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NAVIGATION SYSTEMS OF SPACECRAFT

By V. P. Seleznyev and M. L. Kirst

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(Translated by J. L. Zygielbaum)

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ABSTRACT

(By J. L. Zygielbaum)

Introduction

The achievements of Soviet science and technology in the conquest of space and the orbital flights by Soviet astronauts make it possible to consider prolonged, long-distance manned flights as one of the next items in the program for the development of Soviet science and technology. Almost all branches of science and technology participate in the effort to solve the problem of long-distance manned flights.

Even now projects for manned flights to the Moon are in their final stages of development. This will be followed by flights to planets of the Solar System. New types of rockets and equipment are under construction, and astronauts are being trained for the difficult task of interplanetary flights.

Flight control of a spacecraft is, in fact, the most important task during a prolonged, long-distance flight. This problem includes the selection of a least-energy trajectory, orbital injection, orientation of the spacecraft, guidance and control along all sections of the trajectory, maneuvers for the purpose of landing on the target planet, and finally the return to Earth. The problem of flight control is also of utmost importance during rendezvous maneuvers between spacecraft in orbit for the purpose of assembling an orbiting space station, interception of hostile targets, etc.

The purpose of this book is to evaluate, on the basis of available Soviet and foreign material, the general problems and methods of space navigation, orbital flight elements of spacecraft, etc. Particular attention is directed toward the construction of complex, on-board navigation systems, as well as ground facilities.

Many problems related to the statement of principles for the selection of optimum parameters of navigation systems and an evaluation of their errors require the application of a complex mathematical apparatus. Therefore, these problems are discussed only superficially in this book. These problems can be studied according to a special literature, a list of which is given at the end of the book.

CHAPTER I

Basic Assumptions in the Development of Space Navigation

There are two types of spacecraft: artificial Earth satellites and interplanetary probes (spacecraft). The flight trajectories of all spacecraft are influenced by various fields of gravity: Satellites are influenced by the gravity of the Earth, and interplanetary spacecraft are influenced by the fields of gravity of the Earth, the Sun, and other planets. The influence of fields of gravity is one of the factors which determines the flight trajectory of a spacecraft. Such a trajectory consists of three principal sections: orbital injection, flight through cosmic space, and re-entry into the dense layers of the atmosphere for the purpose of landing.

Interplanetary spacecraft trajectories might consist of several specific sections along which initial readings, equations of motion, and fields of gravity are subjected to changes. For instance, in the case of a flight trajectory to Mars, the first section would be along the space between the Earth and the Moon. The flight trajectory along this section might be an approximated hyperbola with its focal point at the center of the Earth. The second section of the trajectory is along the space between the Moon and the Sun. Here the trajectory gradually changes into a large ellipse with its focal point at the center of the Sun. Along the third section the Sun is the principal source of gravity, and the flight continues along an elliptical trajectory. The fourth section of the trajectory begins during the approach to the planet Mars. Along this stage in the flight, the principal influence on the trajectory is exerted by Mars and the Sun. The ellipse changes into a hyperbola with its focal point at the center of Mars. Along the fifth and final section of flight, the field of gravity of Mars is the decisive factor and the trajectory is distinctly hyperbolic.

The various investigations conducted by spacecraft of specific designations (scientific research, meteorological, communication, navigation control, television relay, reconnaissance, strategic, etc.) may be controlled by command from Earth, independently by automatic devices on board the spacecraft, or by the crews of manned spacecraft. In connection with these methods, the development of effective engines, deep space communication systems, control of flight parameters, life-support systems, and the development of systems for automatic navigation and flight control are of extreme importance.

In order to conduct space flights, it is necessary to know the flight parameters of the spacecraft. These parameters are determined by means of a navigation system, which represents one of the most important components of flight control. The parameters of primary navigation information which must be known are:

-- direction of axes of the navigational system of coordinates;

-- angles, angular velocity and the spacecraft's rotational acceleration in relation to the navigational system of coordinates;

-- components of linear accelerations and the velocities of the center of mass of the spacecraft;

-- time of flight and time of flyby of available reference points in space;

-- coordinates of the location of the spacecraft in relation to the navigational system of coordinates and reference points at the start and termination of the flight course;

-- navigational parameters which deviate from the values prescribed by the flight program;

-- velocity and coordinates of position of celestial bodies, their dimensions, masses, and forces of gravity.

There are three types of navigation systems: self-contained, nonautonomous and complex. Self-contained navigation systems conduct measurements of the instrumentation on board the spacecraft. The operation of such systems does not depend on radiotechnical or optical information facilities located on Earth or other cosmic bodies. Self-contained systems, which are used primarily for deep space flights, include:

-- inertial systems for determining the velocity and the coordinates of the spacecraft's position;

-- astronomical systems for obtaining the coordinates of position, velocity and flight period by measuring the angular dimensions of celestial bodies and direction toward them, as well as the magnitude of the Doppler shift in the radiation spectra of stars and planets;

-- astro-inertial systems which combine the functions of the inertial and astronomical systems;

-- systems based on the utilization of energy of the electromagnetic radiation of the Sun and planets;

-- systems used for the modeling of flight parameters.

Non-autonomous systems of navigation are used primarily for guidance and control of the flight parameters of the spacecraft along the powered section of the trajectory after lift-off. By means of these systems are measured the angular positions and distances between the spacecraft and the radiotechnical or optical stations, as well as the velocities of spacecraft. The non-autonomous systems include:

-- radio guidance systems (radar, interferometers);

-- optical goniometric-range finder systems.

The complex systems of navigation represent a combination of the above-mentioned systems. At the present time these systems of navigation play a decisive role in the execution of space flights.

CHAPTER II

Determination of Navigational Parameters of Spacecraft

The navigational parameters of a spacecraft are necessary in order to determine the character of the spacecraft's flight as a solid body in cosmic space, with the consideration of the flight character of other celestial bodies. The basic navigational characters are used to determine the position of the center of mass of a spacecraft. The navigational system of coordinates is used as the beginning of readings of the linear and angular coordinates of a spacecraft. Following are several varieties of navigational systems.

A navigational system of coordinates known as a geographic or geocentric system of coordinates is used during the launching of a rocket from Earth. The geographic system of coordinates utilizes the ellipsoid of the Earth, and the plane of the equator is adopted as the principal plane of this system.

In astronomy and navigation in near-Earth space, a so-called equatorial system of coordinates is used most frequently. This system is a variation of the planeto-centric system of coordinates, using the plane of the equator as its principal plane.

