THE CONTROL OF MOTION DURING ENTRY INTO THE ATMOSPHERE

УПРАВЛЕНИЕ ДВИЖЕНИЕМ ПРИ ВХОДЕ В АТМОСФЕРУ
(Upravleniye Dvizheniyem pri Vkhode v Atmosferu)

by

D.Ye. Okhotsimskiy, A.P. Bukharkina, and Yu.F. Golubev
Д.Е. ОХОЦИМСКИЙ, А.П. БУХАРКИНА, Ю.Ф. ГОЛУБЕВ

SPACE RESEARCH
КОСМИЧЕСКИЕ ИССЛЕДОВАНИЯ
(Kosmicheskiye Issledovaniya)

Vol. VII. 1969 No. 2
pp 171-173

Nauka Publishing House
Moscow

Translated by the Center for Foreign Technology
Pasadena, California, on 4 Aug. 1969

Prepared for and issued by the Jet Propulsion Laboratory,
California Institute of Technology, Pasadena, Calif.,
under NASA contract NAS 7-100.

КОСМИЧЕСКИЕ ИССЛЕДОВАНИЯ
Kosmicheskiye Issledovaniya
Space Research

Vol. VII 1969 No. 2

UDK 629.196.3

The Control of Motion During Entry Into the Atmosphere

by
D.Ye. Okhotsimskiy, A.P. Bukharkina, and Yu.F. Golubev

ABSTRACT

Results are presented of an investigation on the construction of an algorithm for the control of a spacecraft descending into the atmosphere at a second cosmic velocity*. A multi-staged adaptive algorithm is constructed for control during the descent segment of the flight. Results are presented of the modeling operations of the algortihm in a digital computer. It is shown that the algorithm provided sufficient accuracy of control and smoothness in the adjustment process for the existence of significant variations in the distribution of the atmospheric parameters. The paper is a continuation and development of the results of earlier statements (Refs. 1-4).

1. Statement of the Problem

This paper is devoted to the problem of constructing an algorithm for the control of spacecraft motion during reentry into the earth's atmosphere at velocities on an order of the second cosmic*. It is assumed that the craft has a stabilized platform having three accelerometers installed along a mutually perpendicular axis. Flight control is effected due to change in direction of the lifting power of the spacecraft with change in the bank angle. A calculation of the necessary bank angle is produced by means of an on-board computer and is based on an analysis of the measrement data.

* Translator's Note: The expression "second cosmic velocity" is generally accepted to mean "escape velocity".

In Refs. 1 and 2, an example was given of the construction of an algorithm for control by the longitudinal motion of the spacecraft. In Ref. 3, an algorithm for control was constructed by spatial motion ensuring the achievement of the assigned landing sites by distance and laterally. In Ref. 4, an algortihm was presented for determining the conditions of entry into the atmosphere and a calculation for the for the initial conditions for integrating a system of navigation equations; in addition, an analysis was presented of the effects of errors in method, instrumentation, and operation, and the range of atmospheric parameters on the operation of the algorithm.

An algorithm for control during the segment of the first immersion I, constructed and thoroughly analyzed in the cited references, ensured the reliable introduction of the spacecraft into the final segment of free flight II in a sufficiently narrow region of the parameters permitting compensation for the obtained deflection in distance and flank with a utilization of the limited possibilities for control in the segment of the second immersion III (Fig. 1).

The algorithm was shown to be sufficiently stable as regards to error and uncertainty in information on the range of atmospheric parameters and ensured control at practically all possible ranges of altitude to perigees on an order of ±15 km.

The results obtained disclosed a means for constructing even more refined algorithms. In particular, it was desired to present instead of a stepped dependence of the bank angle γ on time, to obtain a continuous dependence which would more accurately be realized with the motion of the spacecraft near the center of mass. It was also desired that the limitation of the control moment be considered for a bank turn and produce a calculation for the time necessary to process the measuring data and obtain a solution regarding a change in the bank angle. This paper appears to have made progress in this direction.

2. Logic of the Accepted Solution

We checked, first of all, on an algorithm which was constructed on the assumption that the processing of data is performed instantly. Then we show how a consideration was made of the time for the calculations necessary for the accpetance of the solution.

