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DESCRIPTION OF THE CONCEPTUAL ARRANGEMENT FOR THE RENDEZVOUS AND DOCKING OF SOYUZ TYPE SPACECRAFT

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DESCRIPTION OF THE CONCEPTUAL ARRANGEMENT FOR THE RENDEZVOUS AND DOCKING OF SOYUZ TYPE SPACECRAFT

ABSTRACT. Data on automatic rendezvous systems and automatic and manual docking and maneuvering systems of the types used with the space vehicles of the Cosmos series and with spacecraft of the Soyuz type are presented in a mathematical formulation.

Introduction /1*

Presented herewith are data on automatic rendezvous systems and automatic and manual docking and maneuvering systems of the types used with space vehicles of the Cosmos series and with spacecraft of the Soyuz type.

The entire rendezvous process can be broken down into four successive stages in the case of space vehicles (Figure 1).

The first stage is the entry of the satellite into a near-earth orbit and correction of its trajectory to bring it into the zone in which mutual automatic search and "LOCK-ON" will take place between the satellites, using electronic, or other means.

The second stage is closer approach of the satellites, during which process the correction engine of one of the satellites, hereinafter called the "active" satellite, is fired to bring it to within 300 to 400 meters of the "passive" satellites.

The third stage is automatic, or manual, docking, during which both satellites approach each other at low relative speeds until the docking units are in contact.

The fourth stage is direct link-up, a process involving the rigid coupling /2 of the space vehicles, and during which mechanical and electrical connections are made.

The following systems of coordinates will be used in what follows (Figure 2): O_1xyz - the orbital system, with the y axis directed with respect to the

* Numbers in the right margin indicate pagination in the foreign text.

current radius vector KA, and the z and x axes directed along normals to the plane of the orbit and to the transversal, and the origin O_1 of the system of coordinates coinciding with the center of mass of the passive satellite; $O_1\xi\eta\zeta$ - a moving rectangular system with origin in the point O_1. The $O_1\xi$ axis is directed along the center line connecting the centers of mass of the two satellites with the line of sight. $O_1x_1y_1z_1$ and $O_2x_2y_2z_2$ are rectangular systems, the axes of which are directed with respect to the main central axes of intertia of the passive and active satellites, respectively (see Figs. 9 and 10).

The index i = 1, 2 designates the satellite to which reference is being made. Hereinafter, the number 1 will be associated with the passive satellite, the number 2 with the active satellite.

The mutual positions of the Oxyz and $O\xi\eta\zeta$ systems can be expressed in terms of the angles of pitch, yaw, and roll, accomplishing three successive rotations of the $O_ix_iy_iz_i$ system with respect to the $O_1\xi\eta\zeta$ system. The first rotation at the angle of roll γ_i is made around the direction of the ξ axis, the second rotation, at the angle of yaw ψ_i, is made around the new direction of the η axis, and the third rotation is made at the angle of pitch ϑ, around the resulting direction of the z_1 and $-z_2$ axes.

<u>Composition of the rendezvous and docking control system</u> /3

As usual, the control system contains sensitive elements, amplifier-converters and computers, and actuators. The system also has indicators, located on the pilot's instrument panel, and control levers (Figure 3) when the vehicles are manned.

The sensitive elements include the following.

I. The electronic equipment ensuring mutual detection by the satellites. The control signals generated by this equipment are used to control the satellites over the pitch ϑ and yaw ψ channels. As will be seen from Figure 4, the control signal has a linear zone near the O_2x_2 axis. The devices reviewed provide complete scan of the surrounding space.

II. The electronic equipment ensuring measurement of relative range ρ and the rate of change in that range $\dot{\rho}$. The signals from this equipment are used in the computers during the approach and are brought to the pilot's instrument panel.

III. The electronic equipment for guidance, used to determine the angular velocity of the center line Ω (we have ω_η and ω_ζ, respectively in the projections on the $O\eta$ and $O\xi$ axes), and the two error angles ϑ and ψ between the axes of the active satellite and the center line.

The axis of sensitivity of the guidance equipment is directed along the O_2x_2 axis of the satellite in the initial position. The antenna of the guidance equipment can be rotated 180° around the O_2z_2 axis with respect to the satellite.

IV. The angular velocity sensors, measuring the absolute angular velocity /4
of the satellite in the projections on the x, y, and z axes and rigidly coupled to the target (ω_x, ω_y, ω_z). The output signals from the angular velocity sensors are linear with saturation (Figure 5).

V. The electronic roll sensor, generating a signal proportional to the mutual roll angle for the two satellites. This sensor can be used during the docking phase. The output characteristic of the sensor is linear with saturation.

VI. The optical sight (manned vehicles), providing a direct image of the second spacecraft in the Ox_i direction. The screen of the optical sight has a special grid for use in observing the movement of the image in the field of view.

VII. Closed circuit television, on the screen of which is the image from the upper and lower transmitting cameras in the Ox_i axis direction. This image can be transmitted to the ground. The vehicles have signal lights, the configuration of which on the screen of the optical sight and on the television screen are such that relative distances, and mutual positioning of the vehicles, can be judged so work can be performed in the earth's shadow.

VIII. Range and relative speed indicator, provided with signals from the electronic equipment.

Two control levers are included in the system:

(a) the orientation control lever has three degrees of freedom, with tilt of the lever providing the desired angular velocity of the vehicle hull;

(b) the lever for controlling the shift in the center of mass too has three degrees of freedom, and its tilt cuts in the corresponding thruster assembly.

The amplifier-converter and computer process information supplied by the sensitive elements and control levers, and form the actuator control commands. /5

The actuators in the approach control system are:

IX. the recurrent-use approach engine assembly, used to shift the center of mass of the active satellite during the last stage of the approach. The engine assembly thrust vector is directed along the O_2x_2 axis. When analyzing the dynamics of the approach, this engine can be considered as a relay in some link operating in the pulse mode;

X. the docking and orientation engines, small thrusters operating in the relay-pulse mode. These engines are used for orientation and stabilization when the approach engine assembly is functioning, and are the main actuators ensuring the shifting of the center of mass of the satellite during the docking phase.

This system makeup is maximum, that is, it is the one used for the active, manned, vehicle. The corresponding instruments and devices are not provided for the passive, or unmanned, vehicle.

Control laws

The proportional approach method was used to bring the Cosmos and Soyuz pairs together because of its simplicity from the point of view of vehicle realization.

