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Chapter 11

DEVELOPMENT OF THE THEORY OF CORRECTION MANEUVERS FOR THE FIRST TRANSFER TRAJECTORIES TO MARS AND VENUS[*]

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INTRODUCTION

The studies concerning correction maneuvers were initiated in the U.S.S.R. by Academician M. V. Keldysh in the late 1950s in connection with the preparatory stage of the project of interplanetary transfers to Mars and Venus. Successful accomplishment of the Moon fly-by missions, which aimed to photograph the Moon's far side, provided a required base for the theory and software to present a feasible problem of interplanetary trajectory corrections and a choice of necessary algorithms. Moreover, it created premises for developing the hardware of correction systems, since a most difficult problem—the correct orientation of spacecraft in space—had been solved.

M. V. Keldysh was fully aware that fly-bys of Mars and Venus, or landings on their surfaces, could not be done without preliminary investigations of specific features of correction maneuvers to optimize correction system characteristics. It was important to understand the demands imposed on the structure and parameters of the spacecraft correction system: a possible direction and required accuracy of orientation in space, necessary fuel supplies, a required number of engine switch-ons, expected times of corrections, etc.

A complexity of the problem was defined by analyzing the correction characteristics for an entire possible cluster of trajectories, determined by insertion errors at the boost portion of trajectory, errors of prediction, and execution of correction maneuvers.

Below, we shall briefly describe the way adopted by Soviet scientists and engineers to solve these problems.

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HISTORY OF DEVELOPMENT OF THE CORRECTION THEORY

Correction of spacecraft trajectories is a maneuver of the spacecraft to correct its trajectory in agreement with the results of trajectory measurements and the corresponding prediction of motion.

It is impossible to insert a spacecraft into orbit with absolute accuracy. Errors of insertion, which are unessential by the time of termination of engine operation, may lead in time to inadmissible deviation of the flight trajectory from the given one. For example, on flights to planets, relatively small angular deviations of the actual trajectories lead, with increasing distances from the Earth, to excessively large linear deviations from the given trajectory, which makes the attainment of a target planet impossible. Therefore, in space flight to a remote planet, it is usually necessary to carry out corrections of the flight trajectory by switching on the jet engine, which produces an additional impulse to provide a required velocity increment in the desired direction.

The energy consumption, as well as accuracy with which a value and direction of the correction impulse must be provided, depend on the location of correction along the spacecraft trajectory to the Moon, Mars, Venus or some other celestial object. From an energy standpoint, correction in the early flight stages is most beneficial. However, in this case the required accuracy of the correction impulse is high. As a spacecraft approaches a target, the accuracy may be lower but the energy consumption increases. Hence, when choosing the location of the correction impulse along the trajectory, a compromise between these two contradicting requirements must be made. Inevitable errors in the trajectory correction and the subsequent accumulating discrepancy between the actual and calculated trajectories make it necessary to repeat the correction (once or twice or even more) in the distant transfers [1].

Investigators have not arrived at a clear definition of correction and formulation of its problems. The history of this issue is as follows. By the time of the first satellite launching, and, in subsequent years of the space era, the works by D. F. Louden (1960) were known [2], where the correction problem was formulated in an elementary statement. The one-dimensional problem was considered (i.e. only one coordinate—a miss—was removed) with a monotonically growing function of correction impulse and a monotonically decreasing error of correction. As a result, a geometric progression was obtained for the number of correction impulses (for example, for the transfer to Mars, 15 corrections were needed). In such an abstract statement, the problem proved to be very far from real, and its solution could not be used in spaceflight.

The correction theory in the U.S.S.R. was developed in two ways: in the mathematical formulation close to that by Louden, and in practice by organizing corrections during spaceflight.

