

# FOREIGN TECHNOLOGY DIVISION



## PROBLEMS OF ASTRODYNAMICS

by

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## EDITED TRANSLATION

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**ABSTRACT**

Questions concerned with calculations for orbit and movement of a cosmic vehicle relative to the center of mass are discussed. The significance of the selection of the section for the inertia of the cosmic vehicle, investigation of sensitivity of orbit to error, to perturbations and corrective actions is noted in the first question. The combination of simplified methodology during the first stage of orbit planning, and of more precision in subsequent ones, is suggested. The second question notes the importance of investigating the effects of gravitational, aerodynamic, magnetic, and other forces, on vehicle movement. The use of the results of angular motion calculations, along with sensitive element readings, is suggested in order to determine the angular motion of the vehicle. The importance of investigating the movement of a body with liquid-filled spaces under conditions of weightlessness is noted.

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### The Emergence of Astrodynamics. Its Content

The rapid progress in investigating and conquering space has led to the emergence and development of a new field of mechanics - astrodynamics or the mechanics of space flight. The amount of work devoted to the various problems of spacecraft movement is quite considerable and growing steadily. Along with the designation "astrodynamics," other names are used, such as "space dynamics," the "theory of motion for artificial celestial bodies," "celestial ballistics," and others. We have chosen the term "astrodynamics" because of its brevity and wide use in literature.

Astrodynamics investigates the movement of both unguided and guided spacecraft, develops and uses methods of orbit projection, and also solves other dynamics problems with respect to cosmic flight.

Formally, astrodynamics falls under Laplace's definition of celestial mechanics, which states that celestial mechanics is the study of various mechanical movements of celestial bodies under the effect of gravitation and other forces. Astrodynamics can be considered as the modern branch of celestial mechanics. However, it seems to be expedient to designate the group of tasks and methods which make up the problems of this science as "celestial mechanics" or classical celestial mechanics.

The movement of both natural celestial bodies and artificial ones launched by man is subject to the same laws. Therefore, astrodynamics uses the methods and results of celestial mechanics. At the same time, the characteristics of the subject under investigation and the specifics of the approach have led to the examination of new problems and the development of new methods lying outside the realm of traditional celestial mechanics.

Classical celestial mechanics was concerned with the study of the motion of natural celestial bodies, but with the advent of space flight there arose the problem of projecting movement, projecting

cosmic flights and choosing orbits which would best satisfy requirements imposed on the flight. Such problems appeared as flight control of spacecraft, orbital corrections, maneuverability, and the movement of spacecraft under the effect of thrust, which though small would be effective during a considerable portion of the flight.

The classical chapter in mechanics - the investigation of the movement of a body relative to the center of mass - has achieved interesting development in connection with rotary and librational motions of satellites under the effect of perturbances. A great number of other dynamics problems have appeared.

Below we will examine briefly only certain astrodynamics problems.

### Projecting Orbits

As has been shown, the development of cosmic flight has made it necessary to work out various methods of projecting orbits. By projection we mean the selection of an orbit with the aim of accomplishing the basic task of the flight as fully as possible with the most economical use of technical means.

In the original examination it is essential that we investigate the entire set of orbits which would ensure, at least in theory, the accomplishment of the flight's basic task. For example, when planning a flight to the Moon, it is important to establish all possible trajectories, to be able to determine initial conditions necessary to realize these trajectories, and to determine the kinematic and dynamic characteristics of orbits (flight time, impact velocity with the Moon, initial power required, observation conditions with assigned points on the ground, etc.).

With analysis we can map those orbits which best satisfy requirements for both an effective solution of the basic task and a simple and economic flight. These requirements, for the most part, are contradictory and the final solution is most frequently the result of compromise and calculations which have actual technical possibilities.