The proportional guidance method involves maintaining the angular velocity of the center line within predetermined limits. Moreover, the projections of relative speed on the center line must be controlled within specified limits in order to complete a "soft" docking. /6

The active satellite must have information on the distance between the satellites, ρ, on the radial velocity of the approach, $\dot{\rho}$, and on the angular velocity of the center line, and precisely with respect to two of its components, $-\omega_\eta$ and ω_ζ, in order to realize the proportional approach method.

The guidance equipment can be used to obtain this information. Realization of the method during the distance approach phase requires that the approach engine thrust vector lie in the guidance plane, that is, in the plane passing through the center line and the relative speed.

The guidance plane for the active spacecraft is made by rotating the satellite about the $O\xi$ axis until the component ω_η, measured by the guidance equipment, is equal to zero. At this time the component ω_ζ will equal the vector total for the angular velocity of the center line.

Because one engine is used for the approach during the distant phase, the active satellite must be turned around in order to impart a pulse in the necessary direction to its center of mass. The active satellite is turned in the guidance plane around the O_2z_2 axis by angle ϑ from 0 to 180°. Angle $\vartheta = 0$ corresponds to the position when the longitudinal axis, O_2x_2, of the satellite coincides with the center line O_1O_2, and the approach engine installation thrust vector coincides with the direction O_2x_2. The magnitude and direction of the angle of rotation of the active satellite will depend on the magnitude and the signs of the control signals generated by the approach control system.

A special approach law, depending on present range, ρ, and speed, $\dot{\rho}$, is programmed for the active satellite computer in order to regulate the approach parameters along the center line. /7

The idea behind this law can be understood if we turn to Figure 6, in which two deceleration parabolas are shown in the plane of parameters ρ and $\dot{\rho}$. The upper parabola can be considered the boundary for cutting in and cutting off the engine to accelerate, the lower the boundary for cutting in and cutting off the engine to decelerate. The motion parameters lying between these parabolas correspond to a neutral zone, a zone in which the satellite will move without controlling forces.

The law for the control of the angular velocity of the center line can be understood from consideration of Figure 6, which shows the zone for cutting in and cutting off the approach engine, depending on the angular velocity of the center line. The Ω_1 and Ω_2 limits, like the range control functions, are selected for the condition of a minimum number of engine starts, and a minimum consumption of the working substance. It should be pointed out that these limits are functions of the relative distance ρ.

The approach method remains as before during the docking phase. The distinguishing feature of this phase is that the guidance plane is not constructed, and suppression of the angular velocity of the center line is accomplished by the coordinate engines.

Let us move on to a description of the laws for controlling the angular movements of satellites.

A control signal, σ, the structure of which differs with the control channel and the stage of the flight, is used in the control system to cut in the small thruster.

The control signal for the pitch, yaw, and roll channels will be in the following form in the mutual search modes, in the mode when the passive satellite is constantly tracking the center line, and in the stabilization mode during the docking phase /8

$$\sigma = U_1 + U_2 ,$$

where

U_1 is a signal proportional to the error angle;

U_2 is a signal proportional to the projection of the absolute angular velocity on the specified axis.

The law depicted in Figure 7 is that applicable for stabilization engine cut-in and cut-off. The magnitude of Δ is selected for the condition that stabilization be precise. The stabilization law is nonlinear with pulse linearization. The zones of switching to the phase plane are shown in Figure 8. The laws for stabilization control of the active satellite during the distant approach phase have more complex relationships than those cited in the foregoing because it is during this stage that the construction of the guidance plane takes place.

The projection ω_η of the angular velocity of the center line Ω is used to form the roll control signal.

<u>The logic in the operation of the automatic system</u>

The distant approach stage for the artificial earth satellite begins after the second satellite has entered the zone in which mutual radar lock-on is ensured.

The spherical field of scan of the radar equipment aboard both satellites permits mutual detection by the satellites, and this is followed by the stage during which they turn around in a manner such that they point their docking units at each other. The turns are made relative to the O_2y_2, or O_2z_2, axis in accordance with the control laws, and depending on the zone in which the "partner" may be. The sign of the rate at which the turn is made is determined by the initial conditions of the angular attitude of the "partner." The picture of how the search is made, and the final transition process, are shown in the phase plane (Figure 8). On succeeding stages of the flight the longitudinal axis, O_1x_1, of the /9 passive satellite is brought into coincidence with the center line by the orientation system with an accuracy to within the errors determined by the amplitude of the self-excited oscillations and by the static error (caused by the residual velocity of the line of sight). Orientation about the O_1x_1 axis proper is by the use of the angular velocity signal only.

Once the stage in which the active and passive satellites have turned around in accordance with the control laws is completed, the active satellite begins to turn about the O_2x_2 axis to construct the guidance plane. Operation of the equipment in the approach control system depends on signals supplied the computer by the sensitive elements. During the distant approach stage the antenna in the guidance system is constantly directed along the center line. The satellite itself can turn around in the guidance plane. This is provided for by turning the approach engine assembly in the necessary direction. As has already been pointed out, the magnitude of the angle by which the axis of this assembly is turned will depend on the magnitude and signs of the command signals measured and the approach logic input.

Suppose the control system establishes the fact that the angular velocity of the center line has exceeded specified limits. The satellite will then be turned about the O_2z_2 axis 90° in the guidance plane in such a way that when the engine assembly is cut in its thrust vector will be in a direction opposite to the linear transverse velocity of the center line. The engine is cut in after the signal indicating completion of turning of the satellite has appeared. The engine is cut off when the angular velocity of the center line achieves a magnitude equal to Ω_1 (Figure 6).

It should be pointed out that the angular velocity of the center line is included as a disturbance in the system's first equation (Figure 2), so it is /10 desirable that the velocity of the line of sight be as low as possible. This can be done by shifting the magnitude of the cut-in limit, Ω_2, to the left. On the other hand, it should not be forgotten that a reduction in Ω_2 will result in an increase in the number of times the engine is cut in.

If the imaginary point in the phase plane (Figure 6) proves to be below the II line, the engine must be cut in to decelerate, and to do so the active satellite's control system should make a 180° turn about the O_2x_2 axis in the guidance plane with respect to the initial position of the O_2z_2 axis and cut in the approach engine. Deceleration will occur until the imaginary point is no longer in zone 2. Flight will then continue without controlling forces.

The imaginary point can once again appear in the phase plane below the II line as a result of disturbing forces, such as the difference in the earth's gravity at various altitudes. Now recurrent cutting in of the approach engine occurs. When the imaginary point enters zone 1 of the phase plane the control system will carry out the required turn and the approach engine will be cut in to "accelerate."

