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THE SOVIET SPACE RESEARCH PROGRAM

MONOGRAPH VI
GUIDANCE AND CONTROL

CIA/SI 36-59
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CENTRAL INTELLIGENCE AGENCY

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Scientific Intelligence Report

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NOTICE

The conclusions, judgments, and opinions contained in this finished intelligence report are based on extensive scientific intelligence research and represent the final and considered views of the Office of Scientific Intelligence.

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PREFACE

The advent of the space age has brought man face to face with guidance and control problems which heretofore were discussed only by theoreticians. Although man has demonstrated the ability to propel vehicles outside of the earth's gravitational field, considerable effort must still be devoted to the problems involved in the precise computation of trajectories, as well as to the development of high-speed computers and the guidance and control systems which the vehicle will use to pursue the required course. While tentative solutions to these problems have been available for some time, a full-scale space program including earth and moon satellites, moon probes, and flights to other planets, necessitates further investigation into better guidance and control systems, higher-speed computers, and greater control thrust capability in the vehicles.

The term "guidance" as used in this paper refers to the ability to measure position and velocity vector as a function of time and to calculate and command adjustments to these values which will result in the vehicle arriving at a preselected spot within predetermined tolerances. The ultimate in space travel envisions the development of power systems of sufficient thrust and duration to enable a space mission to change direction at any time throughout the flight, thus reducing the guidance problem to positioning navigation. At the present time, however, major power sources are limited to short duration and, during the greater part of the flight of ESV's * and space probes, the vehicle follows a path which is a direct result of the ability to control the velocity vector and position within precise limits for approximately the first 1,000 miles.

"Control" in this paper implies the ability to stabilize the vehicle and to maintain vehicle attitude, i.e., orientation with respect to a reference axis, so that primary and corrective propulsive forces will act along the desired direction and on-board instrumentation will be properly oriented.

Little information is available on Soviet research and development concerning the guidance and control of space vehicles, probably because such work is closely associated with military projects. The cutoff date of the background information used in the preparation of this paper is 1 July 1959.

This monograph is one of 12 (listed below) on the Soviet space research program. Monographs II through XII are designed to support the conclusions found in Monograph I, which

* Earth satellite vehicle.

is to be an overall evaluation of significant Soviet space research capabilities. Monograph I will be published last.

The Soviet Space Research Program:

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MONOGRAPH VI
GUIDANCE AND CONTROL

SUMMARY AND CONCLUSIONS

The Soviets probably have developed their guidance capabilities sufficiently to launch earth satellites into predetermined orbits. [redacted]

Guidance for all Soviet space missions previous to and including the launching of Mechta (sometimes called Lunik) was probably of military ballistic missile design and radio-inertial type.** The Soviets are known to have conducted research and development in inertial guidance with celestial correction. This work can probably be applied to midcourse space guidance. Additional propulsive force would be necessary for corrective maneuver. Soviet space missions involving targets more difficult than moon objectives will probably use a different guidance system than that in Mechta and earlier space shots, probably one incorporating midcourse or terminal guidance.

Soviet theory of control is estimated to be very good, and it is probable that their control hardware would be adequate for the space missions within their estimated program.

The Soviet earth satellite, Sputnik III, is believed to contain a combined solar-chemical battery pack that could provide power for guidance and control. This pack has demonstrated reliability by providing transmitter power almost continuously in excess of one year.

DISCUSSION

INTRODUCTION

At the present time the Soviet space guidance program, as an adjunct to the space program itself, is probably directed by the Soviet Interagency Commission for Interplanetary Communications. Soviet interest in the conquest of space can be traced back decades, but present realization of some of their objectives is a direct result of missiles systems research, particularly in areas of propulsion and guidance. Outward manifestation of Soviet space guidance and control capabilities came rather abruptly to the world with the launching of Sputnik I on 4 October 1957. Two more satellites, Sputniks II

* CEP (circular error probable) is the radius of a circle centered on the target within which 50 percent of the missiles would land when fired from the specified range.

** See the appendix for an explanation of guidance types.

and III, were put in orbit within 7 months of the first. Mechta was added to their space achievements on 2 January 1959. This succession of events over approximately a 15-month period makes the forecast of a future 15-year period extremely difficult, but Soviet objectives are believed to include guidance and control systems for:

(a) Recoverable satellites (unmanned and manned),

(b) Soft lunar instrument landings,

(c) Instrumented flights to the vicinity of other planets (Mars and Venus), and

(d) Manned lunar landings.