We marked off a time interval within a section of the first immersion at intervals of uniform length. We shall assume that a solution for control is taken at the moment of transition from one interval to another, that instantaneous changes of bank angle at an end value is impossible, and that within one time interval the rate of change of the bank angle γ is constant. The function $\gamma(t)$ shall be presented as a broken line the salient points of which coincide with the boundaries of the time intervals.

We also note that the change of γ during the passage through the boundary of an interval is limited by specific boundaries, namely

$$|\gamma_{i+1}-\gamma_i|\leq\Gamma \qquad (2.1)$$

Such an assumption simulates the boundedness of the control moment in a bank. The value Γ simulates an increase of angular velocity which may be obtained by the effect of the control moments in the course of one time interval. In the accepted (assumed) model, impulses are transmitted instantly at the moment of transition through the boundaries of the intervals.

The derived function $\gamma(t)$ is similar to the motion in a bank which may, in fact, be realized by a spacecraft under influences limited by the magnitude of the control moments.

In each moment of the accepted solution, the value γ, and consequently, the bank angles at the nearest time interval, are selected from the condition, which together with the bank angles in the remaining time of travel in the segment of the first immersion, shall provide the necessary flight distance. Just as this was done in Refs. 1-4, a double integration for the equation of forward motion was performed from the moment of the acceptance of the solution to the end of the segment of the first immersion on the basis of the results which may determine both the value for distance (range) obtained during the selection of some value for $\dot{\gamma}$ in the nearest interval, and the magnitude of the effect on the distance of changes in the selection of $\dot{\gamma}$. These data made it possible to compute the necessary value for $\ddot{\gamma}$.

The logic of the accepted solution was shown by the feasibility to take differences in the initial stage of motion up to a moment close to acheiving maximum thrust velocity and in the remaining part of the segment in the first immersion. We described some of the examined variants of the logic and presented arguments in justification of the accepted variants.

One of the simplest may be a variant when a change in the bank angle is set along this or another consideration outside the limits of the nearest interval (t_i, t_{i+1}) in which γ is selected from the conditions obtained by the required distances. At the end of the nearest interval, a disruption of γ is considered (Fig. 2a). Inasmuch as at point t_i, a drop is not considered, repeated use is made of the algorithm at point t_{i+1}, etc. producing the function $\gamma(t)$ in the form of a break. However, the assumption of a disruption at the end of the interval is reduced to the appearance of an undesireable serrated change in $\gamma(t)$.

This can be avoided if a selection is made of not one, but simultaneously, of the two nearest sections of the break, as shown in Fig. 2b. The origin of the first of the selected links is determined by the value γ available to the moment t_i, and the end of the second link is determined by the condition of the continuous union with the already accepted factor $\tilde{\gamma}(t)$ after a moment of time t_{i+2}. The value γ at moment t_{i+1}, is determined by the selection of the γ in the first interval and varies with its changes. For all possible values of γ in the first interval of the examined factors, $\gamma(t)$ appears to be a continuous function. The use of the described double-link made it possible to get rid of the serration.

An examination of Fig. 2b shows that if all conditions in which a solution at point t_i was taken were retained and, subsequently, the counstructed double-link did not contradict the condition in Eq. 2.1, then, at moment t_{i+1} the first link of the new double link would match with the second link of the preceding, but the second link would coincide with a segment of the accepted factor $\gamma(t)$ for the subsequent value of time; that is, would have accomplished a passage at $\tilde{\gamma}(t)$ by means of the double-link found at point t_i. This indicates, specifically, that if we had deflected, for some reason, from the given factor $\tilde{\gamma}(t)$, then after two time intervals we would again have returned to it. This also indicates that if in the capacity of $\tilde{\gamma}(t)$ any break from a permissible number is taken, then the angle γ leaves in the process of control and will deteriorate.

In reality, because of the ignorance of the actual distribution of the atmospheric density, the conditions for accepting the solution lessen from point to point, and the indicated process, in a pure form, does not occur. In addition, depending on the detected appearance, during the flight, of a character of change in the atmospheric density, it is expedient to produce a change in the $\tilde{\gamma}(t)$. Nevertheless, the algorithm utilizing the logic of the double link proved to be sufficiently effective and was accepted initially in the second part of the segment of the first immersion.