The distant phase of the approach is concluded when the approach parameters ρ and $\dot{\rho}$ reach the values $\rho \approx 350$ m, and $\dot{\rho} \approx 2$m/sec, respectively. It is at this moment that the automatic docking of the satellites begins.

The satellites must be oriented so their docking units are pointed at each other during the accomplishment of rigid link-up, when the satellites must marry their docking units. Small thrusters are used to make the proper orientation. They not only stabilize the satellite, but provide for the coordinated transfer of its center of mass. There is no need to construct a guidance plane in this case. The movements of the satellites during this stage are in accordance with /11 the control laws described in the foregoing.

The satellites should converge so that each probe of one satellite enters the corresponding socket of the other satellite during mechanical link-up. This task can be simplified by installing a special mutual roll sensor aboard each of the satellites to function during the docking phase.

Manual docking with automatic tracking

The passive vehicle, as in the preceding case, functions to automatically track the active vehicle in pitch and yaw.

Movement of the center of mass is controlled manually. The pilot of the active vehicle, guided by readings on the range and relative speed indicator, cuts in the controlling longitudinal acceleration, maintaining the assigned approach program $\dot{\rho} = \rho(\rho)$.

At the same time, the pilot, observing the passive vehicle through the optical sight and on television, cuts in and cuts off the controlling transverse accelerations, trying to keep the image of the passive vehicle fixed without using the orientation lever.

Control of the angular movements of the active vehicle is semiautomatic. The pilot moves the orientation lever as he watches the image of the passive vehicle, and the following control signal is formed in the corresponding channel

$$\sigma = \omega \cdot \delta$$

where

δ is the orientation lever signal.

Thus, the movement of the orientation lever by a fixed angle imparts to the vehicle a fixed angular velocity around the corresponding axis.

Manual docking in the case of concurrent control /12

Each pilot controls the angular movement of his own vehicle in the same way that the pilot of the active vehicle did in the preceding case. In the case of concurrent control, the difference between the active and passive vehicles is done away with and control of the movement of the center of mass can be exercised by the pilot of either vehicle, or they can distribute the functions between them, with one of the pilots controlling longitudinal movement, the other transverse. If, at the same time, the electronic equipment is used, the necessary information on range and relative speed can be obtained by observing the size of the image of the "passive" vehicle on the optical sight and television screens.

Hovering at constant range

The pilot of the active vehicle cuts in the controlling longitudinal acceleration, maintaining range within specified limits and trying to keep relative speed to a minimum. Control by the other channels has no special features. The passive vehicle can be generally unoriented.

Special features of short range approaches

When a system is operating at distances comparable to the geometric dimensions of the vehicles a number of special features, associated with the effect of parallaxes on the measurement of relative motion parameters, arise. In this situation there is no way to assume that measurements are being made relative to the center line.

The errors obtained result in the occurrence of undesirable feedbacks and /13 interchannel effects in the control system, investigation of which by analytical means is extremely difficult. The effect of errors can be investigated expediently by using analog and analog-digital modeling of the system with the geometry of the spacecraft taken into consideration.

Arrangement of the approach and link-up equipment

The flight-design tests made of the Cosmos type space vehicle, and of the manned spacecraft of the Soyuz type, confirmed the desirability and effectiveness of the arrangement, schematic, and design decisions made (see Figs. 9, 10) for providing for the rendezvous and link-up in orbit of an artificial earth satellite.