These represent logical steps in the exploration of outer space and, of course, will require guidance and control of varying degrees of precision depending on the mission.

GUIDANCE AND CONTROL ACCURACIES REQUIRED FOR SPACE OBJECTIVES

Discussions of guidance and control accuracies in connection with ballistic trajectories is normally associated with the powered flight phase, which represents approximately the first one thousand miles or less of flight. On this basis, the approximate accuracy requirements for several missions are tabulated below for reference purposes. These missions are arranged in order of complexity and do not include midcourse or terminal corrections.

ACCURACY REQUIREMENTS *

Mission	Total Angular Error in Velocity Vector (in Degrees)	Total Cutoff Velocity Error (in Percent)
Earth satellite	3	1
To hit moon	.2	.15
To hit moon within circle of 150-nautical mile radius	.02	.02
ICBM [redacted] at 5,500-nautical mile range	.02	.02
To hit Venus	.012	.0005
To hit Mars	.003	.0002

* There is a 68 percent (one sigma) probability that a mission will be guided successfully if errors are kept within these limits.

SOVIET GUIDANCE CAPABILITIES

Demonstrated

The launching of Sputniks I, II, and III by the Soviets demonstrated a certain degree of competence in the field of space guidance, but these launchings went further toward establishing system reliability than guidance accuracy. The earth satellite mission may be compared to the creeping stage before walking out further into space, and guidance errors which can be tolerated in this mission must be reduced to approximately one-tenth of their value to make a strike on the moon.

The general makeup of Mechta (with its Soviet medallions and other national identification markings) [redacted] indicate that the Soviets actually attempted to hit the moon. [redacted] Component failure appears to be the most acceptable reason for the large miss, because the preponderance of evidence, including their successes in developing complicated missiles systems, indicates that they are capable of hitting the moon.

Feasible

Progressively more difficult is the task of hitting the moon with a [redacted]. This requires about the same guidance and control accuracy as is required for an ICBM system [redacted] at 5,500-nautical mile range.

[redacted]

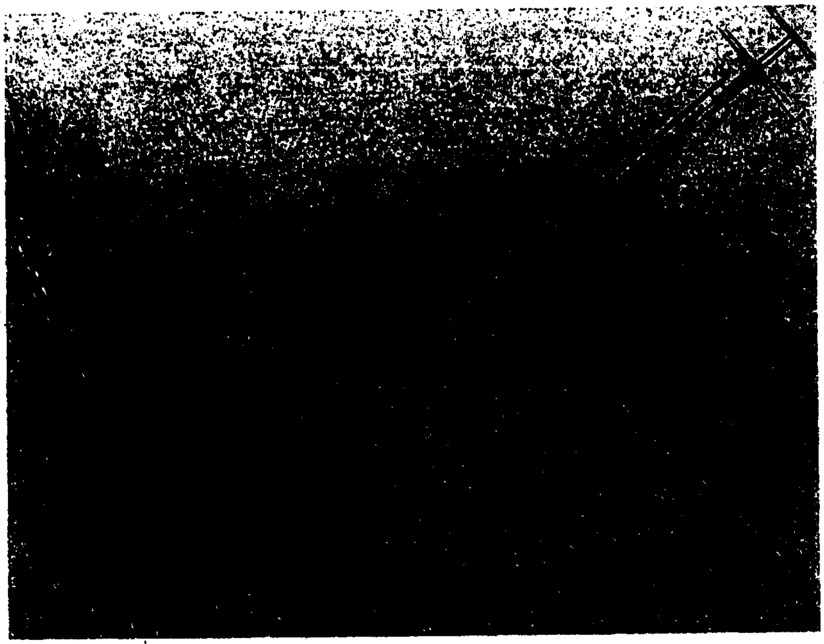

Figure 1. Radar antenna used in tracking the Sputniks.