One of the most important orbital requirements is the economy of power during launch and insertion. Two basic methods of insertion are used: a continuous powered phase and launch from a parking orbit. The first method is technically simple; however, in certain cases it is difficult. The fact is that selection of a launch site is inevitably limited and for boosting certain spacecraft it can be necessary to use trajectories which are slanted steeply to the local horizon. This increases losses from surmounting gravity and decreases terminal speed or (under given insertion conditions) decreases weight of spacecraft. The method of continuous boost limits the range of velocity directions in the beginning of orbital motion, making more desirable not only those orbits with the lowest possible initial speed but also those orbits with the least possible slant of velocity vector to the local horizon at the end of the powered phase.

The launch from parking orbit method is free from power limitations on direction of boost. Any direction of velocity vector is achieved by proper selection of the time of launch into intermediate orbit (which gives azimuth sighting by turning the intermediate orbit together with earth in its diurnal motion) and proper selection of the time for launching from orbit (which gives elevation sighting owing to the fact that departure from orbit occurs when orbital motion has the necessary direction). Boost of the spacecraft both during insertion into satellite orbit and during departure from it occurs at minimum angles of slope to local horizon and ensures maximum use of the power capabilities of the carrier rocket. The fact that Soviet scientists and engineers have mastered the method of launching spacecraft from satellite orbit is an outstanding technical achievement. The use of such a method of insertion limits only the initial velocity of orbital motion, while allowing the insertion of very heavy spacecraft, expanding widely the range of possible orbits, and easing the conditions for their appropriate choice.

With the insertion method which uses the intermediate satellite orbit, the most desirable spacecraft will be those with the very lowest initial speed. When boosting with the continuous powered phase it is important that both the speed and the angle to the local horizon be the least possible.

Other problems connected with orbit projection include the study of the precision required in accomplishing a selected nominal orbit and the choice of correction method. When a flight is made without path corrections in the trajectory, the problem consists of the appearance of a zone of parameter deflections at the end of the boost phase so that the basic task of the flight could be solved if the deflections did not go beyond the limits of this zone. For instance, if the goal of the flight is to reach the moon, we seek those deflections of insertion parameters with which the orbits will pass through the moon, and this means the moon will be actually reached. Naturally, the less restrictive the limitations are on the zone where the insertion parameters spread, the simpler it will be to accomplish the flight, the lower the precision requirements will be on the insertion system, and the less weight and greater reliability this system will have. Therefore, it is desirable to select those orbits which allow the greatest deflection of insertion parameters. This requirement can be and usually is inconsistent with optimum power characteristics of an orbit, but the situation is a typical one in orbit projection.

It can happen that the permissible zone of initial deflections is excessively small and cannot be realized by existing technical means. In addition, the knowledge of the celestial mechanics constants, such as the solar parallax or the elements of the planetary orbit, may be insufficient so that the ideal fulfillment of insertion conditions will not guarantee that the flight's purpose will be accomplished. In these cases we must apply an orbital path correction - a correction in the parameters of movement - which can be done by sending pulses of the proper magnitude and direction at certain spots in the orbit. The orbit can be corrected once or several times throughout the flight.

Orbital correction requires the presence on board of a propellant system for making corrections and a fuel reserve. The amount of additional weight which must be taken on board the spacecraft in connection with orbital corrections depends on the magnitude of the correcting pulse or the magnitude of the total pulse in the case of multiple corrections. The magnitude of the correcting pulse depends on the spread of the parameters of motion at the end of the boost phase and will be greater the larger the area of spreading. In addition, the magnitude of the pulse necessary for orbital correction depends on where in the orbit this correction is accomplished. For example, if the correction occurs too near target, a very great alteration in velocity and a large correcting pulse are necessary. This means considerable additional weight on board the spacecraft.

When selecting orbits we will have to give preference to those orbits which allow the simplest and most economical correction. At the same time there arises the task of optimizing corrections; i.e., selecting such an orbit and such correcting points on it that accomplishing the correction requires a minimum total pulse and minimum additional weight on board the spacecraft.

To solve the problem of corrections it is necessary to have an accurate determination of the actual parameters of motion during the flight, a calculation of the deflections of these parameters from the nominal parameters, and a computation of the necessary correction parameters.

