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TRAJECTORY AND GUIDANCE PARAMETERS IN FLIGHT CONTROL OF THE VENERA 9 AND VENERA 10 SPACECRAFT

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TRAJECTORY AND GUIDANCE PARAMETERS IN FLIGHT CONTROL OF THE VENERA 9 AND VENERA 10 SPACECRAFT

S. K. Abramovich, et al.

The Venera 9 and Venera 10 spacecraft constitute a natural development of spacecraft for direct study of the planet Venus, begun in 1967 with the flight of Venera 4. With the advent of more powerful launch vehicles it was possible to develop and construct a spacecraft which considerably surpassed prior spacecraft in regard to the onboard scientific and research equipment and the trajectory and guidance capabilities. The high efficiency of the Venera 9 and Venera 10 flights, for which one of the main tasks was to investigate the atmosphere, particularly the upper layers, and obtain pictures of the planet surface by means of entry probes, stemmed to a considerable degree from choice of a new flight plan, which, in particular, allowed the mass of scientific equipment in the total spacecraft mass to be increased appreciably. In contrast with previous flights to Venus, the information from the probe was transmitted by relay from an orbiter, separating from the probe in the pre-planet flight phase, and injected into orbit around Venus. This provided a highly efficient data system for quite low mass of radio equipment and electrical supplies. /667*

*Numbers inthe margin indicate pagination in the original foreign text.

The mission plan provided for the following basic operations: insertion of the launch vehicle into an intermediate Earth orbit; a launch from intermediate Earth orbit at the end of one revolution into an interplanetary transfer orbit; two mid-course corrections in the transfer orbit to acquire the design conditions for entry of the probe into the planetary atmosphere and landing in the chosen region of Venus; separation of the probe and the orbiter two days prior to pericenter of the approach hyperbola and transfer of the orbiter to a non-entry (flyby) trajectory with a direction of rotation around the planet opposite to the probe motion; deceleration of the orbiter near pericenter for transfer to a satellite orbit around Venus; flight of the probe along a descent trajectory until it enters the atmosphere of Venus; aerodynamic deceleration of the probe and landing, with successive use of parachutes and decelerating landing panels.

The orbiter performs both its maneuvers near the planet, separation and deceleration, to acquire a lead over the entry probe, so that at the moment of probe entry into the atmosphere of Venus, the orbiter is already in a satellite orbit in the region for communication with the probe. These maneuvers were rendered more difficult for Venera 9 and Venera 10 by the fact that the attitude-control systems lose the star-Sun reference before the deceleration motors /668
are fired, since the orbiter passes into the planet's shadow, and then communication with Earth is lost as the orbiter sets behind Venus. An autonomous system was chosen for the spacecraft in the deceleration phase, to solve the problem of transfer to satellite orbit.

This flight profile provided conditions for a highly accurate probe landing in the given region of the surface of Venus, provided insertion into orbit around Venus of the first two artificial satellites of the planet, provided synchronous operation of the orbiter and the probe during the probe atmospheric entry and during its operation on the surface, and provided a long period of study of the planet and its immediate environment by two concurrent scientific satellites.