In the first case, the best results were obtained by V. A. Ryasin, D. E. Okhotsimsky, N. N. Chentsov (1967), as well as V. A. Yaroshevsky and F. L. Chernous'ko. Unlike Louden, with his variational statement of the problem on searching for momenta and correction impulses, minimizing the fuel consumption for correction with a given accuracy, in the above studies of the soviet authors, the correction problem was formulated as the one on searching for an optimal rule (now it closes down upon the artificial intelligence theory), or a strategy in the game formulation, where a cause of the trajectory errors plays the role of an adversary. For solving this problem, the information space is introduced, (i.e., the space of measurements of the motion parameters for various spacecraft trajectories). By using the dynamical programming principle, this space is divided into regions corresponding to the optimal cases of one, two, three, or more corrections. However, like Louden, these authors solved the problem in a simplified, linear one-dimensional statement.

The second and most practical way of developing the correction theory consisted of investigating celestial mechanics of orbits to determine more accurately the specific features of the correction impulse function. The first studies in the U.S.S.R. in this direction were carried out by K. V. Kholshchevnikov (1965). He used a traditional approach; the analysis was performed in the space of orbital elements in the framework of a two-body problem. The expressions obtained were too bulky and could not be used in practice.

There were some other attempts of Soviet investigators to build the correction theory by basing them on the Lambert problem about rendezvous with a given planet at a given time. Such a theory is evidently deficient since the classical Lambert problem is a problem with fixed times at the beginning and end of spaceflight. Meanwhile, in the correction problem, the time of approaching the planet, as well as the correction time, are often free parameters, which are chosen for optimization of correction characteristics.

The most accurate solution was obtained by D. E. Okhotsimsky and A. K. Platonov (1958, 1959). They used methods for linearization of the approach characteristics which had been developed in the course of generating the Moon fly-by trajectories for taking photos of the Moon's surface. Since the deviations to be corrected are small in comparison with distances between planets, the problem of correction can be considered in the linear formulation as the first approximation. Here the idea was first stated that there was no need to hit the planet at a given time, but at the time convenient from the energy point of view to decrease the correction impulse. It was then that the notion of the picture plane, the optimal correction plane, the ellipse of influence, and the ellipse of zero direction were introduced [3]. Some time later, Soviet investigators became acquainted with the publication by J. Lorell (1961), who also mapped the aiming plane onto a certain plane similar to that for optimal correction [4].

Investigations of correction characteristics in the linear space of aiming parameters allowed the determination of optimal directions and values of correction impulses in the whole possible domain of trajectory dispersion. In a number of cases, the simplest schemes of orientation systems were proposed, and the requirements of fuel supplies and correction system accuracies were formulated.

In particular, it was shown that the orientation system for correction can be simplified in the middle of spacecraft flight without considerable loss of correction efficiency. For example, during a flight to the Moon it can be done by rotating around the direction of the Moon; on flights to Mars, the rotation should be around the spacecraft – Sun line; however, on flights to Venus, such a simplification in the middle of the flight is impossible, hence the three-axis orientation system should be applied.

At the same time, Platonov (1960) showed how invalid the correction analysis was under the assumption of coplanarity of the spacecraft trajectory and the target planet orbit, because the major correction impulse consumption follows the need to correct the deviations orthogonal to the trajectory plane [5]. For the same reason, the Louden assumption about a monotonic decrease of the correction impulse function proved to be wrong also. In fact, the effective component of this function increases to the middle of the flight, and only then does it begin decreasing.

A graphic proof of this statement is the influence ellipse of the minor semi-axis, which can increase considerably to the middle of the flight. It was shown that as the flight time grows, the influence ellipse tends to describe a circumference (the minor semi-axis increases while the major semi-axis decreases), the radius of which tends towards zero. For example, in transfers to Venus and Mars, the influence ellipses turn into circumferences: 15 days before approaching Venus and two months before approaching Mars. At each instant of time, a radius of this circumference is rather accurately equaled to the time remaining until it approaches the planet.

From the celestial mechanic's point of view, a cause of increasing a minor semi-axis in the middle of the flight is the degeneration of the correction characteristics at passage through the point of trajectory, which is located at the angular range of 180° to the target planet, i.e. when the spacecraft, the Sun, and the target planet are situated almost on the same straight line. In this case, due to noncoplanarity of orbits, the correction impulse, as a rule, must be directed along the flight time gradient, which eliminates independent correction of lateral deviation in the picture plane and the arrival time. The efficiency of such a correction of the lateral deviation is low, so the minor semi-axis is small, and the correction impulse function grows with time as the distance from the singularity (degeneration) point increases.