The determination of orbital parameters is a classical problem in celestial mechanics. However, its solution for spacecraft is connected with the fulfillment of a number of specific requirements. For instance, it is frequently necessary to determine orbital parameters with maximum speed. Therefore, the algorithm for the computation, which usually contains the iterative process, must be very economical and must ensure that few iterations are involved and little time is required to fulfill each iteration. This algorithm must also be highly reliable and dependable, guaranteeing convergence of the process even when the choice of initial approximation was not made very successfully.

Precision in determining actual orbital parameters depends on the composition and accuracy of the measured parameters and also on the location of the measured interval in the orbit as well as its dimensions. With given composition and precision of measurement, as a rule, the parameters of actual movement can be determined more accurately and this means the orbital corrections will be more reliable and accurate the larger the segment of the orbit in which the change takes place. However, excessive prolongation is not wise since it can lead to corrections which are too late and a correcting pulse which is too big.

Early correction can be more economical; however, insufficient precision in determining orbital parameters beforehand can lead to insufficient accuracy of correction and to the necessity for repetition.

These considerations illustrate the complexity and contradictory character of problems connected with the projection of a system of measurements and orbital correction; i.e., the projection of a system of flight control, obviously, lies in the creation of a system which would ensure the solution of the basic task of the flight in the simplest and most reliable manner and most economically with respect to weight on board. Therefore, when choosing, it is expedient to give preference to those orbits for which the most optimum flight control is possible.

Orbit projection is reduced to the development and computation of a number of contradictory orbital requirements, some of which have been mentioned briefly above. It also includes the complex analysis and choice of that orbit which satisfies the established requirements to the maximum degree. Thorough analysis of a flight requires the calculation of a great number of variants. At the same time, the requirement for calculation accuracy in the initial stage of projection is usually not too high. Therefore, a reasonable solution is the development and use of various approximation techniques which allow us, simply, economically, and graphically, although with limited accuracy, to analyze orbits with respect to satisfying orbital requirements and to seek compromise variants which would offer the best solution for the task at hand.

The subsequent stage of the projection for selected variants requires more precise refinement of calculations, taking into consideration all necessary factors affecting the flight of the spacecraft. These calculations are usually carried out by numerical integration with the use of the most precise constants and have as a goal the obtaining of precise values of flight parameters and orbital insertion parameters. Since more precisely defined calculations are frequently quite time-consuming, the task of developing effective methods for calculations here is no less acute than with calculations for the stage of preliminary projection. An effective technique for more precisely defined calculation must combine the necessary accuracy with speed of computation. Therefore, when setting up this technique, it is necessary to use everything that is known about the orbit. For example, the motion of a spacecraft relative to earth inside its sphere of influence is nearly motion along a conic section with a focus in the center of the earth. Motion outside the earth's sphere of influence is nearly heliocentric motion along an unperturbed orbit, etc. Taking into account these circumstances opens the way to the perfection of a technique for more precisely defined calculations. Of course, other ways are also possible.

Methods for investigating orbits are determined essentially by the character of the flight. We can select multispeed orbits and orbits with little angular range. Orbits of the first type include those of earth satellites, the moon, and the planets, which accomplish many revolutions. For the study and projection of these orbits we use methods which allow us to develop the pattern of parameter evolution of an osculating orbit when under the influence of perturbing factors such as an off-center gravitational field, atmospheric effect, disturbances from other celestial bodies, the effect of light pressure, etc. The task of calculating the process of evolution can be considered as a problem of nonlinear oscillations. Wide use of various

methods of averaging and the technique of constructing asymptotic solutions can ensure the creation of simple and effective methods for both preliminary and more precisely defined calculations.

Orbits with little angular range are, for example, those orbits for flights from earth to the moon or from earth to Mars, Venus, or other planets. These orbits are, in the first approximation, arcs of conic sections, and the problem of evolution does not arise. Approximation methods are expedient to use either while disregarding perturbations or considering them roughly. Thus, the orbit for a flight to Mars can be considered as consisting of portions of conic sections - unperturbed geocentric motion in earth's sphere of influence, and an unperturbed conic section with a focus in the center of Mars when motion occurs inside its sphere of influence.