The application of a double link in the first part of the motion proved to be insufficient because of the tendency to provide a selection of the parameters of the double link in conditions of low efficiency and its subsequent increase in proportion to an increase in the velocity of the thrust leading to the need for strong modulation by the parameters of the double link, as a result of which, the process of regulation is found to be not sufficiently smooth. When descending, the efficiency of using a double link is found to be completely feasible.

In the first part of the motion, a more extended interval of change in the bank angle was found by suitable modulation; this consisted of a link of fixed (constant) value of the angle γ encompassing several time intervals, of one link, developing in that segment from the available value of the angle γ to point t_i, and a segment of forced modulation of the further passage of γ (Fig. 2b) for providing the continuity of interlinking with $\tilde{\gamma}(t)$. The modulated condition of the function $\gamma(t)$ is shown by a dashed line. In proportion to the advance to the region of maximum thrust velocity, the segment of constant γ selected is shorter and produces sufficiently smooth interlinking of the described logic with the logic of the double link.

Increasing the capacity of the algorithm to cope with the uncertainties in determining density was accomplished by decreasing the time intervals and, more often, producing the accepted solution. In this instance, the range of temporary bases for the double link would be insufficient which would lead to a strong perturbation of its parameters and a disturbance of the eveness of the control in the same way as occured during the utilization of the double link in the first segment of the motion up to the zone of greatest thrust velocity. For overcoming this difficulty, it proved to be expedient to somewhat modify the logic of the double link, doubling the length of both of its links. In the accepted scheme, each of the links of the double link consisted of two intervals of time. After arriving at point t_{i+1} (Fig 2d), the construction of a new double link was produced with the same time span of the links, but shifted to one time interval, etc.

The logic of the first stage of motion in a segment of the first immersion also proved to be feasible by a slight modification because of a link derived in a plot of the constancy of γ and selected by two similar time intervals; however, a review of the solution was produced after the passage of each interval.

With the solution of the boundary value problem about reaching the assigned distance, it could be shown that an abrupt change in the angle of inclination produces more than this is possible according to the constraint of Eq. 2.1. In this instance, we selected maximum possibilities for the examined interval for the value $\dot{\gamma}$.

For control of the flight distance, it is sufficient to have the opportunity to change the angle γ within a range of from 0 to π. When $\gamma = 0$, the entire lift is up; when $\gamma = \pi$, it is down. During the intermediate values of γ, a vertical projection of lift has an intermediate value. Specifically, when $\gamma = \pi/2$, the component lifting force in a plane of the longitudinal motion is equal to zero, and the longitudinal motion is similar to the motion of a spacecraft without lift.

In order to overcome, effectively, the uncertainties of the atmospheric parameters, an analysis is conducted, during the flight, of the deviations in density from standard distributions. Using kinematic parameters of motion and obtaining integrating systems of navigation equations based on initial conditions and current values, the component of acceleration for aerodynamic forces may be computed at each moment of motion for the value of density ρ and the value $\xi=\rho/\rho_{st}$ providing a relation of the actual density at a given point to its value from the accepted standard distribution. The longitudinal motion of the value ξ is found by some function of time the behavior of which, in the former, shall be known for each moment of time. Assuming, as in Refs. 1 - 4, that ξ is sufficiently even coordinate function, we obtain the function $\xi(t)$ for the longitudinal motion which will also be sufficiently smooth permitting an extrapolation forward in a brief time interval. The utilization of such an extrapolation is proved to be useful while conducting integrated equations of forward motion in the process of accepting the solution.

Information about the possible character of change in $\xi(t)$ in the immediate future was also used during the selection of $\tilde{\gamma}(t)$ outside the bounds of that time interval in which the selection of γ was made from conditions ensuring the assigned distance. In this manner it was possible to ensure an adaptation and reserve margin of control for overcomming a deviation in density, the appearance of which, judging by the passage of the function $\xi(t)$, could be anticiapted in the immediate future.

The original function $\tilde{\gamma}(t)$ is seen as a broken line in Fig. 2d. A segment of the constant value $\gamma = \ell$ joins an oblique line with another segment of constant value taken initially as $\pi/2$. Brake moments t_1 and t_2 were chosen beforehand and fixed. With modulation ℓ in the process, of the solution of the marginal problem of the inclined segment was also modulated as shown in Fig. 2d by the dashed line. During the transition from one time interval to another, the length of the modulated segment is naturally decreased. In the vicinity of t_1, a transition occured in the logic of the double-link or its modified variant.