Another variation of a planeto-centric system of coordinates used in astronomy and space navigation is the orbital system of coordinates, illustrated in Figure 4. The principal plane in this system is the plane of the orbit of the spacecraft. The orbital plane passes through the center of the Earth.

An ecliptical system of coordinates is used during interplanetary flights outside the sphere of gravity of the Earth, when the principal force of gravity is emitted by the Sun. The origin of this system of coordinates is located at the center of the Sun and the principal plane is the ecliptic (the plane of the Earth's orbit).

In the not-so-distant future, during flights to other stellar systems, a navigational system of coordinates encompassing the space outside the Solar System will be necessary. The galaxy will be used as a reference point in such a case. This is the co-called galactic system of coordinates, and in the capacity of the principal plane will be utilized the mean plane of the Milky Way (the plane of the galaxy). This system of coordinates is illustrated in Figure 6.

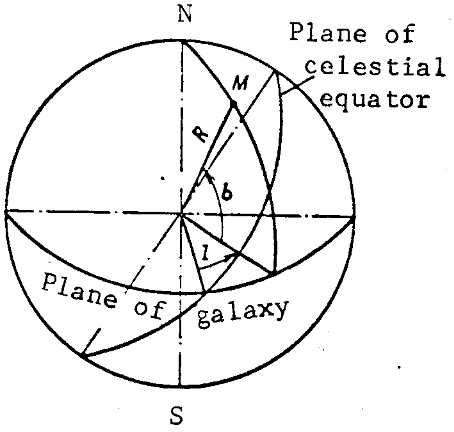

Fig. 6. Galactic system of coordinates

The following data is also necessary during a flight: the angular orientation of the spacecraft, and the determination of the coordinates of the position of reference points in respect to the system of coordinates, which shifts along with the spacecraft. In the capacity of such a system of coordinates during flights near the surface of the Earth is used the horizontal system of coordinates.

The position of the spacecraft in respect to the horizontal system of coordinates $O\xi\eta\zeta$ is determined by three angles; the actual course ψ, the pitch angle ϑ, and the bank γ.

A spacecraft does not have a direct contact with the above-mentioned systems of coordinates. Therefore, a spacecraft must be equipped with a device which simulates the navigational systems of coordinates. The axes of such devices must be parallel to the axes of the navigational systems of coordinates. Such devices, known as stabilizers, determine the angular position of the spacecraft, the direction and magnitude of acceleration, flight velocity and the coordinates of position. A diagram of a stabilizer which simulates the equatorial and geographical systems of coordinates is shown in Figure 9.

During its flight a spacecraft is influenced by the forces of gravity of celestial bodies, the forces of gravity of the engines, the force of resistance of the environment (particularly during flights through the upper layers of the atmosphere), and the forces of interaction of the spacecraft with the various fields. The aggregate of these forces is equalized by the inertial forces of the mass of the spacecraft. By comparing the equations of equilibrium of all external forces, and the equalizing inertial forces according the direction of the three axes of the coordinates, we obtain three equations for the dynamics of motion of the center of mass of the spacecraft. The solution to these differential equations makes it possible to find the velocity and coordinates of the center of mass of the spacecraft during any moment of time with the consideration of the initial velocity and coordinates of the launching area.

In order to solve these equations it is necessary at first to study the unperturbed motion of the spacecraft within the central field of gravity

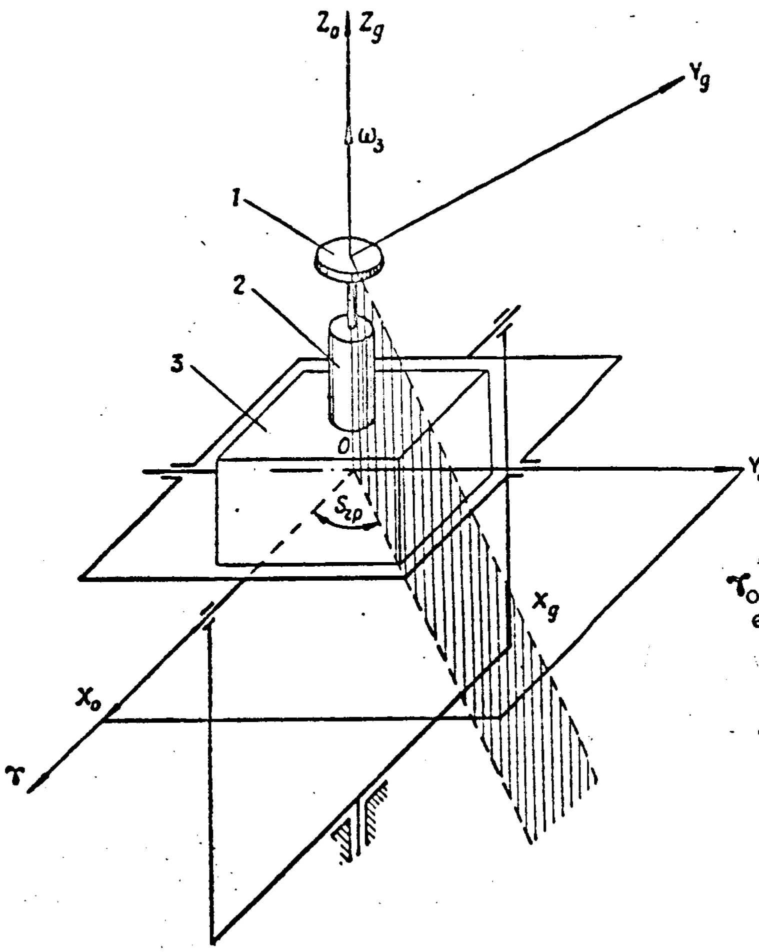

Fig. 9. Stabilizer for finding of equatorial and geographic systems of coordinates.

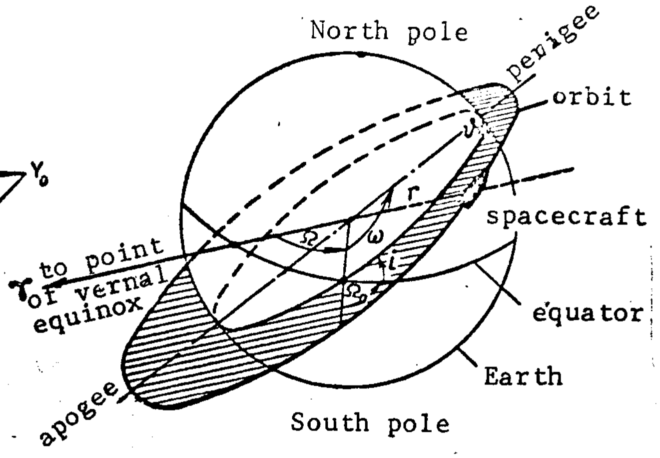

Fig. 10. Orbit of a spacecraft and the orbital elements.

of the Earth. Then we determine the changes in the parameters of motion, caused by perturbing forces. Knowing the coordinates and the velocity of the spacecraft during a perturbed motion, we determine the perturbing forces, and according to these, we find the corrections for the variation of coordinates and velocity of the spacecraft. After that the perturbing forces are defined more accurately and additional corrections are made to the flight parameters, etc. The orbital elements of a spacecraft are shown in Figure 10.