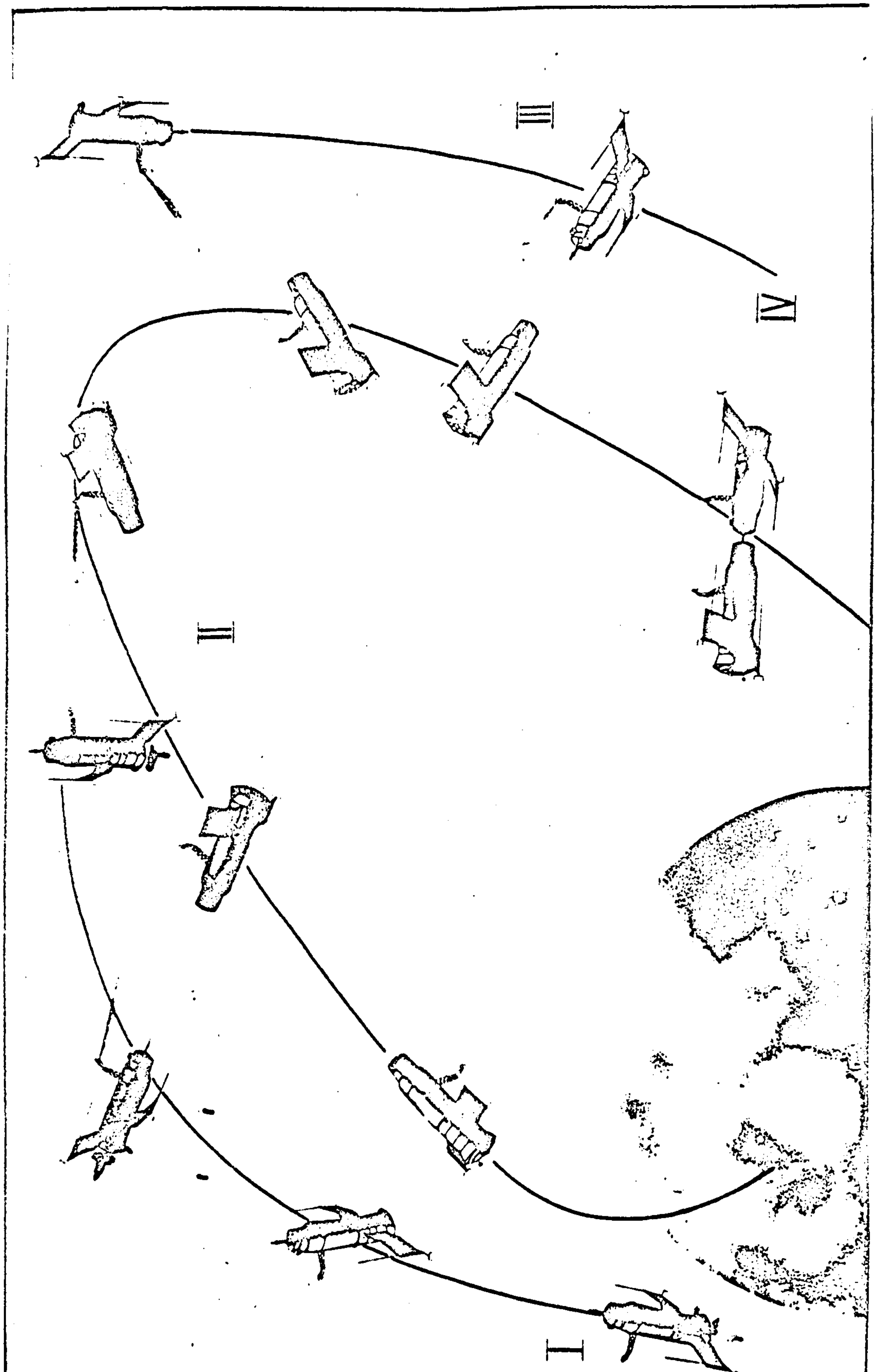
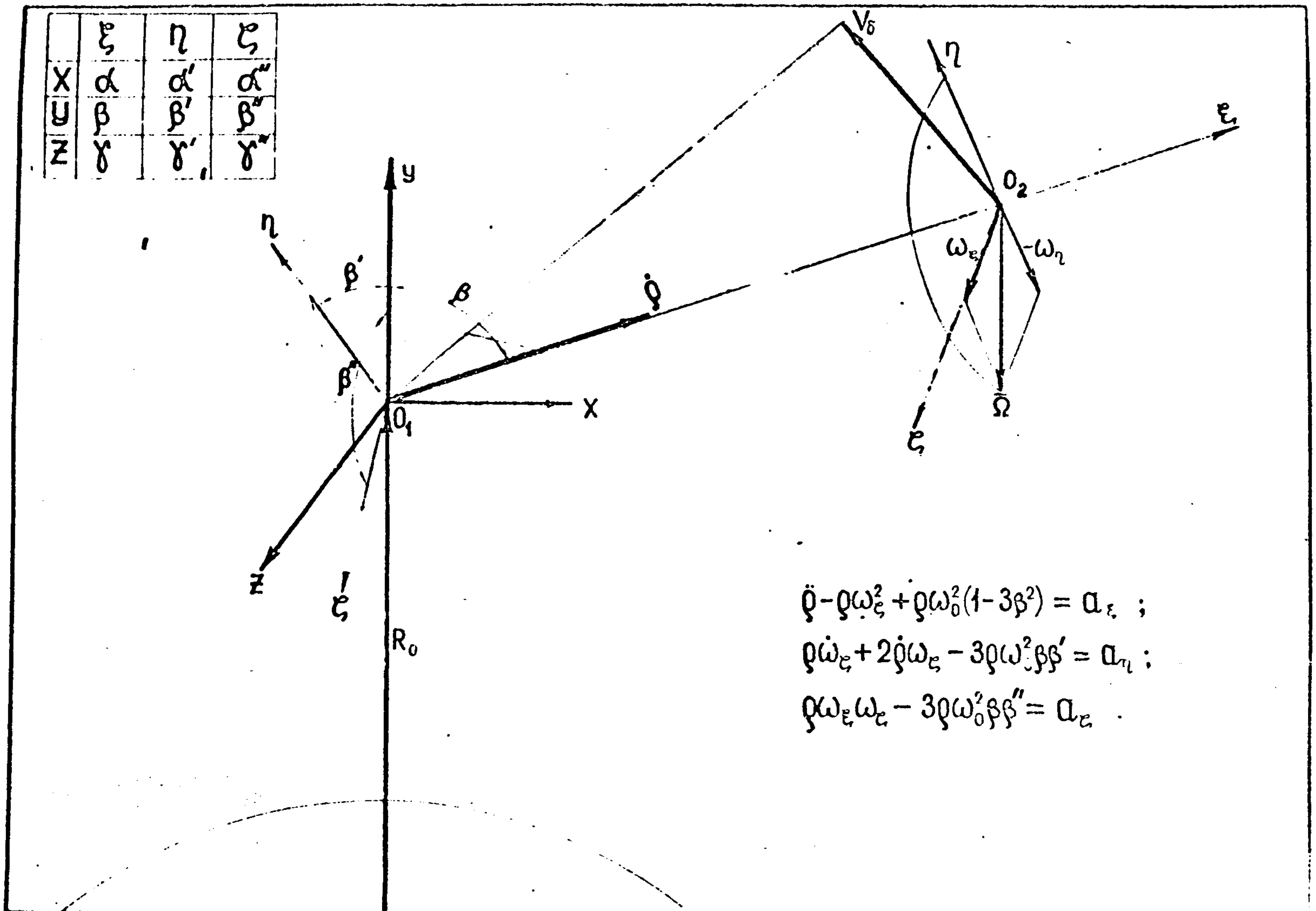


Figure 1.



	ξ	η	ζ
X	α	α'	α''
Y	β	β'	β''
Z	γ	γ'	γ''

$$\ddot{\rho} - \rho\omega_\zeta^2 + \rho\omega_0^2(1-3\beta^2) = a_\xi \;;$$
$$\rho\dot{\omega}_\zeta + 2\dot{\rho}\omega_\zeta - 3\rho\omega_0^2\beta\beta' = a_\eta \;;$$
$$\rho\omega_\xi\omega_\zeta - 3\rho\omega_0^2\beta\beta'' = a_\zeta \,.$$

Figure 2.