Adaptation is produced by means of introducing a change in the position of the segment of the curve of $\tilde{\gamma}(t)$ following point t_2. The value m (Fig. 2d) was computed by the formula

$$m = \frac{\pi}{2} + \Delta\tilde{\gamma} \qquad (2.2)$$

where the second component, just as in Refs. 1 - 4) was determined by the formula

$$\Delta\tilde{\gamma} = f(t)[A\xi + B\dot{\xi}] \qquad (2.3)$$

where A and B are the selected experimental constants, $\dot{\xi}$ and $\ddot{\xi}$ are the values of the first and second functions of $\xi(t)$, computed at the moment of the accepted solution for a multiple approximated passage $\xi(t)$ in which the interval of time, preceding this moment, $f(t)$ is a certain function of time equal tozero (null) to a zone of maximal thrust velocity, then linearly increasing and reaching a given value then remains constant. The parameters of the function $f(t)$ were selected experimentally. The considerations leading to an introduction of adaptation of this type, are provided in detail in Refs. 1 and 2.

3.A Calculation for the Time of Processing Data

In the preceding accoui t, it was assumed that the calculations associated with a reduction of the measurements that the acceptance of the solutions were produced instantly. We eliminated one time interval from the computations. We shall consider that all calculations associated with the control selection are produced by basic information obtained by the initial interval. Simultaneously, an integration of the equations of navigation problems were made and data concerning the passage of the function $\xi(t)$ were stored; however, these data were only used in the next act of accepatance of the solution in the next time interval. Between the end of the admission of information for the acceptance of the solution and the beginning of the completion of the solution, there is a lag of one time interval.

It is possible to compute for the lag by introducing a small change in the algorithm, the logic of which was described in the preceding section. We shall consider that the entire logic is retained, but the selection of γ in the nearest time interval is based on information obtained up to a moment of one time interval sooner. In order to enter into the logic of the algorithm without a lag it is necessary to conduct a calculation for a value of one time interval. The value of function $\xi(t)$ we obtain by extrapolation. The coordinate conversion and component of velocity we obtain by integrating the equations of motion in one interval using an extrapolated value for $\xi(t)$. Values entering the formula for an addition to the function $\tilde{\gamma}(t)$ were obtained by means of extrapolation. After such a conversion, everything is done as if the indicated data were obtained from a solution of the navigation problem based on measurements made in a time interval eliminated in this instance for completion of the calculation.

Such an approach proved to be convenient because it was sufficiently simple to investigate the effect of lag by a small modification of the algorithm constructed without calculation for the lag.

The accepted assumption is that in a time interval deleted for the acceptance of the solution, the incomming measurements and navigation data may not be used; this may be the most simple and convenient way for constructing the algorithm. Together with this, the results obtained with this assumption, give an upper estimate of the negative effect of th lag since the data entering during the time of the calculation could,in principle, be partially utilized; this can positively be stated to be characteristic of the algorithm of control.

4. Results of Modeling

The development and testing of the algorithm was conducted by a compter. The components of aerodynamic acceleration were computed by the integration of a system of equations imitating the moving object. In these equations, divergencies of the atmospheric parameters were interpolated from the standard distribution and the equations according to the selection of the bank angle which were developed by the control algorithm. The control algorithm, realized in the form of the programed complex, took the information from the imitated equation as the measured one, conducted the integrated system of navigational equations, accomplished the predictions of motion, the solutions of the boundary value problems, adaptation, predicted the function $\xi(t)$, and produced other operations, provided for the logic of its operation,and developed a solution for a change in the bank angle in the nearest time interval.

The same deviation of direction was used as a disturbance of the atmospheric parameters which was used during the development of the preceding algorithms and described in Refs. 2 and 3. These deviations are imitated as variations in the distribution of density along the vertical and as variations along the flight route. Their value, evidently, is somewhat greater than the variation which may be encountered in actual flight,and the algorithm capable of successfully overcoming them shall have a certain margin of safety.