The motion of a spacecraft within the plane of the orbit is characterized by the polar coordinates r and ϑ. The expression which binds these m magnitudes is as follows:

$$r = \frac{p}{1 + e \cos O}, \qquad (2.1)$$

p is the parameter of the orbit; e is the eccentricity of the orbit.

A majority of spacecraft travel along elliptical orbits. It is thereby expedient to determine the relation of the satellite's coordinates to the current time. Such a relation is supplied by the Kepler equation which binds the polar coordinates r and ϑ of a point of the orbit with time, taking into consideration certain auxiliary variables. Such an auxiliary variable is the mean anomaly M, which is the curve described by the spaceship after reaching the perigee. This is expressed by the formula

$$M=\frac{2\pi}{T_0}(t-\tau)=n(t-\tau), \qquad (2.8)$$

where τ is the moment at which the spaceship reaches the perigee.

A navigation method is a combination of measurements of primary parameters and computer operations which is used to determine the flight velocity and coordinates of the position of an object. Navigation methods are divided into the following groups:

1. Path computation methods,
2. The position surfaces methods,
3. Survey comparison methods,
4. Flight trajectory modeling methods.

To the first group pertain methods of aerial, radar doppler, and inertial computation of the path.

To the second group pertain the various radio guidance, astronomical, magnetic, isobaric and other methods of navigation.

To the third group belong methods which are based on the comparison of optical, infra-red, radar and other images of the surfaces of the Earth, planets, or the star-studded sky with geographical charts and geographical or stellar globes.

To the fourth group belong methods which are based on the preliminary determination of the flight trajectory of a spacecraft and the modeling of that trajectory by means of computers aboard the spacecraft. These are known as elliptical methods of spacecraft navigation.

All navigation methods contain some merits as well as some deficiencies which appear under specific flight conditions. Therefore, spacecraft are equipped with several navigation methods in order to increase the accuracy and reliability of the navigational measurements.

CHAPTER III

Pickups of Navigational Information

Acquisition of navigational information which assures the determination of the position of the spacecraft is accomplished by a complex of pickups of primary information. The pickups are instruments and devices which make it possible to determine the basic system for obtaining readings and measure acceleration, velocity, angular deviations and distances in respect to this basic system for obtaining readings. Data transmitted by primary pickups is processed by computers. Pickups of primary navigational information include accelerometers, doppler and astro-doppler speedometers, rangefinders, altimeters, verticals, course systems, time standards, and other devices.

Section 3.1 of this chapter gives a detailed description of the various accelerometers and the mode of their operation under such conditions as, for instance, when the spacecraft is influenced by active forces, gravity, during angular motions of the spacecraft, etc. The values of accelerometers in all these cases are proven mathematically. Special attention is given to pendulum accelerometers. Such accelerometer is used for the measurement of linear acceleration. Some variations of the pendulum accelerometer are: the integrating pendulum accelerometer and the dual integration pendulum accelerometers.

Another important variation of accelerometers are the axial compensation accelerometers which neutralize automatically the forces which act on an inertial body by means of a force developed by the engine.

During the flight of the spacecraft at a comparitively close distance from a celestial body, for instance the Earth, it is necessary to measure the flight velocity in respect to the surface of that body. Knowledge of this velocity is necessary for the purpose of photographing the surface of a celestial body, aiming of the measurement instrumentation toward reference points, and particularly for the landing of the spacecraft. Velocity can be measured by the application of a synchronization of the angular motions of the sighting device and the reference point which is visible on the surface of the celestial body. Knowing the flight altitude, H, and measuring the angular velocity of rotation of the sighting tube, ω, it is possible to calculate the flight velocity, V , according to the formula $V = \omega H$. Synchronization by means of vertical sighting devices is also applied. Optical sighting devices have a high resolving capability and do not require a great power consumption which is particularly important in the case of spacecraft.

However, such a sighting device has one shortcoming which is contained in the fact that at night and during a heavy overcast in the absence of illuminated reference points, for instance cities and large settlements, it is impossible to survey the Earth's surface and consequently to determine the flight velocity. Surveillance of an area can also be made by means of television cameras. An example of a successful surveillance of the surface of a celestial body by a television system is the photographing of the hidden side of the Moon and the transmission of the images to Earth conducted by "Luna -3" on October 4, 1959, and by "Zond-3" on July 16, 1965. This instrumentation can also be used for measuring flight velocity.

In order to measure flight velocity in respect to the Earth, the planets, the Sun, and other celestial bodies, as well as in respect to satellites and spaceships, it is also possible to use doppler speedometers.

A complete doppler frequency shift, measured by the receiver, is related to the flight velocity W by the following dependence:

$$f_d = \frac{2W\cos\alpha}{\lambda}, \tag{3.12}$$

where $\lambda = \frac{c}{f}$ is the wave length and α is the angle between the velocity vector W and the direction of the beam. The range of velocities measured by the dopplers system is established in accordance with the range of velocities of the spacecraft. For the purpose of measuring flight velocity it is also possible to use the radian of the Sun, the planets, the stars, as well as spacecraft. Doppler shifts of the wave lengths of spectral lines are measured by means of radiational direction finders. During the measurement of doppler flight velocities in respect to planets, it should be taken into consideration that the light received from them is, in fact, a reflection of solar illumination. Therefore the doppler frequency shift of radiation received from planets corresponds to the geometrical total sum of the velocity of the planet in respect to the Sun and the velocity of the spaceship in respect to the planet. Doppler speedometers might also be used for the determination of coordinates of the location.