We have discussed above only a few considerations involved in orbit projection.

#### Motion of a Spacecraft Relative to the Center of Mass

Rotational and librational motions of unguided spacecraft relative to the center of mass can be considered. Motion is called rotational if the energy of the outer moments for one revolution is small in comparison with the kinetic energy of the apparatus. In this case the craft accomplishes nearly free Eulerian motion, the parameters of which change slowly in time. The motion of non-oriented satellites is usually rotational.

When investigating rotational motion, it is frequently expedient to use the methods of the theory of perturbations, wherein Eulerian motion is considered unperturbed. Averaging allows us to achieve evolution controls which depict the change in vector of kinetic moment and other parameters of Eulerian motion. Dynamic symmetry in this case is the simplest.

Such methods make it possible to investigate rather thoroughly the effect of gravitational, aerodynamic, and magnetic moments as well as a number of other factors on the motion of satellites.

Of interest to further research is a more detailed development of dissipative factors and also a more detailed examination of the total case of the absence of dynamic symmetry.

The motion of a body or spacecraft can have a oscillatory character around a certain unperturbed position because of the effect of perturbations. Such motion is called librational. An example is the moon, maintaining an almost unchanging position (turned with one side constantly facing earth) and experiencing only extremely small oscillations - librations. Such natural stabilization is ensured because the moon's ellipsoid of inertia differs from a sphere and because restoring moments of the earth's gravitational field arise during the deflection from a position of equilibrium.

This same effect can be used for the stabilization of artificial satellites. The necessary orientation of a satellite in space can be

ensured by adding a stabilizer to the satellite so that the satellite-stabilizer system would be gravitationally stable. In order that the satellite not somersault and its motion be oscillatory in nature with rather low amplitude, it is necessary to extinguish perturbations arising during separation from the carrier and to introduce damping into the satellite-stabilizer system. Such damping can be achieved, for instance, by introducing relative mobility for the satellite and stabilizer and including a dissipative section in relative displacements.

To correctly interpret the readings of scientific instruments in unoriented research satellites, it is frequently necessary to know the orientation of the satellite when metering. Satellite orientation information can be obtained both from the readings of the research instruments and from the readings of special orientation data units. However, in a number of cases such information is incomplete and does not permit an immediate, unambiguous pinpointing of the satellite's spatial position. The precision of such immediate location is insufficient.

Knowledge of the laws of motion is a considerable aid when statistically processing the available information. Movement controls can take into account the effect of both known and incompletely known factors whose indeterminacy depends on an unknown quantity of parameters applicable to the solution along with the parameters of motion. The task of determining the motion and calculating the orientation of the satellite at any moment is similar in character to the problem of processing trajectory measurements and is an integral part of space research.

The task of determining motion relative to the center of mass in measurements not only has direct practical value, but is extremely important for studying the laws of motion, the appearance of dynamic effects, the determination of perturbing moments and the character of their action, and for making proper dynamic designs for spacecraft.

The problem of calculating the effect of liquid filling is an important, though unfortunately little studied, area in the investigation of spacecraft motion.

Of interest, for example, when spaces are filled, is the problem of the disruption and evolution of rotational motion because of dissipation due to the viscosity of the liquid. In the presence of a free surface the study of motion is quite complex. The rather far advanced problem of small oscillations of a heavy liquid in a vessel during light perturbations of the plane free surface is meaningless in weightless conditions. Such effects as surface tension acquire considerable significance.

All of this interesting group of problems, where hydrodynamics and the dynamics of solid bodies meet, await solution.

This has not been an exhaustive discussion, to any extent, of the manifold mechanical problems involved with the motion of a spacecraft relative to the center of mass. We have had a more modest goal - to mention briefly only some of the problems.