed. The assumed functions in the model were the equations that related three groups of values, namely parameters under determinations, their a priori values and measurements; besides a priori characteristics of the two last groups are taken into account in the model [9].

To debug computer programs, make all the necessary precomputations and carry out theoretical investigations, algorithms and programs for preparation of mock-up overlapping radar panoramas were developed. Computation of points coordinates for the mock-up radar panoramas obtained under different parameters of surveying is made with iterative method [9].

The theoretical and practical investigations carried out made it possible to complete the main stage of photogrammetric processing of radar surveying data obtained with "Venera-15" and "Venera-16" probes and to prepare the photoplans and photomaps of Venus in which relief of the planet was shown with contours.

Proceeding from resolution of radar panoramas, 1:5,000,000 scale was chosen for photomaps of Venus. To prepare the maps at this scale the planet's surface was conventionally divided into 90 quadrangles located in different latitude belts. Several cartographic projections were tried for each latitude belt. Thus, stereographic projection was used for venerographic latitudes from pole to 80°, and Gauss-Lambert conformal conical projections were used for mean latitudes, i.e. 80° to 20° [3].

The surveyed surface of Venus can go into 27 quadrangles, 12 of which located in the 20° - 40° latitude belt are not quite complete. The total area of Venus's surface coverage is 115 million sq.km.

Contours in photoplans are plotted every 0.5 km. Just like in the case of cartographic projections computation, elevations were measured with respect to spherical reference surface adopted for Venus, radius of the surface being 6051 km [4] .

Thus, the radar surveying of Venus by "Venera-15" and "Venera-16" probes and processing of surveying information made the following contributions to further development of photogrammetry: a new geometric model of radar panoramas formation was developed, a new approach to determination of resolution and elimination of systematic errors from radar images was found, new formulas to relate coordinates of the same points in radar panorama and on the planet's surface were derived, new equations and techniques to solve photogrammetric problems using probe velocity components and range values were obtained as well as new laws that govern stereoscopic perception of overlapping images were discovered. Besides, digital methods to transform radar panoramas into cartographic projections were further developed.

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