Some results of the modeling are presented in Fig. 3a. The heavy broken line represents a change in the bank angle of γ during a period of flight in the first immersion sector. The readout for time is carried from a point having an altitude of 150 km. The inclusion of the algorithm takes place at a momentwhen an interval from a g-load reaches a certain given value. At first, in a zone where the effectiveness is still not great, the equation is not carried out and the angle is established as equal to the value γ_0 selected in relation to the height of the conditional perigee. After the passage of an interval of time of 45 sec, the logic of the prediction is put into motion and the acceptance of the solution. A thin solid line represents the dependence $\xi(t)$ formed along the flight trajectory. The dashed line, at times, was given the value m equal to the height of the right band in Fig. 2b. This value changes in relation to the passage of the function $\xi(t)$ in conformance with Eqs. 2.2 and 2.3.

We can see that for a variant, pictured in Fig. 3a, flow γ began quite mildly. The development of the tendency to a deflection of the density to increase is fended off by a lessening of the γ angle and an increase in the component of lifting forces influencing the longitudinal motion.

The increase of $\xi(t)$ ceases quite abruptly and is replaced by a decrease. In view of such a situation, there is produced, beforehand, a transition to an increase of γ and bearing of the lifting forces of the craft downwards with a goal of preventing the flight of the craft from the atmosphere until its velocity shall be in a sufficient degree of braking.

The rapid change of the situation with regard to the passage of the function $\xi(t)$ requires very rapid reaction. In consequence of the accepted limitation on the value of the skip $\gamma$and the presence of the time interval dividing the moment of the receiving of information from the moment of acceptance of the solution, in the system there is a certain inertia which lessens the rapidity of the reaction. An abrupt change of the passage $\xi(t)$ leads to the yield of the angle γ on the upper pause where it remains until the end of the motion in the segment of the first immersion. The lag occurs with a slewing of all lifting forces of the craft downwards which, in spite of the accepted measures, leads to the craft's emerging in a segment of free flight at excess speed, and the point of entry into the atmosphere in a segment of the second immersion is shown by a displacement longitudinal to the flight at 210 km. Such a deflection may be compensated for without difficulty by control in a segment of the second immersion since there is a profound inner admissible range of deflection.

We note that the variant shown in Fig. 3a appeared to be the greatest of the observed variants of deflection in the distribution of the density of the atmosphere. This variation of density distribution proved to be difficult for processing, especially because after the abrupt change of passage $\xi(t)$ there was a reduction in density compared to the standard. As a consequence of that, the available margin of influence of the craft's lifting forces on its motion is shown to be inadequate. As shown by the calculations, such steep transitions from a decrease of the fuction $\xi(t)$ to an increase proved to be significantly more easy to overcome.

The rest of the examined variants in the deflection of density, reduced to a deflection of the range of the points of entry, are significantly less than the variant shown in Fig. 3a. In this instance, when the process of control was completed, not at the pause, the deflection in range was usually within several tens of kilometers and essentially determined the accuracy of the integration ahead with a solution of the boundary value problem.

The curve in Fig. 3b is more even than in Fig. 3a for the passage of function $\xi(t)$ during the transition from increase to decrease although it attracts a brief exit of the bank angle at a pause, but the process of control is concluded in the inner region and ensures a high accuracy in the entry points for a segment of the second immersion.

A more prolonged period of pause provides a place for the variant in Fig. 3c, however, at the end of the motion a descent takes place from that pause.

In Fig. 3d a variant is presented in a density deflection characterized by that deflection taking place, essentially, to the side of increased density. A sufficiently fast change in the passage of $\xi(t)$ from a decrease to an increase leading to a lower pause which answeres the utilization of all available lifting forces for the possibility of a more rapid exit from the atmosphere in order to prevent excessive damping of the velocity and the associated deflection of the entry points to an undershot. As a result of the timely pause, the resulting undershot was insignificant.

In Fig. 3e the entire process of control takes place without pause. The deflection in range is small. It can be seen that the flow of function $\xi(t)$ influences the amount of the parameter of adaptation m and the passage of the bank angle.

In Fig. 3f a variant is presented where the intense decrease of ξ leads to an upper pause in a certain time. The deflection in range is also very small.