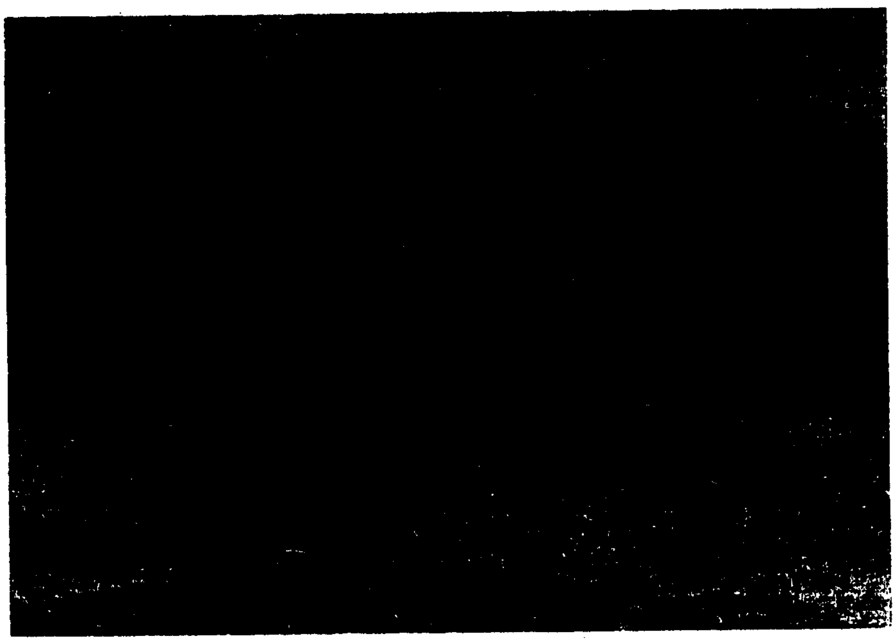

Figure 2. Radio telescope at Pulkovo observatory, estimated to be 10 to 12 feet in diameter.

to base the creation of a suitable rocket with which to solve the problem of an artificial earth satellite and to bring about the realization of interplanetary flight in the future.[9]

These and many other statements occurred prior to the first Sputnik launch, all notable by their reference to radio-technology, automatic guidance, radio telecontrol, and so forth and hinting at a preprogrammed or radio controlled system of guidance. An analysis of statements issued after the 2 January 1959 Mechta launch supports the belief that such a guidance system may have been used. For example, the Soviets published such statements as:

> Guidance of the flight of the space rocket during launching into a specified trajectory with great accuracy was effected by a special automatic system. The multistage space rocket was launched from the ground vertically. It was gradually made to veer away from the vertical line of flight by the program mechanism of the automatic guidance system. The last stage of the space rocket was a guided rocket connected by an adapter to the preceding stage. Guidance of the rocket was effected by an automatic system which stabilized the attitude of the rocket in a specified trajectory and ensured the calculated velocity at the end of the engine's operation. [A frequency of] 183.6 megacycles per second was used to measure coordinates and elements of trajectory.

Such statements strongly suggest that the Mechta guidance system was a programmed automatic control system, evidently supplied with supplementary trajectory correction data by means of a radio link.[10]

For some time prior to the launching of the first Sputnik, the Soviets indicated an awareness of the necessity for extreme guidance precision to attain their space objectives. In 1954, A. A. Shternfel'd wrote,

> The success of cosmic flight depends not only on the possibility of obtaining great velocities, but also on the precise control of these velocities and their direction to a fixed point in space. In flying to the moon, at its perigee a difference of ± one meter per second in the velocity of takeoff from the earth will alter the range of a cosmic ship by ± 3,797 kilometers. This figure increases to ± 4,244 kilometers for the mean distance to the moon and to ± 4,717 kilometers for the apogee distance. Deviation in the instant and the angle of takeoff also involves serious consequences. At the mean distance to Mars, an angle [error] of one minute corresponds to an arc [or miss distance] of 66,250 kilometers, at the orbit of Pluto, this arc length increases to 1,716,000 kilometers.[8]