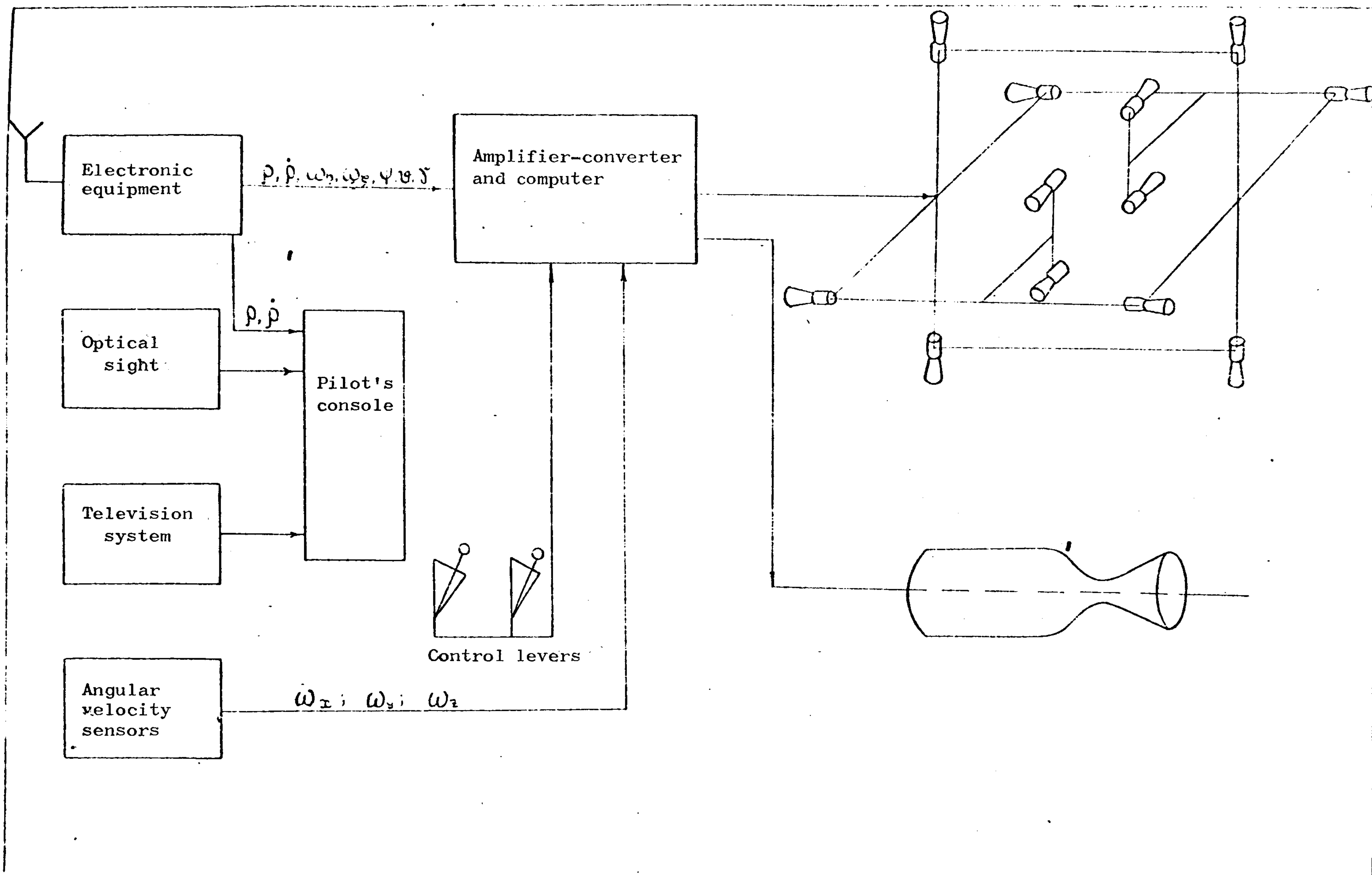

Electronic equipment
$\rho, \dot{\rho}, \omega_\eta, \omega_\xi, \psi, \vartheta, \gamma$
Amplifier-converter and computer
$\rho, \dot{\rho}$
Optical sight
Pilot's console
Television system
Control levers
Angular velocity sensors
$\omega_x;\ \omega_y;\ \omega_z$

Figure 3.

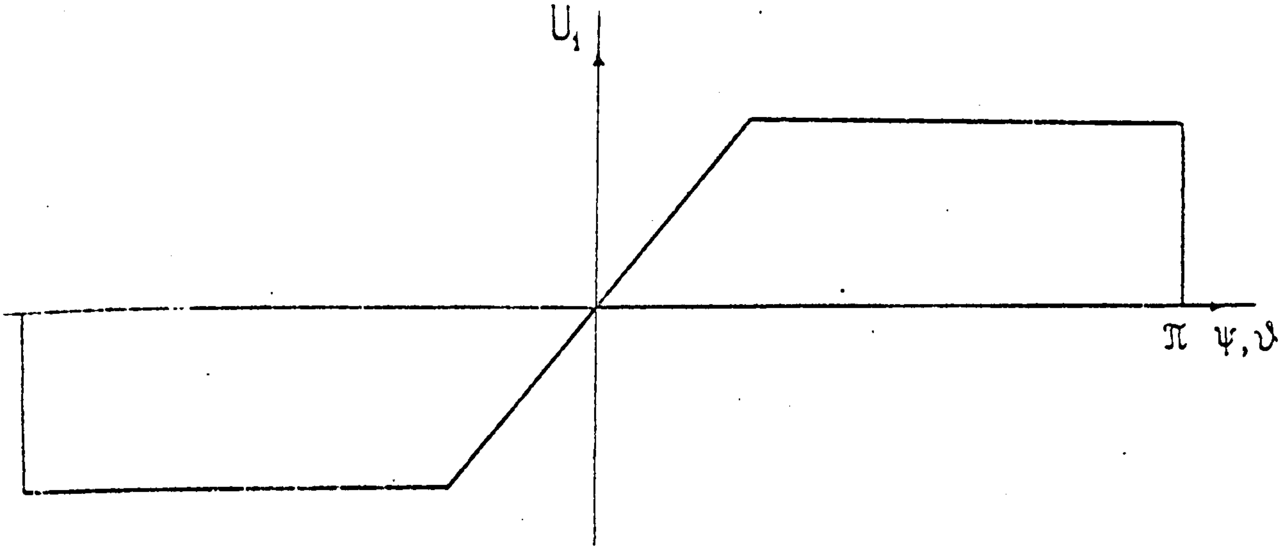


Figure 4. Diagram of output signal from search equipment in terms of angles ψ and ϑ.