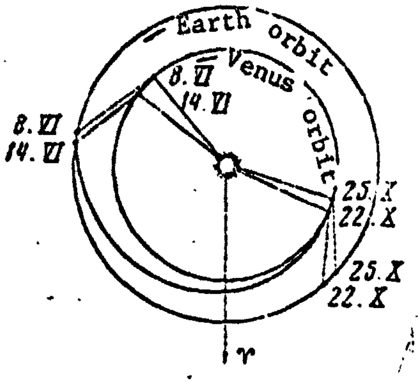

Figure 1. Flight profile of Venera 9 and Venera 10 in 1975

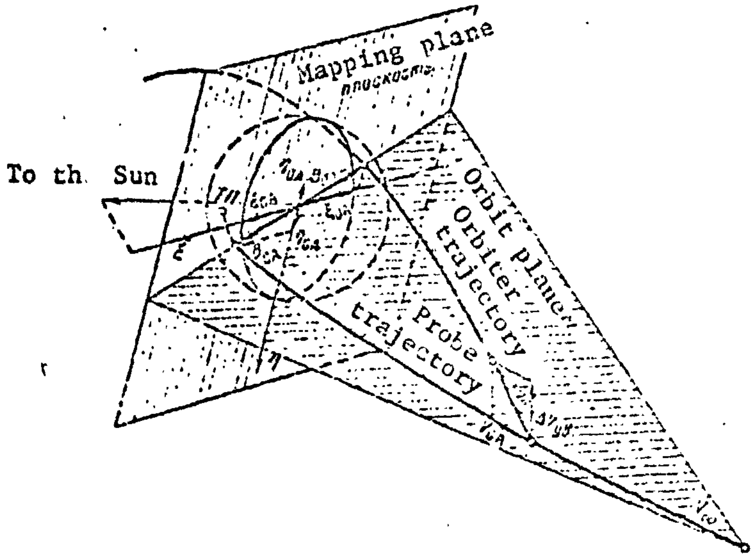

Figure 2. The target system for Venera 9 and Venera 10:

B_{CA} — target probe range CA; ξ_{CA}, η_{CA} — coordinates CA in the mapping plane; B_{OA} — target distance of the orbiter OA; ξ_{OA}, η_{OA} — coordinates OA in the mapping plane; $\tau\pi$ — CA landing point

During mission design and launch preparation for Venera 9 and Venera 10, near-optimum Venus-transfer trajectories were chosen, with transfer times of 137 and 134 days, respectively, provided by the given launch-date windows and the three-day displacement in flight time to the planet. It was proposed that the separation and deceleration manuevers be carried out in the plane of the probe approach hyperbola. Since an apsidal deceleration of the orbiter would not provide the required interval for communication of the probe and orbiter during the acquisition of scientific information, provision was made for the orbiter to be decelerated after passing pericenter, with an angle of - 20 to - 30° between the direction of the retromotor and the local horizon. Then an orbiter-probe communication period was provided in favorable conditions, at a separation of 12 - 35 thousand kilometers and with the orbiter at an angle of 60° or more relative to the probe landing point. /6

In accordance with the chosen flight profile, Venera 9 and Venera 10 were inserted into transfer orbit on June 8, 1975, at 7 [illegible]2 m 00.4 s and on June 14, 1975 at 7 h 30 m 05.8 s Moscow time, respectively (Figure 1).

The aim parameters used by the spacecraft (Figure 2) were: $t_{\rho min}$ — time of spacecraft passing minimum distance from the center of Venus; ξ, η — coordinates of the point of intersection of the asymptotes of the planetocentric hyperbolic trajectories of the spacecraft in the mapping plane.

The mapping plane was assumed to be the plane orthogonal to the asymptotic velocity vector V_∞, passing through the center of the planet.

The planetocentric coordinate axes ξ and η were defined by the unit vectors:

$$\eta^0 = \frac{V_\infty \times r_♀}{|V_\infty \times r_♀|}; \quad \xi^0 = \frac{V_\infty \times \eta^0}{|V_\infty \times \eta^0|},$$

where $r_♀$ is the radius vector from Venus to the Sun.

The predicted parameters of the spacecraft at Venus, obtained by processing the trajectory measurements prior to the first transfer orbit correction, are given below:

Spacecraft	Venera 9	Venera 10
Arrival date, 1975	Oct. 22	Oct. 25
$t_{\rho min}$(hr.min.sec)	5.15.20	11.31.50
ξ, km	23,300	22,400
η, km	18,200	74,900

The transfer trajectory parameters and the predictions were derived from mathematical processing of the radio measurements of inclined range and radial spacecraft velocity relative to the ground tracking stations.

The two planned flight profile corrections to the spacecraft motion were performed and guaranteed optimal conditions for the near-planet operations. The conditions were: entry of the probe into the atmosphere of Venus at angle - 20 to - 23° to the local horizon; landing of the probe on the illuminated side of Venus in a region bounded by longitude 285 and 295° and latitude 15 and 35° (the coordinates are given in the planetographic system, adopted by the International Astronomical Union); the duration of communication between the orbiters and the probes was not less than 115 minutes.