The results of the modeling showed that with a reasonable choice of parameters, an algorithm may make it sufficiently stable with respect to a variation in the distribution of density and to ensure an entry point in a segment of the second immersion a reliable reduction of the craft in a region of the parameters making possible an effective solution of the control problem in a second immersion and the descent of the craft in an assigned area with great accuracy.

Submitted for publication on
3 December 1968

FIGURES

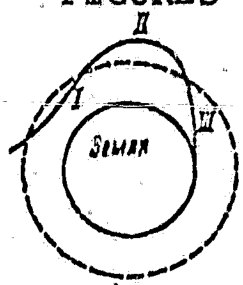

Fig. 1. Descent trajectory into the atmosphere. I- a segment of the first immersion, II-a segment of motion outside the limits of the atmosphere, III-a segment of the second immersion.

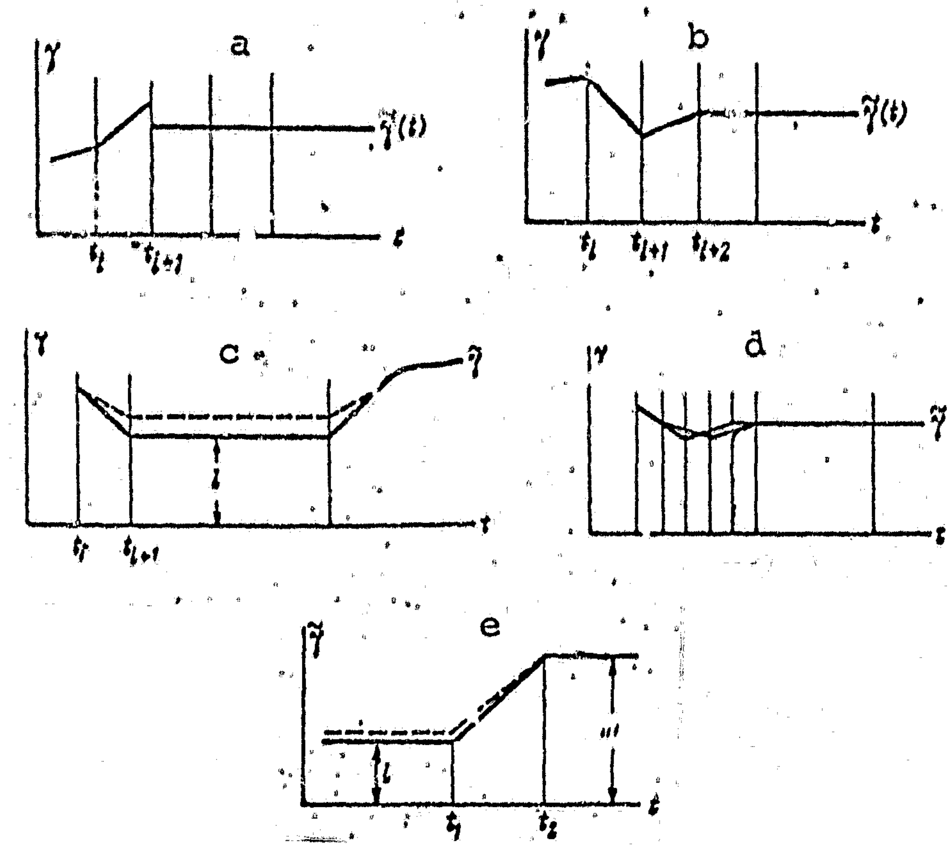

Fig. 2. Change of bank angle with time.