The velocity and altitude of the flight of a spacecraft can be measured in respect to the atmospheric air. This is necessary during flights at low altitudes as well as during the reentry of a spacecraft into the dense layers of the atmosphere. Flight velocity and altitudes in respect to the atmosphere are measured by means of manometric instruments within the lower regions of the atmosphere (troposphere), and by ion pickups equipped with artificial ionizers in the upper regions of the atmosphere (stratosphere). An example of such a pickup, designed for the measurement of flight altitude, is an alpha-electrical altimeter. Due to the temperature change of the air within the ionization chamber and the voltage instability of the power sources, the ion pickup contains an error which does not exceed 2% of the measured value. For the purpose of decreasing the error, automatic thermostats and voltage stabilizers are used.

The flight altitude can also be determined by double integration according to the time of the vertical acceleration of a spacecraft measured by an accelerometer. The accelerometer measures the vertical component of acceleration which is caused by forces of non-gravitational origin. Such an instrument is known as an inertial altimeter.

Other methods for determining flight altitudes are optical altimeters which are based on the measurement of the solid angles of the visible horizon of the celestial body (Earth, Moon, and planets), depending on the flight altitude; and a radiation method for measuring altitude which is based on the measurement of the radiation energy which falls on a sensitive thermo-element. Finally, there are radar altimeters by which measurements are taken of the period of time during which a radio signal bounces off the surface of a celestial body and returns to the instrument.

Section 3.6 of this chapter deals with the necessity of determining the direction of the vertical for navigation and angular orientation of a spacecraft and particularly of the onboard equipment (photo cameras, telescopes, etc.) The instruments which determine the direction of the vertical are called verticals with the addition of a word which indicates the principle of operation. For instance, the expressions "optical vertical," "gyroscopic vertical," and others indicate that during the determination of the vertical, optic, gyroscopic or other principles of operation have been used.

There are several variations of vertical directions depending on the physical nature:

-- the vertical of location (geographical vertical), which coincides with the perpendicular, the point of suspension of which is stationary in respect to the Earth;

-- the gravitational vertical which coincides with the direction of the forces of the field of gravity of the Earth;

-- the geocentric vertical which coincides with the radius-vector which follows from the center of the Earth's ellipsoide to a given point.

Such variations of vertical directions might also be present on other planets and celestial bodies. Onboard a spacecraft can be utilized gauges for measuring the directional vertical based on a variety of principles of operation. These are: a gyroscopic vertical, a gyro-inertial vertical, an optical vertical, an analytical vertical, and a gravitational vertical.

A gyroscopic vertical is used for the flight control of a carrier-rocket during the powered ascent section of the flight.

A gyro-inertial vertical is the basic part of the gyro inertial system of navigation which is described in Chapter 4.

The operation of an optical system for determining the vertical is based on the tracking of the horizon of a planet. The characteristic feature of a horizon of a planet is the sharp variation in the power of infra-red radiation at the border between the planet and the external space. If we determine the vertical in respect to the Earth then the force of radiation near the horizon will depend on the temperature and wave length on which the infra-red radiation is received. A detailed description and explanation of several methods for scanning the horizon is given in this section. Some scanning methods are illustrated in Figure 30. The various instrument systems (television tubes, thermo-resistors, photon detectors, cryogenic bolometers, optical systems, etc.), are discussed in detail.

The analytical method for determining the direction of the vertical is the basis for the preliminary determination of the flight trajectory of a spacecraft by modeling the direction of the vertical in relation to the coordinates of the position directly onboard the spacecraft.

The position of a satellite during an elliptical flight is determined by the length of the radius-vector in respect to the center of the Earth and the argument of the u latitude. The argument of the latitude can be calculated for any desired moment of time according to the Kepler equation:

$$u=M+\frac{2\pi}{T}(t-t_0)+\varepsilon,$$

where $$\varepsilon=2e\sin\frac{2\pi}{T}(t-t_0)+\frac{5}{4}e^2\sin\frac{4\pi}{T}(t-t_0)+\dots \tag{3.16}$$

During the programming of the onboard computer it is necessary to know the allowable degree of approximation during the reproduction of the angle u in order to achieve the desired accuracy. On the basis of measurements and obtained data, the ground computer complex produces correction signals along all basic flight parameters, and these signals are then transmitted to the spacecraft over telemetry channels of communication. The received signals are converted into corrections which are introduced to the plotter of the vertical for the correction of errors.

A vertical can be constructed in principle on the basis of measurements of the variation of gravitational accelerations, as received by the accelerometer. In order to discern the gravitational vertical and the range (to the center of a celestial body) it is necessary to have a a highly sensitive (10^{-9} to $10^{-12} g_0$) and highly accurate accelerometer. Therefore a gravitational vertical is of perspective value but is in fact a difficult to realize measurement system.

The application of direction instruments and systems is discussed in section 3.7 of this Chapter. Such instruments are used on the spacecraft for the orientation of the horizontal system of coordinates along the azimuth. By means of direction instruments is measured the course-angle between the projection of the longitudinal axes of the spacecraft on the horizontal plane and a certain direction within that plane. The course reading in respect to the orbital plane (orbital course) is applied in the case of space flight. The course angle is thereby read out clockwise (from a northern direction towards the east) from 0 to 360 degrees. The following direction instruments are distinguished according to the measurement methods:

-- gyroscopic instruments which are based on the property of the gyroscope to maintain the assigned direction in space;

-- astronomical instruments which are based on the bearing of celestial bodies;

-- radio guidance instruments in which case ground based radio stations and moving natural and artificial radio frequency emission sources are used for the purpose of direction finding.

A gyro semi-compass is used for turning the spacecraft to the desired angle during the execution of a flight along an assigned route and during pre-landing maneuvers. In the capacity of a sensitive element of the gyro semi-compass is used a three stage gyroscope with a horizontal axis of rotation. A kinematic diagram of a gyro semi-compass is shown in Figure 33.

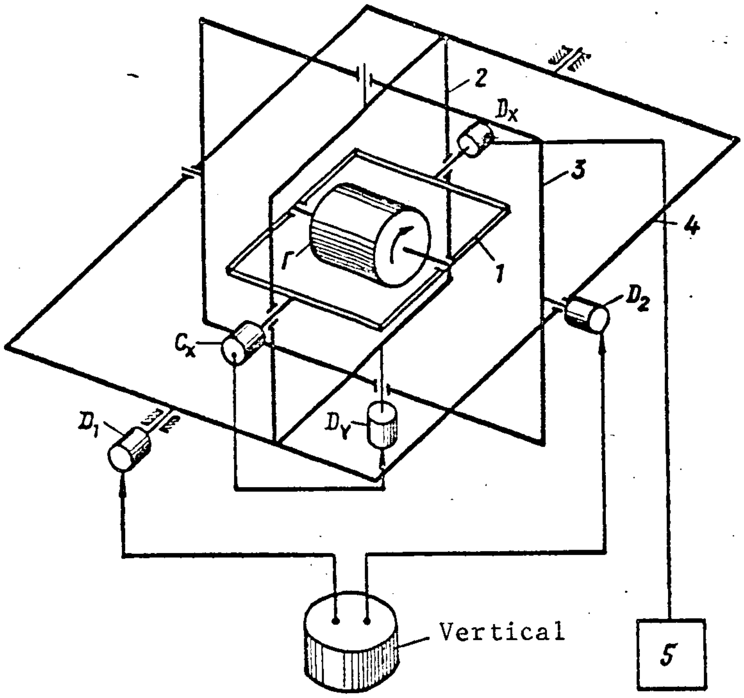

Fig. 33. Kinematic diagram of a gyro semi-compass.