The above nonmonotonicity of the correction characteristics leads to optimization of multiple corrections even in the ideal formulation of the problem, provided the correction errors are absent. This fact was established simultaneously in the U.S.S.R. and the U.S.A.; it was reported in 1965 by the Soviet scientists A. K. Platonov, A. A. Dashkov, U. N. Kubasov, as well as the American scientists R. G. Stern, and I. E. Potter at the 1st IFAC Conference in Stavanger [6, 7].

In the U.S.S.R. such a multiple correction was called the bound correction. Its specific features were described by A. K. Platonov, and, later on, investigated in the variational formulation. The bound correction was applied in the U.S.S.R. to the flights to Venus in the form of a simplified (in terms of orientation) procedure of multiple solar corrections, whose peculiarities were studied in detail by the cosmonaut V. N. Kubasov [8].

For carrying out the correction of spacecraft trajectories to Venus and Mars, the Soviet scientists gave much importance to mapping the properties of the approaching trajectories onto the aiming plane. As a part of the preparation for the Moon flight for taking photos of its back side, M. L. Lidov, and A. K. Platonov (1958) developed a mapping technique to construct an admissible region of aiming in the picture plane, where the effect of the planet's gravitational field was eliminated (elimination of nonlinearity). The technique was reported (1965) at the above-mentioned Conference in Stavanger.

It was used practically in all flights of Soviet spacecraft to planets in the 1960s. Later on (in the late 1960s), it was found from the papers of the well known American specialist Dr. Scal (the author of a Mariner project), that a similar technique was used for calculations of correction characteristics in the Mariner spacecraft mission.

At the present time, the correction theory is developed in the U.S.S.R. to provide for the safety of the Soviet Salyut and Mir stations. The project studies for the Halley comet mission were reported at the IAF Congress. In the case of flights to comets the basic peculiarities of correction are connected with the exact time of the comet arrival at the Sun [9].

The history of development of the correction theory is directly tied to the history of designing the orientation systems for correction. It is an important and interesting issue, which can be reported at the next IAF Congress.

EXAMPLES OF CORRECTION OF THE SPACECRAFT TRAJECTORIES

The 1960s and 1970s were dedicated to active studies of Venus and Mars. In those years, a series of launches of the *Venera 1* through *10* and *Mars 1* through *7* spacecraft were accomplished in the Soviet Union. During the first stages of the exploration of Venus, a main goal was to penetrate and study its atmosphere, to gain information for subsequent landings on the planet's surface. As more detailed data were obtained about the Venus atmosphere, the spacecraft were improved and modified. Fifteen years were required to land a spacecraft on the surface of Venus, and mankind could see a picture of the surface of this mysterious planet. More knowledge was gained in those years than in all the preceding centuries of studying the planet.

In those interesting years all was an enigma, and every launch of a spacecraft to Venus or Mars was an event of tremendous importance. At the first press-conference, hot heads asked about future landings of man on the surface of Venus, because after centuries of telescopic measurements, scientists stated that Venus resembled the Earth. Academician M. V. Keldysh (then the president of the U.S.S.R. Academy of Sciences), patiently explained that there was a problem since instruments could withstand accelerations of hundreds of g's, while a man could only withstand 10-12 g (at that time a question about the surface pressure was open—it was assumed to be in the range from 1 to 100 atmospheres).

For the first time, correction maneuvers were used during spaceflights, i.e. specialists on Earth learned how to effectively guide the spacecraft. Each session of correction, including the spacecraft attitude control and the correction jet switch-on, was awaited as an extraordinary event. Before making a decision about correction, a great number of reserve corrections were computed. (In the case of the correction jets failure, various types of corrections were played up—the solar or star ones, with different numbers of corrections—one, two, or three, and various times of corrections). Different stars were considered for orientation during the correction session, and many versions, sometimes unexpected, connected with the spacecraft configuration, were studied.