A year later Yu. S. Khlebtsevich wrote that a flight to the moon demands extremely high precision in maintaining the calculated trajectory and flight chart. An error of only ± 0.1 percent in the value of the takeoff velocity of a rocket heading for the moon will result in a "short" or an "over" of the order of ± 12.5 percent of the general length of the path, or several tens of thousands of kilometers.[11] Relatively few additional references were made to guidance precision requirements until mid-1958 when L. I. Sedov reported in an official IGY paper that perigees for Sputniks I, II, and III were all within ± 1.5 kilometers of 226.5 kilometers altitude.[12] If the altitudes were intended to be identical and if the data are valid, the Soviets have demonstrated competence in the control of one guidance parameter. On 16 May 1958, following the third Sputnik triumph, Professor Fedorov of the Soviet IGY Committee reported, "the third Sputnik is a big step forward in the development of rocketry and space travel, but the problem of flights to the moon is extremely difficult and will require considerable effort."[13] Fedorov appeared to be talking about basic problems that are involved when humans are aboard a vehicle. Terminal guidance and control become important then, and the inadequacy of preinjection systems * alone is apparent. Even without human cargo, space missions such as planetary probes to hit Venus and Mars will require precision well beyond that believed currently attainable by the USSR without midcourse guidance. Conse-

* Systems in which all guidance must be imposed prior to burnout of the launch vehicle, i.e., prior to injection into free flight.

quently, some system of midcourse guidance will in all probability be employed by the Soviets and, in fact, has been suggested by their reference to a combined inertial guidance-stellar navigation system.[14]

SOVIET CONTROL CAPABILITIES

The emphasis placed on the problem of control by the Soviets is apparent from the calibre and number of Soviet mathematicians working in this field and their published contributions. L. S. Pontryagin, one of their leading mathematicians on the theory of optimal control, has performed outstanding research on automatic control.[15-17] Numerous sessions of the Soviet Academy of Sciences (for example, the Greater Moscow Seminar on Automatic Control Theory, 6 April 1957) have been devoted to the same subject. Excellent systems and reference books on theoretical and applied aspects of control systems appear regularly.[18-20] Experienced engineers and scientists who are unacquainted with control systems are being given special training, which may indicate that they are being shifted from other areas into this field.

The Soviets realize the importance of mathematical theory in the design and synthesis of sophisticated optimal control systems and have made several valuable contributions recently that are directly applicable to missile control. A great deal of Soviet work is published in these areas, primarily in the journal *Avtomatika i Telemekhanika*. The work is ostensibly directed toward industrial automation, but much of it is mathematically general and, therefore, applicable to missile, as well as machine-tool control. For example, E. A. Rozenman has written an excellent paper on the mathematical theory of automatic control, using conditions identical to those in the problem of missile control.[21] The ability of the Soviets to solve control system problems mathematically indicates that they also can construct sophisticated mathematical models of proposed control systems and work out many shortcomings on paper. In this way, they can save considerable time and expense in the development of an optimized system.[22-25]

A reference to a stabilizing system used by the Soviets was made by Professor Fedorov of the Academy of Sciences, USSR, in a lecture at the University of Belgrade early in May 1958. Discussing Soviet rockets for making scientific observations, he stated that the rocket used for launching missiles was stabilized by gyroscopic systems which eliminated all possible rotation of the rocket on its own axis during its vertical flight.[26] A single-stage geophysical rocket launched in the Soviet Union on 27 August 1958 had special stabilizers that prevented the rocket's rotation around its vertical and horizontal axes throughout the whole of the flight, including the coasting period.[27] This system was subsequently hailed by the Soviets as a first major step in solving the problem of satellite re-entry.[13]

After the Sputnik III launch, V. G. Petrov wrote that at present there is no fully oriented satellite and that such a satellite is still in the initial stages of development. He reported that the orientation of a satellite is necessary for a complete and effective solution of a whole series of scientific and practical problems involved in the investigation of the sun and the upper layers of the atmosphere. Not only the satellite, he said, but also almost all instruments used for scientific observations require, for their operation over a long period of time, orientation relative to various reference bodies located in space. As an example, Petrov mentioned the solar battery, which requires sunlight to operate and, therefore, must be oriented with respect to the sun.[14] Because Sputnik III was not to be stabilized, solar batteries had to be placed on all possible surfaces to ensure operation.[28] Since the development of Sputnik III, the Soviets have demonstrated an ability to control vehicle attitude by their continuing success in recovering living animals from space.

Petrov also wrote, "Orientation of a satellite can be accomplished by using small jet motors as has been done already for the stabilization of geophysical rockets. A second method of orienting a satellite is accomplished with the aid of gyros located along its axis. A combination of the two methods is obviously most desirable." [14]

These varied activities and achievements concerned with space vehicle control indicate steady progress in the USSR.