Astronomical compasses are used for the measurement of the course of a spacecraft by taking a bearing on celestial bodies with the consideration of the rotation of the Earth and the coordinates of the position. Astronomical compasses are self contained and do not depend on the magnetic field of the Earth or on radio communication with ground based radio stations. Because of these characteristics, an astronomical compass can be used to measure a course over any region of the Earth, including the geographic and magnetic poles, as well as velocities and flight altitudes. Depending on the method of measurement there are distinguished two types of astronomical compasses: horizontal and equatorial.

One other directional instrument used during space flights is an orbital gyroscopic compass. This instrument uses in the capacity of a cosmic vertical the infra-red vertical which scans the visible horizon of the Earth. The measurement accuracy of a gyroscopic compass depends on the precessions of the orbit which cause methodic errors. If the orbital precession is known then the errors can be eliminated.

Section 3.8 of this Chapter discusses in detail the use of a standard clock during space flights. A standard clock is necessary in order to determine the navigational parameters, to conduct scientific research work in flight, and to synchronize the operation of the onboard instrumentation of a spacecraft with the ground based instrumentation at a high level of accuracy. The most suitable time standard for this purpose is a cesium frequency standard. At present such standards are produced at a very low weight of not more than 13 kilograms and a high stability on the order of 10^{-10}.

CHAPTER IV

Self-Contained Navigation Systems of Spaceships

Self-contained navigation systems are used for the measurement of primary information without the help of ground based radio guidance and optical facilities. Astronomical and inertial navigation systems are used most frequently. However, more accurate and reliable results are obtained through the application of combined systems which are known as complex systems, since these make it possible to eliminate the deficiencies of the separate navigation systems and to improve their dynamic properties, as well as to assure the measurement of navigational parameters under all possible flight conditions.

After determining the direction toward celestial bodies and the distance to them, and after studying the spectrum of radiation of these bodies, it is possible to determine many necessary navigational parameters (coordinates of position, angular orientation and flight velocity) and also to determine the astronomical time, investigate the properties of the surface of celestial bodies and their surrounding atmosphere, as well as the characteristics and physical conditions of a flight through such atmospheres. All these functions can be carried out by means of an astronomical navigation system. The principal distinction of an astronomical system of navigation is contained in affect that it is able at any moment of time, and in any area of the universe, to determine the coordinates of the location of the spacecraft. Apparently not a single controlled space flight in interplanetary space or through interstellar space can be conducted without an astronomical system of navigation. Astro-navigation through interplanetary space can be reduced to the derivation and mathematical processing of three surface positions, each of which can be obtained through various measurement methods.

Section 4.2 of this Chapter deals with the automatic direction finders of celestial bodies. Direction finders, designed for automatic tracking of celestial bodies, are used in systems of astronomical navigation, in systems of the angular orientation of spacecraft, during the landing of a spacecraft on the surface of a planet, for the detection of meteoric danger, for scientific purposes, etc. A direction finder consists of an optical part (telescope) designed to concentrate radiation fluxes; a coordinator which determines the direction of inclination of the image of a celestial body from the optical axis of the telescope; a radiation receiver which converts the energy of radiation of the celestial body into an electrical signal; a voltage or current amplifier; a commutator which distributes the signals to power drives; power drives which conduct the rotation of the telescope ; and systems for computation of data which represents the initial information of the direction finder. A block diagram of a direction finder is shown in Figure 38. A detailed description of the various direction finders designed along various principles of operation is given in this section. The various systems discussed in this section are: a system with a differential activator of light receivers; a system using a television scan of the image; a system with a luminous flux modulation; and mosaic systems. One variation, the mosaic astronomical system, is used for the recognition of the chart of the star-studded sky and for obtaining on the basis of this chart the current coordinates of the spacecraft. With this method the luminous fluxes from the celestial bodies are received by an optical system. After modulation the luminous fluxes from the modulator are projected on a mosaic screen which consists of a large number of miniature phote-resistors or photo-elements assembled in a strictly determined order. The photo-elements create a photo sensitive field which is similar to the field of light sensitive cells in a human eye. A diagram of a mosaic astronomical system is shown in Figure 49.

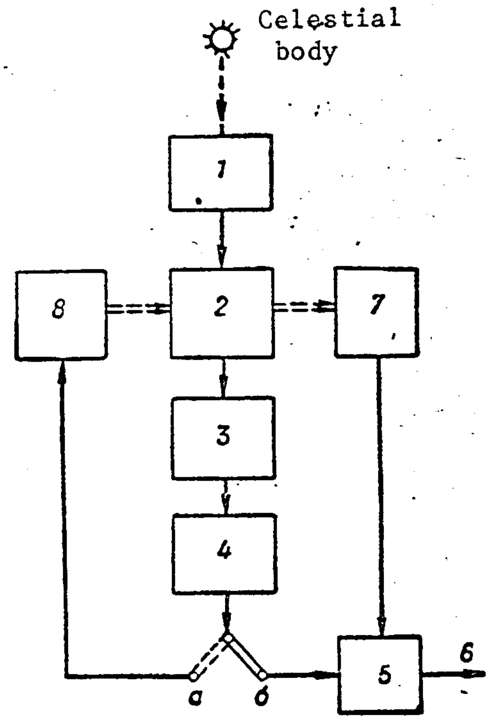

Fig. 38. Block diagram of a direction finder.

1) telescope; 2) coordinator; 3) radiation receiver; 4) electronic unit for signal processing; 5) Readout device; 6) output signal; 7) angular converters; 8) drive.