Gradually a typical picture of spacecraft flight was worked out. Knowledge was gained about a range of launching errors, a miss distance depending on the launch, and prediction and measurement errors. (The distance was measured to within 1 km, the radial velocity to within 2 cm/sec, errors of correction execution to within 1-3 cm/s). These figures became typical, the activity became routine, and more automated.

Now let us dwell on flights to Venus. It should be borne in mind that the Earth-Venus transfer must be performed when the spacecraft passes "ahead" of Venus in its angular motion about the Sun by 45° at the escape time. Such a disposition of Earth and Venus occurs every 584 days, i.e., approximately once in one and a half years.

The *Venera 1* spacecraft was the first automatic interplanetary station launched to Venus on February 12, 1961. A single correction scheme was accepted for the transfer to Venus. The correction parameters were coordinates in the picture plane and possibly the hit time.

Figure 1 shows the influence ellipses for optimal correction, and the correction in relation to the Sun, depending on the time of correction for one of the flight scheme variants. It should be noted that eccentricity of the influence ellipse is small in the case of optimal correction and large when the correction is connected with the Sun. Due to the last circumstance, the scheme of correction in the plane perpendicular to the line directed to the Sun is essentially nonoptimal. The time dependence for correction of the maximal and minimal impulses is shown in Figure 2, if the deviation to be corrected is equal to 100,000 km. From this figure, it follows that the correction should be made not later than 20 days before the end of the flight. An earlier correction was impossible at that time, due to the restrictions imposed by the astronavigation system (subsequently this problem was solved). An insufficient accuracy of the trajectory prediction at the early stages of flight is the second reason why early correction is impossible (this also was eliminated in subsequent missions). Recommendations for the direction of a corrective impulse were as follows: to correct the hit time, it was necessary to provide an additional impulse in the direction perpendicular to the plane of optimal correction; and, the correction of coordinates of hitting the picture plane of Venus could be most efficiently carried out by orienting the corrective impulse in the plane of optimal correction.

Those were the first practical conclusions that followed from the correction theory developed then.

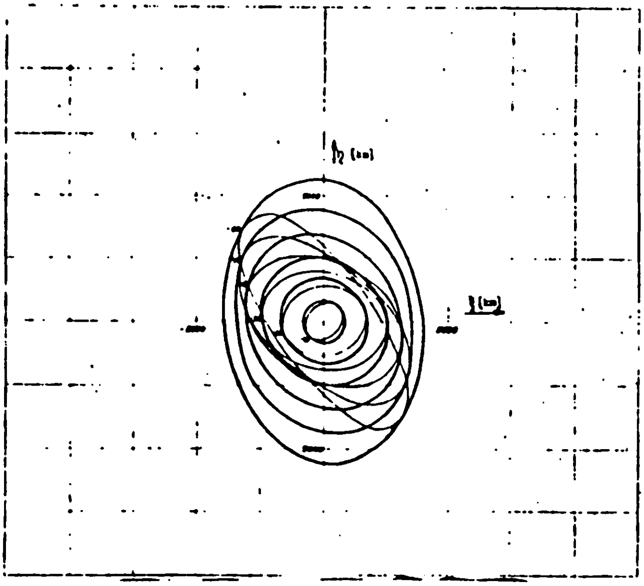

Figure 1 Ellipsis of influence for optimal correlation (line—) and for correction in the plane ⊥ Sun-direction (line –) Flight to Venus.