The design conditions were achieved by choosing aim parameters given below:

Spacecraft	Venera 9	Venera 10
Arrival date, 1975	Oct. 22	Oct. 25
$t_{\rho_{min}}$ (hr.min.sec)	6.40.00	6.42.00
ξ, km	17,900	19,300
η, km	12,500	8.250

To choose the aim parameters, mathematical modeling of the spacecraft flight was carried out, allowing for all the maneuvers performed and their exact characteristics, as well as prediction of a certain set of parameters critical for the flight program. The controlled parameters were projected into the mapping plane, forming an allowable region within which the aim point could be chosen, allowing for possible deviations of the actual trajectory from the design trajectory.

The first correction for Venera 9 was performed on June 16 at 14 h, 30 m, 02.6 s, and for Venera 10 on June 21, 1975, at 12 h, 59 m, 58.5 s. The telemetry measurements and the processed trajectory measurements showed that both spacecraft motors operated for the design time and imparted the required velocity impulses, 11.93 and 14.42 m/sec, respectively. /67[illegible]

On completion of the first corrections, the spacecraft were injected into descent trajectories, for which the predicted values were:

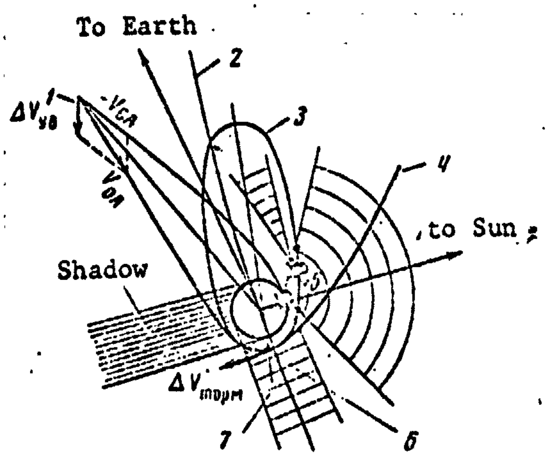

Figure 3. Near-planet operations for Venera 9 and Venera 10:

1 — separation and withdrawal of the orbiter;
2 — orbit of Venus; 3 — orbit of the satellite; 4 — flyby trajectory; 5 — probe-orbiter communication section; 6- deceleration and transfer of the orbiter to a satellite orbit; 7 — radio-shadow of Venus

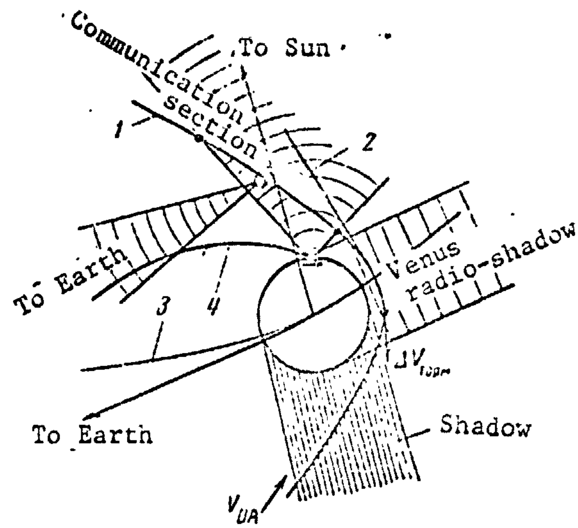

Figure 4. Lander and orbiter communication arrangements for Venera 9 and Venera 10:

1 — satellite orbit; 2 — flyby trajectory; 3 — orbit of Venus; 4 — communication section;

orbiters within the sphere of influence of Venus: the first maneuver was separation, transferring the orbiter to a hyperbolic trajectory in a counter-flyby of the planet with respect to the probe, and a second maneuver, a deceleration to capture the orbiter into a satellite orbit of Venus. The parameters of the two near-planet orbiter maneuvers were chosen in such a way that, for the entire set of possible approach trajectories to the planet, allowing for the special features of operation of the spacecraft systems, the required conditions would be met for carrying out the design flight program of near-planet operations and scientific experiments. The basic conditions were:

- the time spent by the probe and the orbiter in a region where there was mutual communication from the probe via the orbiter to Earth of scientific information in the phases of descent, landing, and probe operation on the surface of Venus (Figure 4) should be not less than 115 minutes, as mentioned above.