SOVIET CAPABILITIES IN PROVIDING POWER FOR SPACE INSTRUMENTATION

In Sputnik III, the power system is based on silver-zinc batteries and mercuric oxide elements working in conjunction with solar batteries that convert the energy of solar radiation directly into electrical energy. The solar batteries consist of a series of elements, thin sheets of pure monocrystalline silicon, with predetermined electrical conductivity. This power system would be adequate to power minimal guidance and control equipment. Such a power system was foreshadowed in 1957 by Soviet reports that it would be reasonable to use solar batteries in oriented satellites in combination with chemical batteries; in this way, they said, it would be possible to secure maximum effectiveness throughout the entire satellite orbit.[29] Although solar batteries were not used in the first two Sputniks, it was estimated in 1958 prior to the Sputnik III launch that the USSR could orbit a satellite equipped with silicon solar batteries wired to trickle-charge chemical storage batteries.[30] The trickle-charging concept explains why Sputnik III is still broadcasting 20.005 megacycle signals over a year after it was launched (15 May 1958). The ability of the system to operate that long in a space environment shows good system planning and a knowledge of operational requirements for space power systems of this type.

APPENDIX

EXPLANATION OF A FEW TYPES OF GUIDANCE

The parameters which must be known in space guidance are (i) position (relative to some reference), (ii) speed and direction (velocity vector), and (iii) rate of change of velocity (acceleration). It is not necessary to measure all of these quantities, because in the event that some of the time-and-position history is known along with one or more of the parameters then the computer can determine the others. There are several guidance methods used to measure and control these values.

Radio Command Guidance

A radio or radar system, usually combined with a computer, determines the three desired parameters (position, velocity vector, and acceleration) and sends commands to the vehicle to make it arrive at a desired destination.

Radio/Inertial

This type of guidance is similar to radio command except that accelerometers and gyroscopes on board the vehicle are capable of measuring rate of change of velocity and direction of movement. A computer can use these values and arrive at position. The radio system acts as a monitor which assists the vehicle guidance system in arriving at more accurate trajectory parameters. Such assistance can also be provided by optical, celestial, and other means, some of which are discussed under hybrid systems.

Pure Inertial

In this type of guidance, the three basic parameters are measured by inertial sensors on board the vehicle. Unlike the radio inertial system, there is no monitor, and the error in the sensing elements must be very small.

Hybrid Systems

For greater accuracy, hybrids involving more than one system will probably be applied to space vehicle guidance. They might involve command guidance for the initial phases of the launch, including final setting of the inertial system, and inertial guidance for the later phases of the launch, midflight guidance, or terminal guidance. Inertial systems degenerate in accuracy in proportion to the time elapsed after the setting and, therefore, require intermittent adjustment. Periodic comparison with an external frame of reference through the use of a celestial navigation device is one method for course correction and readjustment.

A vehicle can measure its own position in space optically by taking angular sightings on the sun, planets, or stars. This is substantially the same procedure that astronomers followed in establishing the trajectory of the earth around the sun. Small field transits weighing less than 10 pounds can measure angles to several seconds of arc, and ideal visibility and excellent optical contrast exist in space. In addition, it is possible to combine the attitude-sensing (control) and position-measuring (guidance) functions in one vehicle-borne optical system. The main problem is that such an orbit-correction scheme must establish the velocity vector in real time by differentiating data on angular position. Since the resolution of such data and the development of smooth flight paths is very difficult, attention may be focused for some time upon ground-based tracking and computer systems which have high data-handling capability and are large and heavy. Steering commands to the vehicle could be transmitted as modulation on the tracking signals.

The correction of trajectories to points millions of miles away requires precise determination of the existing vehicle position and velocity. The absolute radial distance from any planet is difficult to determine since the linear dimensions of the solar system are known only to one part in 5,000. A transponder or stable beacon in the missile, if tracked from the earth, measures range, range rate (change in range), angular bearing, or all three. Yet, earth-bound angle-measuring devices, even if interferometer techniques are used, are limited to the earth's diameter (8,000 miles) for a baseline distance, and this dimension is not large enough for tracking a vehicle at a range of several hundred million miles. One presently envisioned alternative is to use synchronized transmitters on the earth and moon as a sort of interplanetary hyperbolic (Loran) navigation system with a baseline averaging 250,000 miles. Since classical astronomical measurements are based exclusively on angular measurements and have proven to be extremely accurate, such a system should be quite satisfactory for space flight.

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