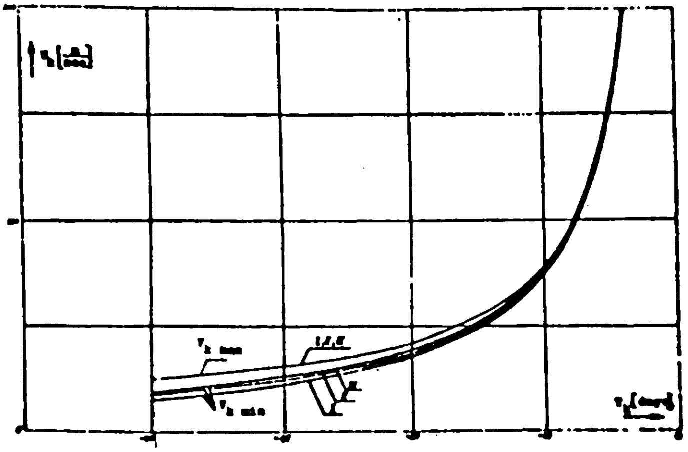

Figure 2 Pulse magnitude for correction of deviation of 100,000 km Flight to Venus, 1961.

Later on, the *Venera 2* and *3* missions were performed. They were the "registering" missions which provided a base for a subsequent scientific experiment on probing the Venus atmosphere. This outstanding experiment was carried out by the *Venera 4* spacecraft, launched on June 12, 1967, which reached the Venus surface on October 18, 1967. This spacecraft was designed to determine the atmosphere composition. For the first time, a smooth descent into the atmosphere of another planet was accomplished. The chemical composition of the atmosphere was measured on the dark side of the planet.

Various variants of the trajectory correction were calculated:

Table 1
VARIATIONS CALCULATED FOR TRAJECTORY CORRECTION

Correction	Solar		Optimal	
T_{cor}	29.07.67 8h	20.07.67 12h	25.07.67 12h	3.08.67 12h
$T_{hitting}$	18.10.67 8h35'21"	22.10.67 10h	22.10.67 17h25'	23.10.67 10h
V_{cor}, m/s	108.03	45.32	43.96	43.23

For hitting Venus, a single correction was carried out at the distance of 12 mln.km from the Earth.

After accomplishment of the *Venera 4* mission, it became clear that the temperature at the surface of Venus was not less than 270°C and the pressure not less than 18 atmospheres. Nitrogen—a necessary element of life—was not detected. Thus another legend about possible life on Venus unfortunately failed.

The subsequent *Venera 5* and *6* missions, with launches on January 4, 1969 and January 10, 1969, lasted 131 and 127 days, respectively, and also had only one correction each, on March 3, 1969 and March 16, 1969, respectively. During the correction session, the spacecraft orientation was carried out with respect to the Sun and Sirius. The corrective impulses were 9.2 and 37.4 m/s. These spacecraft performed measurements in the Venus atmosphere at an altitude 60 km from the surface and showed the temperature as 327° and the pressure as 27 atmospheres.

Beginning with the *Venera 7* mission (launched on August 17, 1970), the correction scheme was two-pronged with orientation by the Sun and a star (Sirius or Canopus). As a reserve variant, the possibility of orientation by the Sun and the Earth was considered. At the landing site, *Venera 7* registered a temperature of 475±20°C and a pressure of 90±15 atmospheres [10, 11].

New scientific goals—taking the pictures of the planetary surface and cloud layer—were put before the designers of the *Venera 9* and *10* spacecraft. These interplanetary automatic stations were a natural extension of the spacecraft systems for direct study of Venus, which had started with the *Venera 4* mission in 1967.

The flight scheme specified the carrying out of two corrections in the transfer orbit to provide the conditions required for entry into the Venus atmosphere and descent of landers at the given region. The *Venera 9* and *10* spacecraft were launched on June 8, 1975 in 7h 12'00.4" and on June 14, 1975 in 7h 30'05.8," respectively. The following quantities were used as the target parameters: $T\rho_{min}$ (the time of reaching a minimal distance to the Venus center); ξ and η (the coordinates of the point at which the asymptotes of planetocentric hyperbolic trajectories crossed the picture plane of Venus; the picture plane was the plane orthogonal to the vector of asymptotic velocity V_∞ going through the planet center).