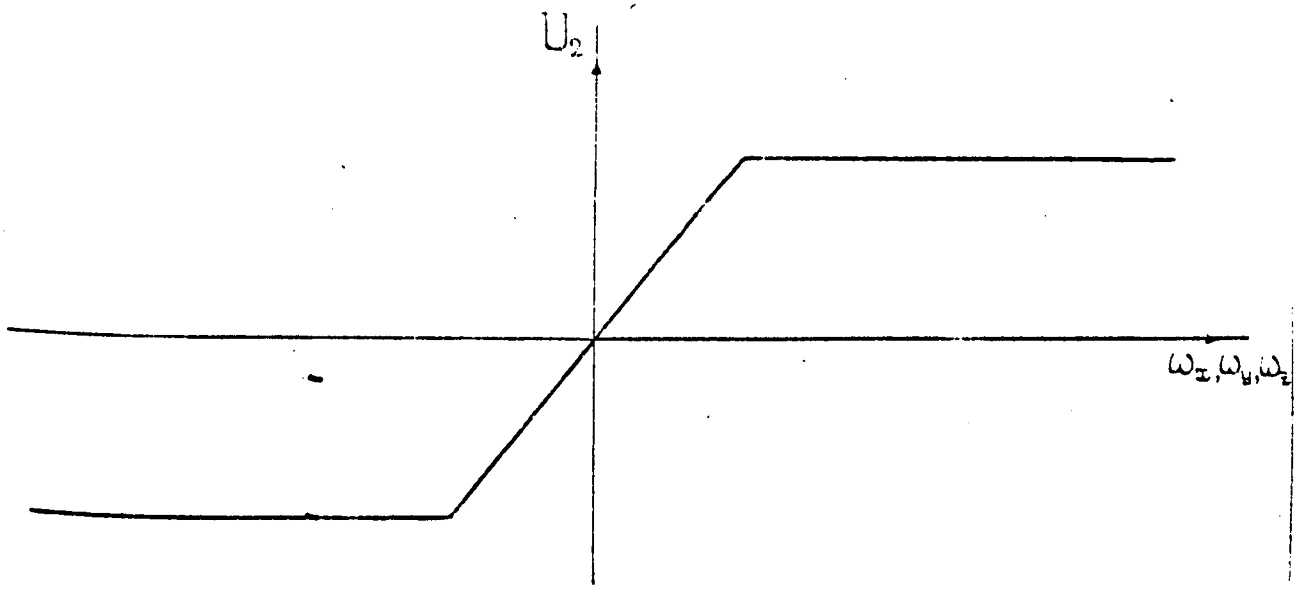
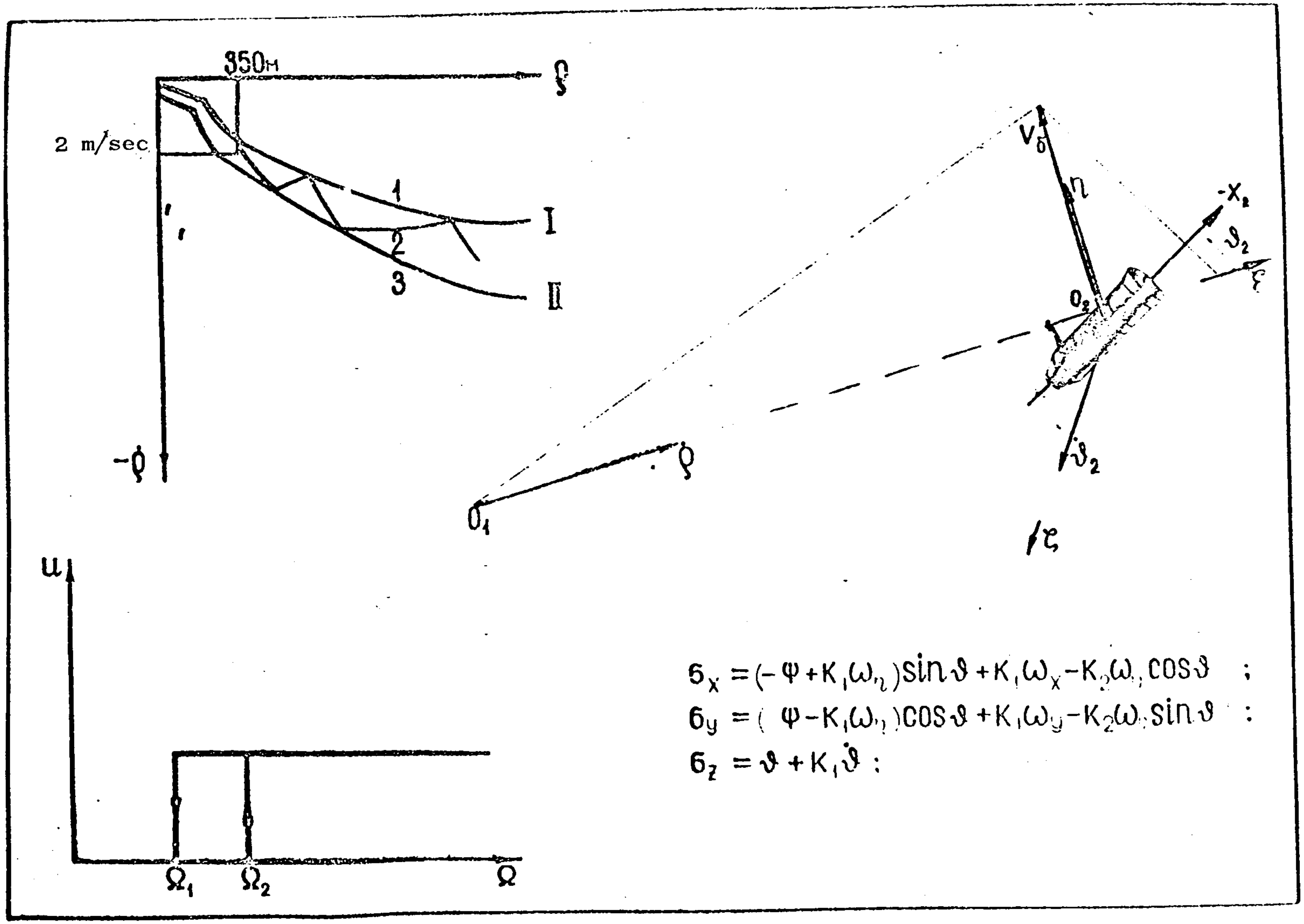


Figure 5. Diagram of output signal from angular velocity sensor in terms of $\omega_{x,y,z}$.



$$\sigma_x = (-\psi + K_1\omega_\eta)\sin\vartheta + K_1\omega_x - K_2\omega_\eta\cos\vartheta \;;$$
$$\sigma_y = (\psi - K_1\omega_\eta)\cos\vartheta + K_1\omega_y - K_2\omega_\eta\sin\vartheta \;:$$
$$\sigma_z = \vartheta + K_1\dot{\vartheta} \;:$$

Figure 6.