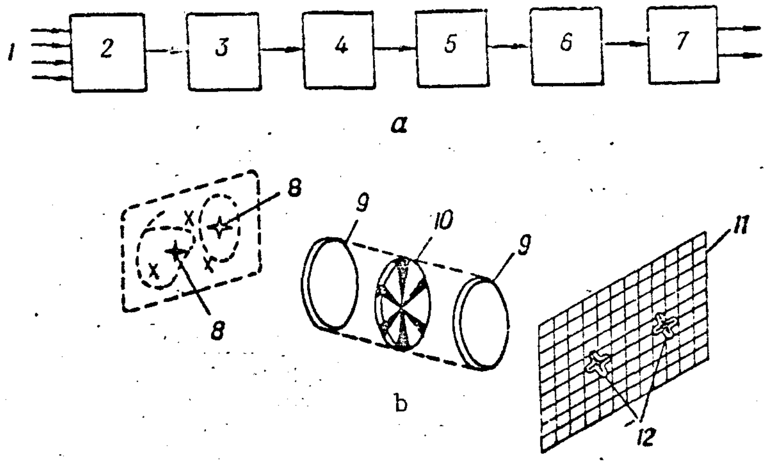

Fig. 49. A mosaic astronomical system.

a) block diagram of a mosaic system; b) diagram of an optical system; 1) luminous flux from celestial body; 2) optical system; 3) modulator; 4) mosaic screen; 5) preamplifier; 6) system for scanning and commutation; 7) onboard computer; 8) stars; 9) optical device; 10) sighting disc; 11) image on mosaic screen; 12) images of stars.

Electro-magnetic radiation of the Sun, the stars and planets, radiation of celestial bodies within the visible and invisible sections of the spectrum might be used for the determination of the navigational parameters of the spacecraft and for flight velocity measurements.

During the motion of the radiation receiver in respect to a radiation source with the speed of V, a shift of spectral lines (doppler effect) can be detected along the wave length. This shift can be presented as follows:

$$\Delta\lambda = \frac{\lambda_1}{c} V = \lambda_1 - \lambda_2,$$

where λ_1 and λ_2 are the wave lengths of the stationary and moving radiation sources; c is the speed of light.

According to the measured magnitude of $\Delta\lambda$ and the known value of λ_1 it is possible to determine the radial velocity V. A widening of the spectral lines caused by the doppler effect is accompanied by a change in the force level of radiation:

$$\Delta\lambda = k\lambda_1 \sqrt{\frac{T}{\mu}} \tag{4.3}$$

where λ_1 is the wave length of the spectral line; T is the absolute temperature; μ is the molecular weight of the radiation source; $k = 7 \times 10^7$ is the coefficient. From this formula follows that in the presence of large values of λ and T and lesser values of μ, the spectral line of the radiation source is much wider. Consequently it is more convenient to utilize for navigation purposes brighter stars which makes it possible to obtain considerable changes of $\Delta\lambda$.

This system, known as the astro-doppler system, makes it possible to measure the velocity of spaceships in respect to the Sun with an error up to 1 m/sec, and in respect to the stars with an error up to 90 m/sec. A general view of an astro-doppler radial velocity measurement device is shown in Figure 51.

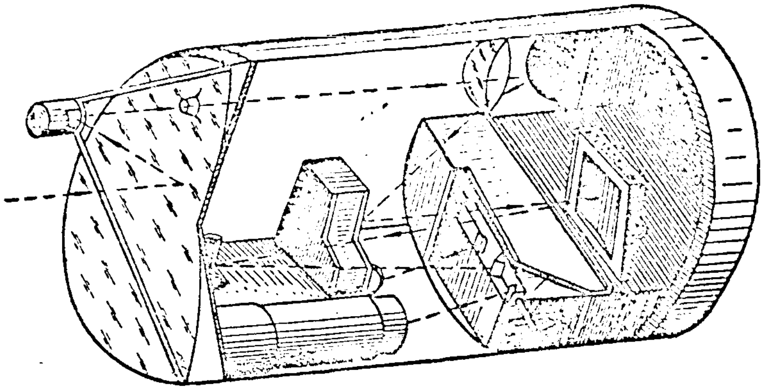

Fig. 51. General view of an astro-doppler radial velocity measurement device.

Astronomical orientation devices (described in section 4.3) are goniometric instruments which make it possible to determine the coordinates of an object analytically, according to data about the measured altitudes, distances, or angular dimensions of planets and stars. An astronomical orientation device should contain also a computing instrument for the solution of spherical problems of astronomy. The value of computations depends on the method of navigation and the frequency with which navigation information is received, i.e., on discreet or continuous measurements. The authors describe in detail several types of astronomical orientation devices in this section. These include: astronomical orientation devices based on the measurement of the distance to three celestial bodies, and an astronomical orientation device based on the bearing on a planet and two stars. In addition to the discussed methods of astro-navigation and the schematics of astronomical orientation devices, there are also available other methods and schematics based on different combinations of the earlier indicated position surfaces or on the utilization of position surfaces of other geometrical forms. Each of these methods might prove to be most satisfactory under specific conditions. In the case of deep space navigation it is expedient to apply methods based on the measurement of the angles between the centers of three celestial bodies or two celestial bodies and stars. Navigation within shorter distances which includes the landing of the spacecraft on the surface of a celestial body might be carried out with the method based on the measurement of the angular diameter of the celestial body and the angles between the centers of this celestial body and two stars.

In addition to natural celestial bodies, artificial Earth satellites can be used as reference points for space navigation. The method used for determining the coordinates of the position of a spacecraft according toartificial satellites is identical with the astronomical method of navigation used in respect to natural celestial bodies. The principal method for measuring the distance to an artificial satellite is by means of radar. A pulsed radio signal, transmitted from the spacecraft, reaches the antenna of the radio receiver onboard the artifical satellite. After reception the signal is amplified, converted, and relayed towards the spacecraft. By measuring the elapsed time between the transmitted and received radio signals $(t_1 - t_2)$ and knowing the speed of propagation of radio waves, the distance to the satellite is determined as follows:

$$R = \frac{1}{2} c \ (t_1 - t_2)$$

A navigation satellite which is designed to serve in the capacity of a navigational orientation point, should be equipped with a radio receiver and transmitter as well as with a device which computes continuously its current coordinates or orbital elements. In reply to a received pulsed radio signal from a spacecraft, the satellite should report the coordinates of its position and this will consequently simplify the orientation task of the spacecraft considerably. The operation of the coordinate computers aboard the navigational satellites should be checked periodically and corrected by ground based tracking stations.

The inertial systems of space navigation (discussed in section 4.5) pertain to the systems of path computation. The computation of coordinates is accomplished by the integration of the components of acceleration which are measured by accelerometers. The axes of sensitivity of accelerometers are oriented according to the direction of the axes of the navigational system of coordinates.