The predicted parameters of spacecraft motion near Venus, obtained as a result of processing trajectory measurements before the first correction, are given below:

Spacecraft	Venera-9	Venera-10
Arrival data (1975)	22.X	25.X
$T_{\rho\,\min}$ (hms)	5.15.20	11.31.50
ξ (km)	23300	-22400
η (km)	18200	-74900

Two corrections of the spacecraft trajectory were carried out. They provided optimal conditions for performing necessary operations near the planet. The main conditions: the entry of the landers into the Venus atmosphere at the angle −20 to −23° to the local horizon; the landing at the lighted side of Venus in the region between 285 and 295 grad of longitude, and 15 and 35 grad latitude (the spacecraft were landed on the planet surface at different sites some 2200 km from each other); the communication times between the landers and the orbiters were not less that 115 minutes. The above conditions were provided by choosing the target parameters:

Spacecraft	Venera-9	Venera-10
Arrival data (1975)	22.X	25.X
$T_{\rho\,\min}$ (hms)	6.40.00	6.42.00
ξ (km)	17900	19300
η (km)	12500	8250

To choose the target parameters, the computer simulation was carried out using all the maneuvers to be performed and their accuracy characteristics; also a set of certain parameters was predicted to provide the mission tasks fulfillment. The parameters under control were mapped onto the picture plane to form an admissible region within which the target point was chosen to provide the fulfillment of mission tasks with possible deviations of an actual trajectory from the calculated one.

The first correction of the *Venera 9* motion was carried out on June 16, 1975 in 14h30'02.6" and the *Venera 10* motion on June 21, 1975 in 12h59'58.5." The telemetric measurements and the processing results showed that the engines of both stations worked for a calculated time, and provided necessary impulses of velocity equal to 11.93 and 14.42 m/sec, respectively. As a result of this first correction, the stations were transferred onto the hitting trajectories with the predicted values as follows:

Spacecraft	Venera-9	Venera-10
Arival date (1975)	22.X	25.X
$T_{\rho\,\min}$(hms)	7.42.38	6.35.16
ξ (km)	17310	20090
η (km)	12510	9270

In calculating the second corrections, the coordinates of the landing sites on the planet surface within a given region and the times of entry into the atmosphere were chosen. The target parameters for the second correction are given below:

Spacecraft	Venera-9	Venera-10
Arival date (1975)	22.X	25.X
$T\rho_{min}$(hms)	7.00.00	7.02.00
ξ (km)	17.800	19.300
η (km)	12.400	8250

The second correction was carried out on October 15, 1975 in 5h59'24" and October 18, 1975 in 5h19'42.2," respectively. The stations were provided with the corrective velocities of 13.44 and 9.68 m/s, respectively [12].

These missions gave new clarified data about the temperature and pressure on the Venus surface: T = 480°C and P = 90 atmospheres. Also the first photos of the Venus surface were obtained from the landers.

Now a few words should be said about the correction of the transfer trajectory to Mars. The transfer trajectories to Mars were investigated simultaneously with those to Venus.

The first *Mars 1* spacecraft to Mars was launched as early as November 1, 1962. The spacecraft approached Mars at a distance of 197 thousand kilometers, and then flew away along the heliocentric orbit.

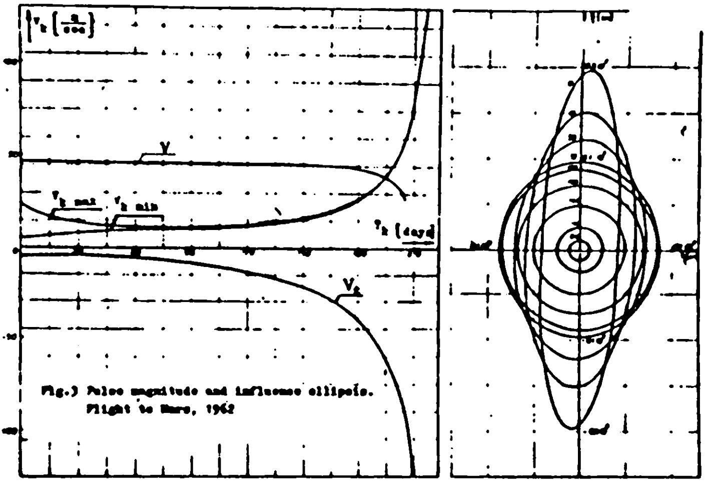

Figure 3 Pulse magnitude and influence ellipsis. Flight to Mars, 1962.