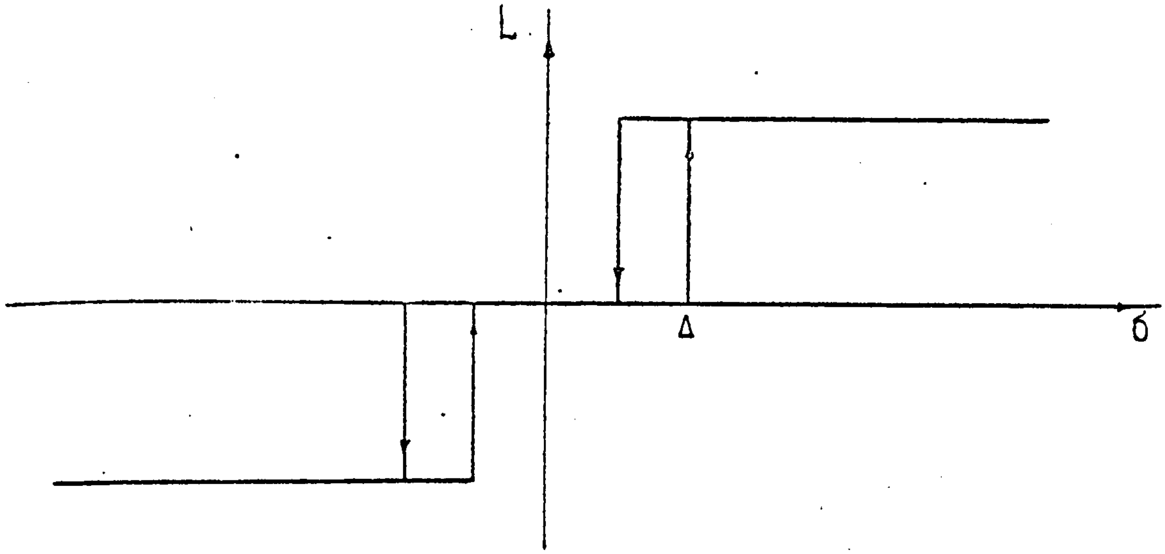


Figure 7. The law governing orientation engine cut-in and cut-off.