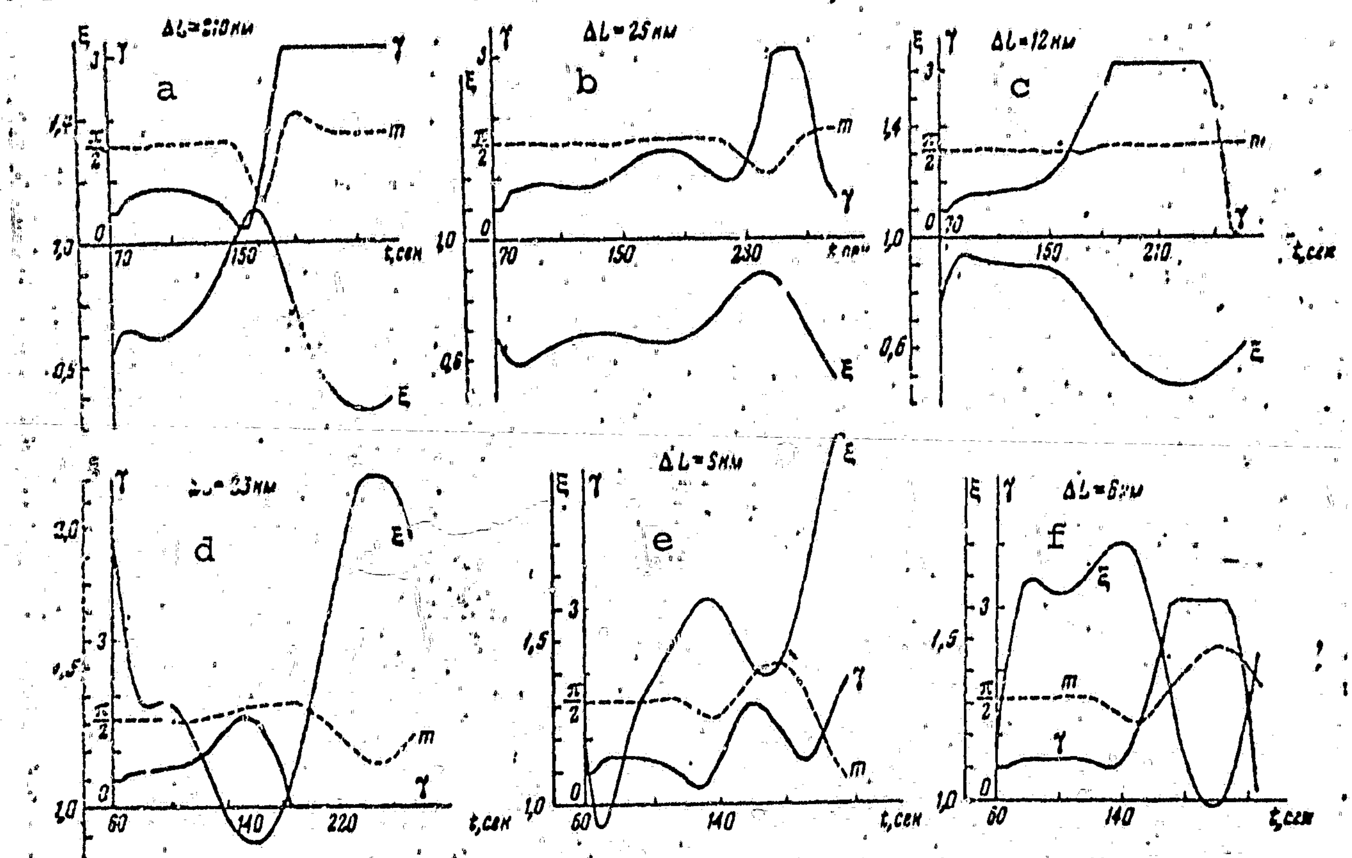

Fig. 3. The process of control. Perigee = 47 km.

REFERENCES

1. D.Ye. Okhotsimskiy, et al, КОСМИЧЕСКИЕ ИССЛЕДОВАНИЯ (Kosmicheskiye Issledovaniya - Space Research), Vol. VI, No. 1, 1968, p. 31.

2. D.Ye. Okhotsimskiy, A.P. Bukharkina, Yu. F. Golubev, and Yu.N. Ivanov, "The Control of Prolonged Motion During Entry of a Spacecraft into the Atmosphere," ОТЧЕТ ИНСТИТУТА ПРИКЛ. МАТЕМ. (Otchet Instituta Prikl. Matem. - Reports from the Institute of Applied Mathematics) 1967.

3. A.I. Bukharkina, Yu.F. Golubev, and D.Ye. Okhotsimskiy, "Control by Spacial Motion During Spaceraft Entry into the Atmosphere," Reports from the Institute of Applied Mathematics, 1968.

4. Yu. F. Golubev, "The Determination of Conditions of Entry into the Atmosphere and the Analysis on the Effects of Errors," Reports from the Institute of Applied Mathematics, 1968.