As in the *Venera 1* mission, only one correction was applied to the *Mars 1* spacecraft. Before that, numerous investigations of the specific features of the mission to Mars were performed. By taking into account the restrictions of forecast which were carried out simultaneously with determining the astronomical unit (the problem was very urgent at that time), the time interval for the correction was very narrow. However, if the forecast is made with the known astronomical unit, the correction time interval becomes wider.

The typical picture of the corrective impulses varying with the flight time for the *Mars 1* spacecraft is given in Figure 3. The available value of correction impulse did not permit the correction later than 1 to 1.5 months before the end of flight. The influence ellipses in Figure 3 show that the deviations are equivalent in terms of correction at the end of flight (i.e. there is no preferable direction in the picture plane).

The subsequent *Mars 2* through *7* missions, with launches in 1971-1973, were aimed for landings on the planet and taking photos of its surface. To provide the necessary accuracy of flight, two or three corrections should have been made. Also, an additional impulse was provided to insert the spacecraft into orbit around Mars.

In 1973, four spacecraft were launched for the first time for comprehensive investigations of Mars. Computing and control engineers had to carry out the strenuous work of calculating the characteristics of simultaneous control of four objects. Moreover, these objects had different tasks to fulfill: the *Mars 4* and *5* spacecraft were designed for investigating Mars from orbit; while *Mars 6* and *Mars 7* aimed to put their landers on the planet's surface.

Variants of corrections for these four spacecraft are given below in Table 2. From this table it is seen that the first correction was usually carried out during the first ten days of flight, the second correction—10-15 days before the end of flight, the third correction—a few days before the end of flight, if necessary, after which a rather large impulse was provided for insertion into the orbit of an artificial satellite. We may evaluate the transfer and forecast accuracies by the values of corrective impulses (impulses of the first and second corrections are not large, mainly, 5-6 m/s).

CONCLUSIONS

As a result of solving a large number of control problems, a specialized language has been created for solving correction and orientation problems [13, 14]. This language was efficiently used later on for creating the large DISPO system (Display Interactive System for Orbit Design) [15]. With the aid of this system in the 1970s and 1980s, design studies were carried out for missions to asteroids and comets (Figures 4-7), in particular to Halley's Comet, for which the film was composed on the display screen by using a computer (it was demonstrated at the 36th IAF Congress) [16, 17].

Additionally, a package of applied programs (PAP) was constructed for solving the celestial mechanics and spacecraft orientation problems. All programs in this package are written in Fortran and are available for users.

Table 2
VARIANTS OF CORRECTIONS FOR FOUR MARS SPACECRAFT

	Mars-4	Mars-5	Mars-6	Mars-7
Launch	21.VII.73	25.VII.73	5.VII.73	9.VIII.73
1st correction	30.VII.73	3.VIII.73	13.VIII.73	16.VIII.73
Orientation		Sun-Canopus		
Correction impulse, m/s	29.4	4.5	5.3	5.7
2nd correction	31.I.74	2.II.74	24.II.74	I.III.74
Orientation		Sun-Canopus		
Correction impulse, m/s	5.5	6.8	2.5	2.2
3rd correction	a few days before approach (if necessary)			
Orbit insertion impulse, m/s	1222.4	1187.9	130	110