The inertial system of space navigation can be divided into two groups:

1. A closed system in which acceleration caused by forces of gravity is introduced to other sources of information, and

2. A closed system in which acceleration caused by forces of gravity is computed by the inertial system and is introduced to the input system by way of a feedback. Most popular is the inertial system which conducts the path computation in respect to the equatorial, orbital, and ecliptical systems of coordinates. The instrumentation of the inertial systems consists of: accelerometers, stabilizers of the angular position of the accelerometers, computers, output information indicators, and the determinators of the initial flight parameters and the parameters of the field of gravity. Of great importance are clocks (generators of stable frequencies) by means of which changes of the coordinates of the celestial bodies are determined. The principles of operation of open inertial systems are discussed in detail and illustrated by diagrams. In order to eliminate the instability of inertial systems it is possible to utilize additional navigational information, as for instance, information obtained from the astronomical system of navigation. The astro-inertial system of navigation combines the astronomical and inertial systems. Such a combination makes it possible to eliminate the increasing errors which are reflected in the inertial system and to increase the "memory" time in the astronomical system, as well as to assure an automatic search for celestial bodies and to reestablish the astro-orientation after a prolonged interval in the operation.

The astro-inertial system can function in two modes of operation:

1. In a "memory mode" when the celestial body is out of vision (errors accumulate thereby), and

2. In a normal mode of operation when the errors of the astro-inertial system are determined by the astronomical correction system.

Spacecraft are also equipped with self contained radio guidance systems of navigation. The operation of these systems does not depend on radio guidance facilities on Earth or on other celestial bodies. The self contained radio navigational equipment consists of radar range finders, radar interferometers, doppler instruments for the measurement of velocity and distance. It is generally considered that radio guidance systems of navigation are distinguished by highly accurate measurements of coordinates of position and flight velocity as well as the angular position of the spacecraft.

CHAPTER V

Non-autonomous Navigation Systems of Spacecraft

The navigation of artificial satellites in orbits around the Earth can be accomplished by a complex of ground based and onboard instrumentation. The operation of navigational systems which control the flight of artificial Earth satellites is based on determining the flight parameters by the onboard instrumentation. Errors which occur due to the introduction of inaccurate initial data, as well as other reasons, are corrected perioically when the satellite comes within range of a control station. A network of control stations, located at large distances from each other, is set up for that purpose at various points of the Earth. The tasks of navigation and control of the position of a satellite include:

-- continuous determination of the flight parameters (distance, direction, and their initial time derivatives);

--- to define more accurately these parameters according to observation data;

-- processing and transmission of commands or ephemeris data to the satellite.

A number of methods are available for the determination of flight parameters of a satellite. The goniometric-ranging method requires the measurement of the azimuth, the position angle, and the slant range. As a rule this system includes onboard instrumentation as well as ground based facilities.

A detailed description of instruments and facilities used by this system and a mathematical discussion of its operation is included in this section. In detail are also discussed the phase method for range finding and the pulse method for measuring distances.

Orbital parameters can be determined according to data on the angular coordinates and the doppler frequencies, as well as by direct distance measurement. These operations, described in section 5.3, are conducted by ground based radar stations. The various operations which have to be carried out fo the purpose of measuring flight parameters of a spacecraft are described in detail.

The operation of a system for the measurement of flight parameters of a satellite with the help of interferometers (discussed in section 5.4) is based on the determination of the phase variation of signals received by ground stations from the satellite's transmitter. These signals characterize the current angular position of the spacecraft and establish the doppler frequency increase. The interferometer system utilized onboard instrumentation as well as ground based facilities. This section contains a detailed discussion on the operation of this system. In order to illustrate the operation of this system the authors have included a number of block diagrams of various interferential systems including the American "Minitrack" system.

Determination of the flight parameters of a spaceship by means of a ranging method is based on the measurement of the distance from the spaceship to several control stations. Knowing the distance between the control stations and by measuring the distances between each station and the spacecraft it is possible to determine its current coordinates by way of triangulation. Knowing also the increment of the satellite's coordinates of a specific time interval it is possible to determine the components of the radial velocities.

The slant range can be determined also by the"inquiry-reply" method, also known as the pulse method, or according to the doppler frequency measurements.

All these operations are carried out by the radar range finding system which is discussed in section 5.5. The characteristics of the above mentioned methods are described in detail in this section. In the case of the pulsemethod, the leading station transmits an inquiry pulse to the spacecraft. The relay transmitter of the spacecraft sends back a reply pulse which is received by all three stations. The other two stations re-emit the received pulse. The leading station receives the pulse from the spacecraft as well as the re-emitted pulses from the other two stations. The time intervals between the inquiry and the reply pulses equals

$$\left.\begin{aligned}\Delta t_1 &= \frac{1}{c}(R_{AM}+R_{MA});\\ \Delta t_2 &= \frac{1}{c}(R_{AM}+R_{MB}+R_{BA});\\ \Delta t_3 &= \frac{1}{c}(R_{AM}+R_{MC}+R_{CA}),\end{aligned}\right\} \tag{5.8}$$

where c is the speed of propagation of radio waves. This method is demonstrated in Figure 67.

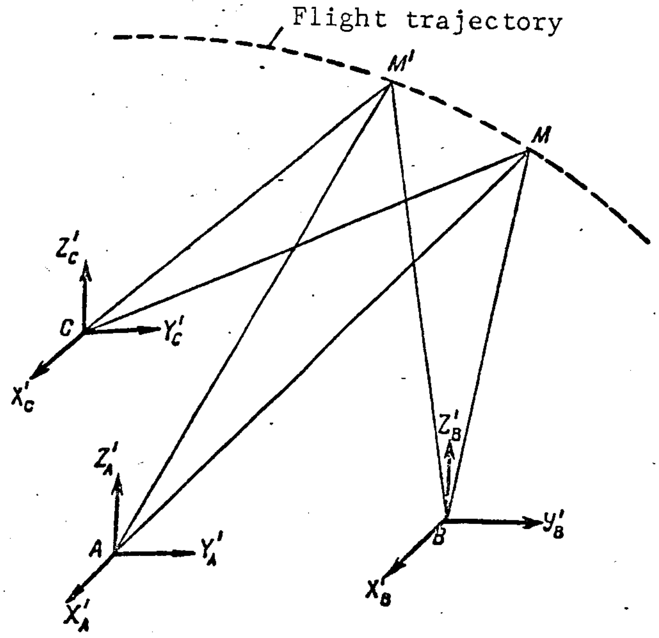

Fig. 67. Determination of parameters by means of a ranging method.