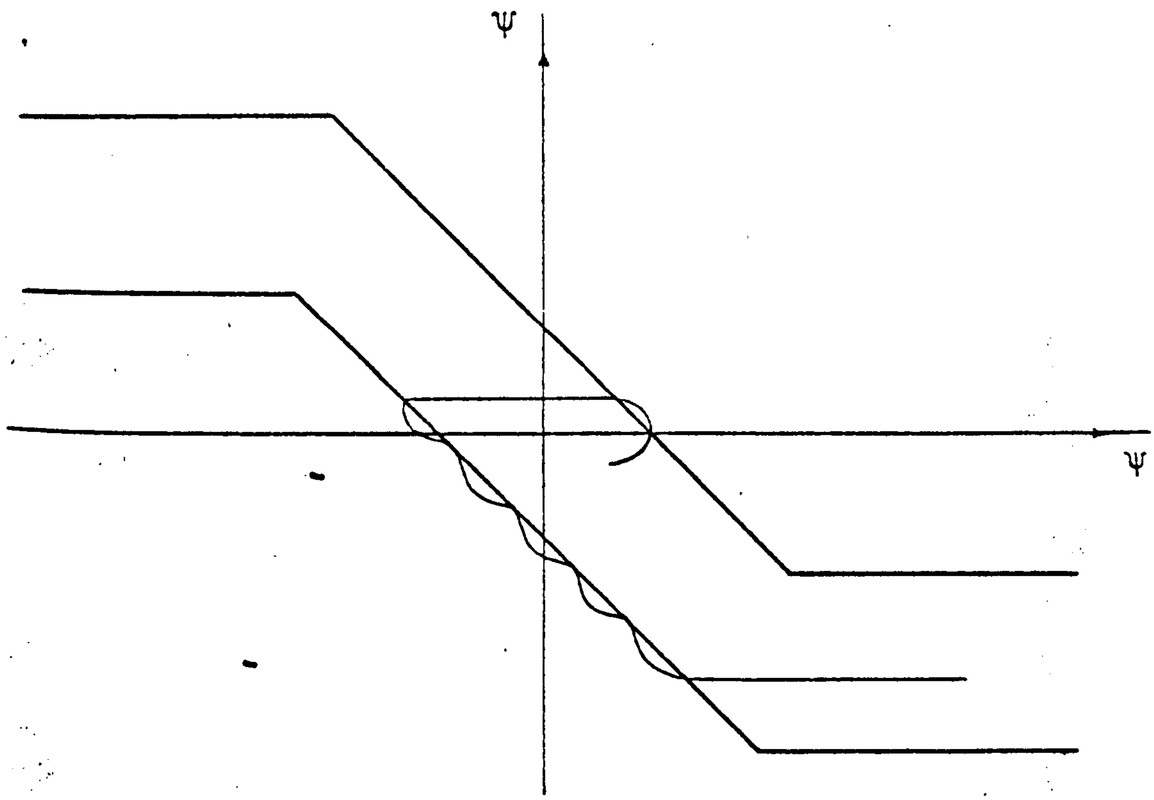
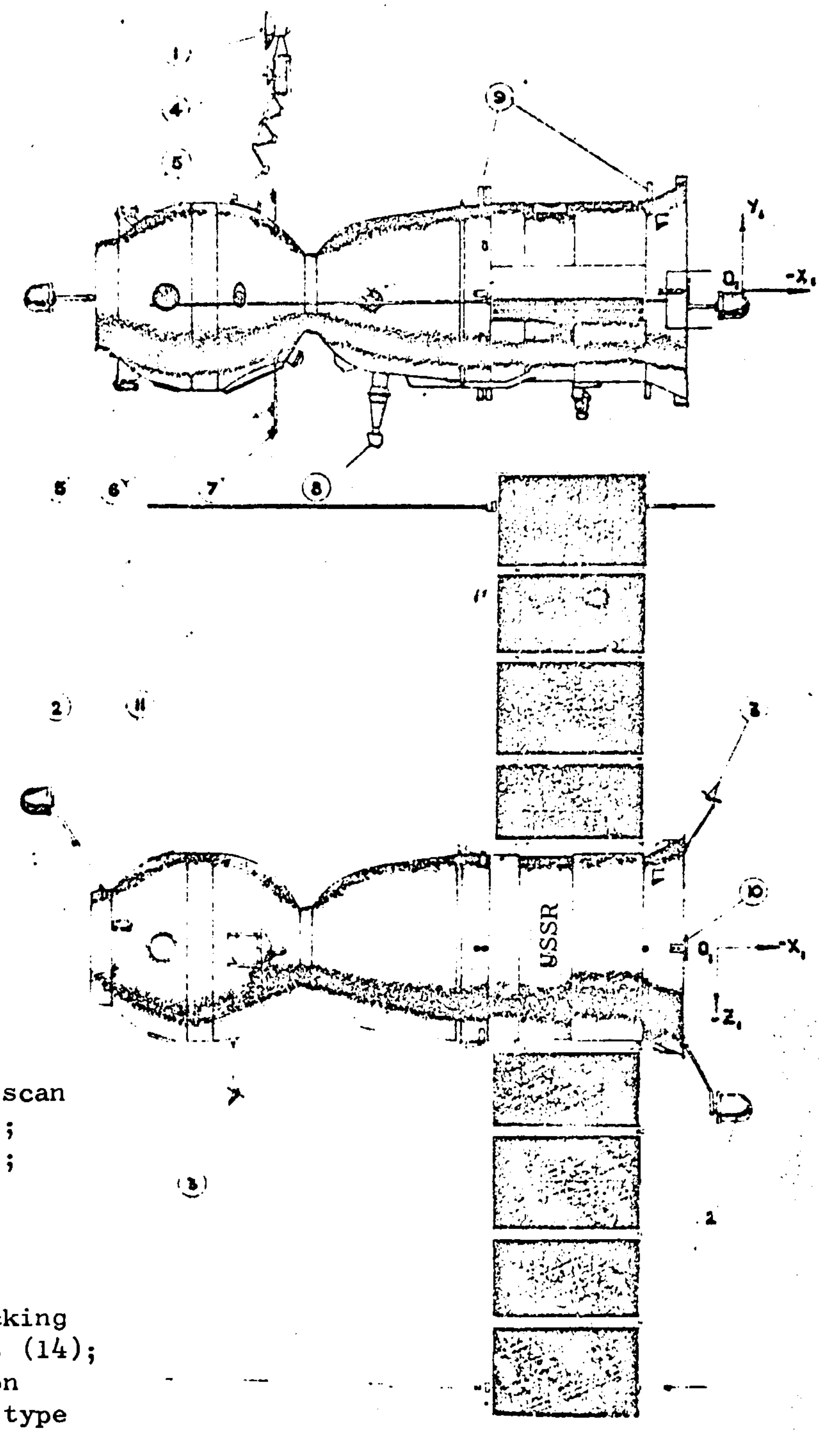
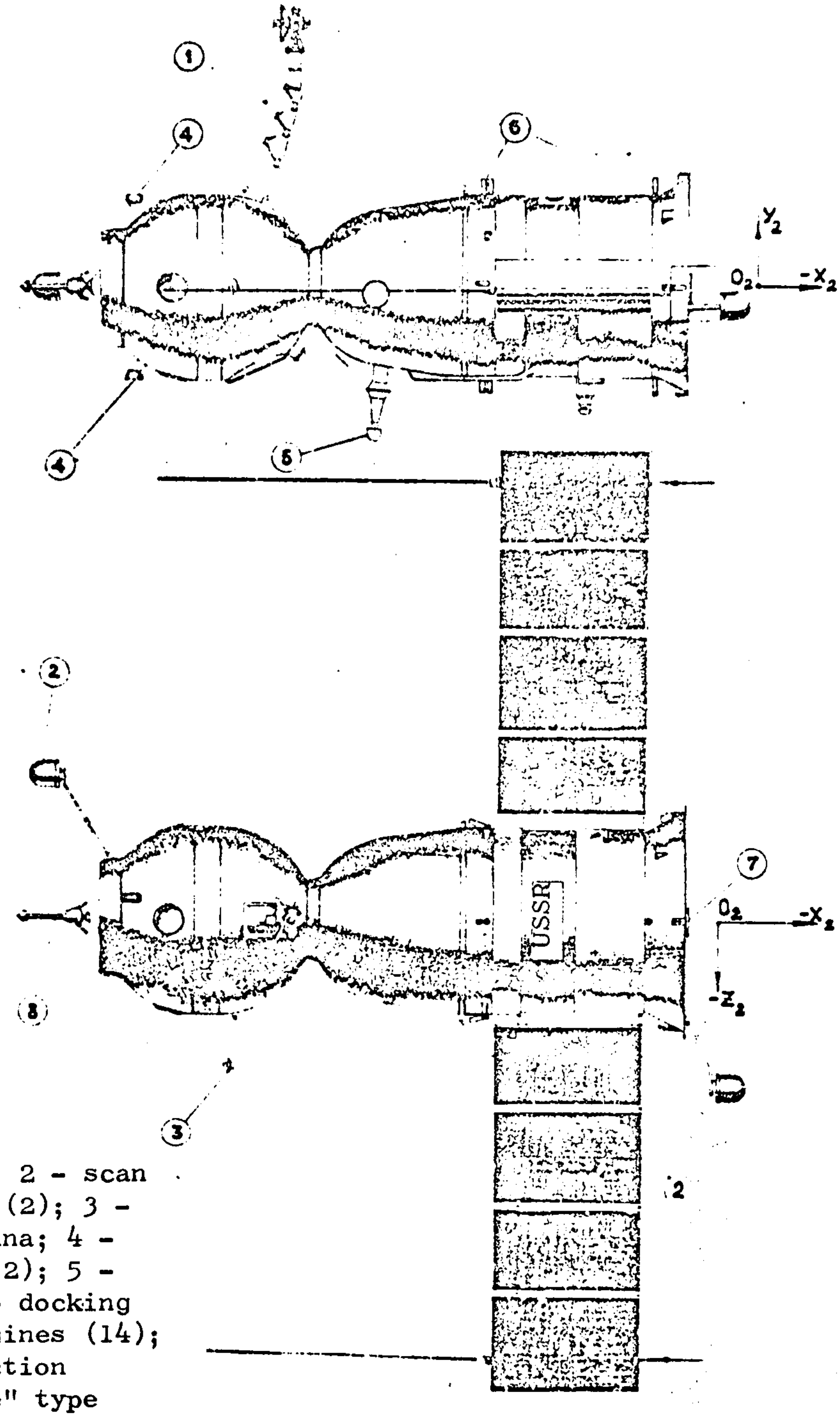


Figure 8. View of the phase portrait of the orientation channel.



1 - relay antenna; 2 - scan and search antennas (2); 3 - beacon antennas (2); 4 - roll antenna; 5 - television cameras (2); 6 - light indexes (4); 7 - light beacon; 8 - sight-orientor; 9 - docking and orientation engines (14); 10 - approach-correction engine; 11 - "passive" type docking unit.

Figure 9. Approach and link-up equipment for a "passive" Soyuz type spacecraft.



1 - homing antenna; 2 - scan and search antenna (2); 3 - interrogation antenna; 4 - television camera (2); 5 - sight-orientor; 6 - docking and orientation engines (14); 7 - approach-correction engine; 8 - "active" type docking unit.

Figure 10. Approach and link-up equipment for an "active" Soyuz type spacecraft.