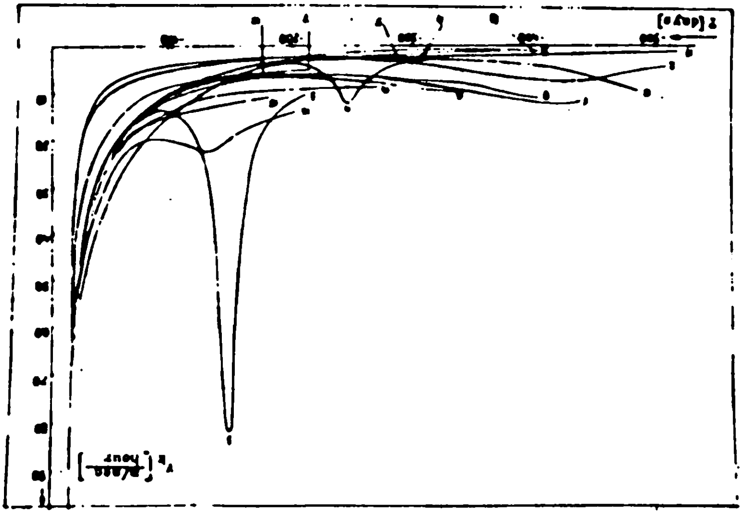

Figure 4 Pulse magnitude for comet's time error correction.

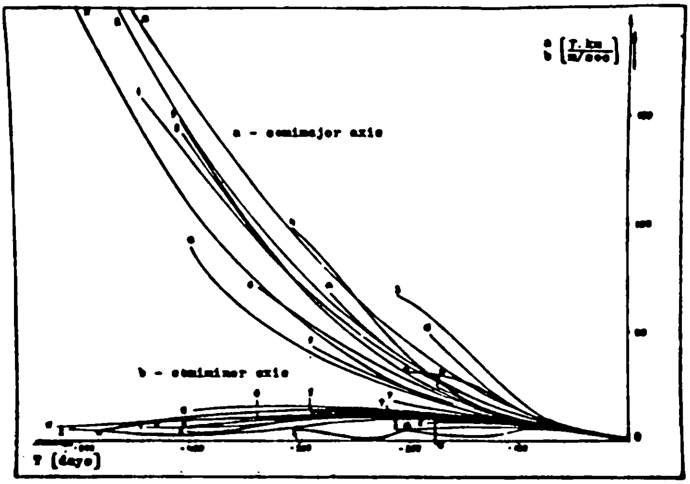

Figure 5 Characteristics of influence ellipsis during flight to comets.

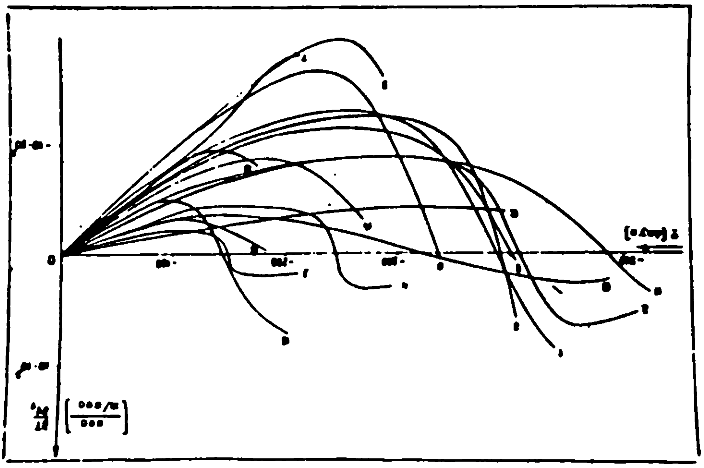

Figure 6 Time correction efficiency along the null-direction during flight to comets.

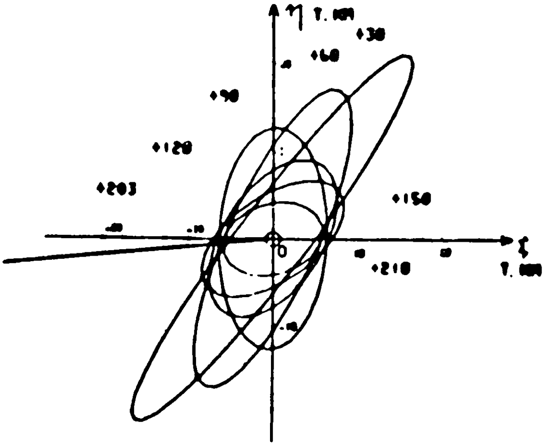

Figure 7 Design studies for missions to asteroids and comets

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