In measuring the distance with the doppler method the magnitude of the frequency shift due to the doppler effect is determined according to the formula:

$$f_d = \pm \frac{V}{\lambda} \left[\frac{t_0 - t}{\sqrt{(t_0 - t)^2 + \left(\frac{R_0}{V}\right)^2}} \right] \tag{5.9}$$

where V is the velocity of the satellite; λ is the wave length; t_o is the moment when the satellite passes the traverse; t is the beginning of the reading; R_o is the minimum distance from the observation point to the orbit of the satellite.

Section 5.6 of this Chapter discusses a variety of combined systems. In connection with this, the authors describe in some detail the "Minitrack" system.

Section 5.7 deals with the optical systems for determining the flight parameters. Optical systems are used for the purpose of observing and fixing the moment when the space ship crosses the vertical plane which passes through the meridian of the observer. The instrumentation consists of a lens with a comparitively large focal length and a movie camera. Determination of the coordinates of a spacecraft by means of optical methods is known as photogrammetry. The high accuracy of this method can be ascribed to the fact that the moving object is fixed in a successive manner on the background of stationary stars. In order to increase the effective range of the optical devices, pyrotechnical devices are installed on board spacecraft for the purpose of igniting periodically bright flashes of light. Thanks to these flashes it is possible to track a satellite optically to a distance of 1,600 kilometers.

In addition to optical means for satellite tracking, there is available also as electron-optical system which combines optical means (a telescope) with an electron-amplifier tube. This system is described in detail in section 5.8. One such system, developed by the Optron Company makes it possible to measure angular coordinates of a rocket or a satellite in flight at a very high level of accuracy.

The progress of quantum electronics led to the development of optical quantum generators and amplifiers (lasers). A laser is capable of producing a pulse of an extremely high power and a very narrow radiation pattern of the beam. Similar systems have been used recently for space navigation purposes. On the basis of these instruments it is possible to construct range finders, instruments for the measurement of the rate of rotation of spacecraft and other instruments. A detailed discussion on the application of lasers for determining navigational flight parameters of spacecraft is included in section 5.9.

CHAPTER VI

Navigational Complexes of Spacecraft

The flight of a spacecraft will be successful if the flight parameters along the entire flight trajectory will be known. The selection of the method of navigation and the required instrumentation depends on the flight trajectory of the spacecraft and the required accuracy. The navigation of artificial Earth satellites and interplanetary spacecraft is carried out at the present time almost entirely by means of ground based facilities. The location and velocity of a spacecraft is determined on the basis of information obtained by means of radiotechnical (radar, interferometers) and optical systems. The methods for the development of navigational complexes to be installed onboard various spacecraft is discussed in detail in this Chapter.

There are available two basic methods for the construction of navigation systems: the open circuit method and the closed circuit method. These two methods are discussed in section 6.2. The open circuit method is based on the utilization of an open system for determining flight parameters. According to this method the flight trajectory of a spaceship is expressed analytically to longitude and latitude. One shortcoming of this method of navigation is contained in the fact that it requires an extensive network of ground facilities for the precise determination of the orbital parameters of spacecraft. This method can be used for the navigation of artificial Earth satellites and spacecraft designed for flights to the Moon and other planets.

With the closed circuit method the navigation task is carried within a preselected system of coordinate axes, the position of which in respect to the inertial space is known and which might be realized by means of onboard instrumentation. Such access might be directed toward stars also toward the direction of the local vertical in respect to the selected planet. Knowing the flight trajectory and the proposed model of the force field in the given region of space for a specific moment of time, it is possible to determine approximately the coordinates and velocity of the spacecraft. With the help of the onboard navigation system, the current values of the directional angles towards the selected reference points are measured. The measurement data is fed into a computer. As a result of a comparison of the measured and calculated data the current parameters are obtained. These parameters are the initial conditions for the computation of the coordinates and the velocity of the spacecraft. This is a self-contained system of navigation.

Section 6.3 of this Chapter deals with the navigational complexes of both recoverable and nonrecoverable artificial Earth satellites. The discussion of the various navigation systems for satellites and particularly the inertial system of navigation is based on the results obtained in this area in the U.S.A. The authors describe in detail the onboard instrumentation as well as the equipment of the ground based facilities which participate in this system of navigation.

The methods of navigation and the instrumentation complexes of interplanetary spacecraft are selected in accordance with the mission of each specific flight. There are two specific flight missions in the case of interplanetary spacecraft: a flight into space without return to Earth and landing on another planet, and a flight to a target planet including a landing on its surface and a return to Earth. Navigational complexes which assure the flight of an interplanetary spacecraft along prescribed trajectories is discussed in section 6.4.

The navigation complex of an interplanetary spacecraft which was launched on a mission to conduct cosmic research without return to Earth, must assure the following operations: injection into a parking orbit, exit from the parking orbit on an interplanetary trajectory and the flight along the interplanetary trajectory. The navigational system for such a mission can be constructed on the basis of the open circuit method with corrections by ground based stations.

The discussion of the problem of the navigational complex of interplanetary spacecraft designed to soft land on other planets and return to Earth is based primarily on the American "Apollo" program. The facilities and characteristics of the application of the separate elements of this system are discussed in this section. The separate elements of this system include: a gyrostabilized platform on which the measurement instrumentation and the control panel are mounted, a sextant, a telescope, an indication and control panel, a computer, and other necessary instrumentation.

Section 6.5 of this Chapter deals with the various navigational means designed for orbital rendezvous and docking maneuvers. Again the authors base their discussion on the American "Gemini" and "Agena" experiments. A detailed description of the various methods and applications used for the execution of these operations include: radar and frequency modulation, infra-red systems, optical systems, doppler systems which operate within a radio and optical range (lasers) and others.

Section 6.6 of this Chapter deals with the instrumentation used for the interception of target satellites. The mission of a satellite interceptor includes the search and detection of the target satellite, recognition and determination of its coordinates for the purpose of making tactical decisions. Most suitable for the execution of these tasks are combined systems which utilize radar equipped with lasers which emit visible or ultraviolet rays and also passive optical systems, and radars which operate within the radio range. A satellite interceptor might be equipped with passive instrumentation for the detection of nuclear radiation or radio frequency emission of the target satellite. Radar pulse stations or frequency modulation stations conduct the search, acquisition, and tracking of the target satellite from a distance of from 150 to 200 kilometers and up to 30 meters. In conclusion of the book the authors give a short description of the operation of complex optical systems which include infra-red installations and lasers.