- the total characteristic velocity required for the maneuvers should not exceed the available resources;

- the orbital parameters of the spacecraft should meet the requirements dictated by the program of scientific investigations, during the given time for active operation of the spacecraft.

The nominal spacecraft orbital parameters and their target values during the flight were chosen from statistical modeling of the approach section, allowing for errors in determining and predicting the trajectory, as well as errors in controlling the spacecraft motion in the interplanetary flight. Mathematical models were used for the attitude systems, the control systems, the radio systems to provide communication from the probe to the orbiter, and the logic for operation of onboard systems providing the separation and deceleration maneuvers. The optimal orbiter parameters derived from these calculations guaranteed a communication period along the probe-spacecraft-Earth channel of not less than 130 minutes, the design values of characteristic velocities at separation and deceleration being, respectively, 247.3 and 922.7 m/sec for Venera 9, and 242.2 and 976.5 m/sec for Venera 10. /671

In order to satisfy the high requirements for accuracy in the orbital parameters, an opportunity was provided for controlling the orbiter directly during the deceleration phase. To this end, a special program unit was developed which was used for real-time computer solution of the navigation problem and for processing the control parameters.

The problems solved by this unit included: processing of trajectory measurements; determination and prediction of the approach trajectory parameters; choice of the optimal control for the deceleration phase; calculation of the deceleration conditions and of orbiter-probe communication conditions, allowing for possible deviations arising from errors in determining the probe trajectory; calculation of probe atmospheric entry conditions and refinement of the landing point coordinates.

Since the value of trajectory measurements increases with approach to the planet, one naturally wishes to process measurements taken as late as possible for greater accuracy in calculating the deceleration parameters. In order not to decrease the control reliability, the updating of control parameters was performed successively, and the calculations were made cyclically in the computer unit. In each new cycle a new packet of measured information was /672 admitted for processing and the accuracy of the result increased from cycle to cycle. In these circumstances, an important factor was the time required to carry out a full cycle of operations. To shorten this time, techniques were developed for solving individual problems, to increase the speed of the numerical subroutines, and to automate computational processes and information exchange and mapping processes.

The special program unit allowed real-time choice of the spacecraft control parameters in the stage of deceleration at the target planet. Onboard commands were given to send the orbiters into satellite orbits around Venus, and the osculating elements at the moment of ascending node passage were as follows.

Spacecraft	Venera 9	Venera 10
Date, 1975	Oct. 22	Oct. 25
t_0, (hr.min.sec)	6.13.42	6.32.31
T, "	48.17.59	49.22.34
τ, "	6.01.17	6.02.19
e	0.8792	0.8791
a, км	62894	63825
ω	314°35′	278°10′
i	34°10′	29°30′
Ω	76°25′	107°05′
r_π, км	7595	7715
r_α, км	118190	119930

The notation is as follows: t_0 — Moscow time at passage through the ascending node of the orbit; T — period of rotation; τ — Moscow time at passage through pericenter; e — eccentricity; a — semi-major axis; ω — angular distance of pericenter from the node; i — inclination to the equatorial plane of Venus; Ω — longitudine of the ascending node, calculated from the direction of the point of the vernal equinox of Venus; r_π — distance from the center of Venus to the satellite at pericenter; r_α — distance from the center of Venus to the satellite at apocenter.

After separation of the orbiters, the two probes continued to fly along the approach trajectories until they entered the atmosphere of Venus, and then experienced aerodynamic deceleration ... atmosphere and landed on the surface of the planet, with suc[illegible]ssive use of parachutes and aerodynamic decelerating panels.

In the descent section for each of the probes, during a communications session from the probe to the orbiter, which was in a satellite orbit of the planet above the landing region, measurements were taken of relative velocity of the spacecraft, and values of the decelerations during the aerodynamic phase were recorded onboard the probe. The relative velocity measurements were continued for ~ 140 minutes, of which ~ 60 minutes was after probe landing. From simultaneous processing of this information and information on the orbiter motion from terrestrial stations, and the good agreement between telemetry data on the dynamics of the spacecraft throughout the entire section near the planet and the trajectory measurements, we were able to calculate accurate values for the probe atmospheric entry parameters, the probe motion in the atmosphere, the value of Moscow time and the coordinates of the landing point (see below).

Probe	Venera 9	Venera 10
Atmospheric entry date, 1975	Oct. 22	Oct. 25
Entry time (Moscow) (hr.min.sec)	6.53.50	6.55.33
Entry angle	-20°30'	-22°10'
Landing time (hr.min.sec)	8.08.23	8.12.11
Landing point latitude	31°42'	16°02'
Landing point longitude	290°50'	291°00'

After the orbiters were inserted into satellit orbit around /673
Venus, a broad program of investigation of Venus and of the space near the planet was commenced.

To support this scientific program, provision was made for regular determination of the orbital parameters, calculation of the conditions during the experiments, and determination of the attitude conditions during observations and photography; attitude control commands were generated and a three-dimensional navigational fix was calculated to support the scientific information.

The motion of the orbiters was subject to perturbations from several sources, of which the most important is the gravitational influence of the Sun, and the least studied is the eccentricity of the gravitational field of Venus. One of the tasks of the first satellites is to check and to refine the hypothesis that Venus is an ellipsoid of rotation with a slight polar compression and a uniform mass distribution.

The satellite orbits evolve under the action of the perturbations. Figure 5 shows the time history of the parameters describing the orientation of the satellite orbits in space.

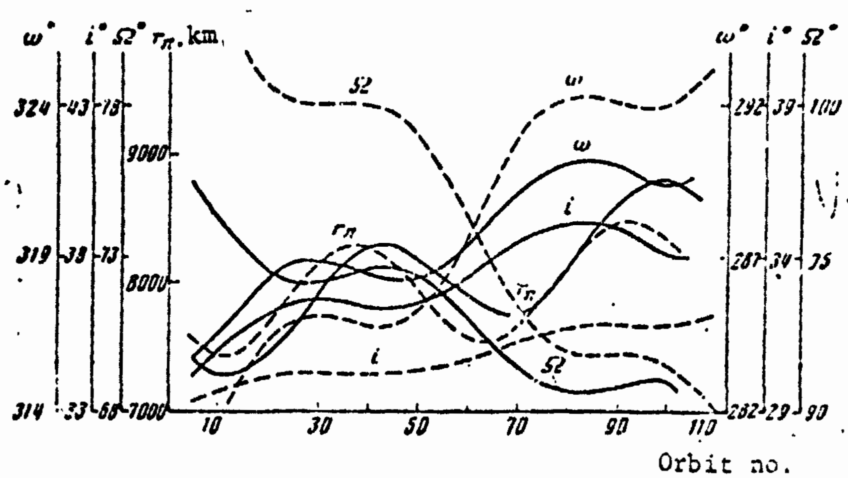

Figure 5. History of the satellite orbital parameters for Venera 9 (solid line, left scale) and Venera 10 (broken light, right scale); the r_π scale is common

The evolution of the radius of pericenter (r_π) is of very great interest from the viewpoint of control of the spacecraft motion and for conducting scientific experiments. Figure 5 shows the variation of r_π as a function of orbit number, and it can be seen that there are periodic oscillations imposed on a secular variation for both orbits.

Preliminary results obtained from real-time analysis to determine and predict the satallites trajectories have shown good agreement between the actual and the design orbit evolution. One can therefore conclude that contemporary ideas as to the nature of the gravitational field of Venus are valid. The results of the trajectory measurements are presently being processed and correlated to obtain reliable numerical characteristics of the gravitational field.

To sum up the results of the Venera 9 and Venera 10 flight control, the comment should be made that the flight confirmed the validity of the estimates, the design solutions, the methods, the computations, and the procedures of the navigation discipline at all stages in preparing and carrying out the 1975 Soviet expedition to Venus.