Stellingen

behorende bij het proefschrift

Gyrostabiliser for Mobile Antenna Post

Irina Popova
Delft, 12 juni 1996
1. Door de constant toenemende hoeveelheid informatie die de mens bij zijn dagelijkse activiteiten gebruikt, is het een vereiste dat reeds bestaande communicatiehulpmiddelen worden uitgebreid en nieuwe systemen worden ontwikkeld.

2. “To be or not to be, that’s the question”. De ontwikkeling van autonome, kleine en goedkope TV-ontvangstinstallaties aan boord van binnenvaart- en zeeschepen lijkt momenteel actueel.

3. “David versloeg Goliat”. Het relatief kleine, mobiele antennesysteem, dat ontworpen is volgens het indicatie-gyroscop principe voor stabilisatie en regeling van de hoofdas van de antenne en van het polarisatievlak in de ruimte, lijkt de meest veelbelovende methode voor mobiele ontvangst.

4. “Kennis is als een straatlantaarn die je pad belicht”. Een niet-traditionele benadering van de constructie van het stabilisatiesysteem als een combinatie van een twee-assige gyro voor horizontale correctie en een één-assige gyro voor azimut correctie, voldoet hoogstwaarschijnlijk het best aan de eisen voor een mobiel ontvangsysteem qua functionaliteit en gebruikersgemak en voorziet tevens in het autonome gebruik ervan.

5. “De kleinsten dragen altijd de zwaarste lasten”. Unirotortrillingsgyroscopen, die werken volgens het systeem met twee hoekspanningssensoren en met slinger-versnellingsmeters, geven de vereiste meetinformatie voor gyrostabilisatiesystemen tegen minimale kosten.

6. Niets is waardevoller voor de praktijk dan een goede theorie: gelineariseerde wiskundige modellen, op structuur en op parameters gebaseerde ontwerpmethoden, alsmede uitdrukkingen voor foutberekeningen bewijzen een zeer belangrijk hulpmiddel te zijn voor het ontwerpen van systemen.

7. De praktijk is de uiteindelijke toetssteen. Fysische experimenten wijzen pas uit of de technische aanpak en de ontwerp-beslissingen de juiste geweest zijn.

8. Het ideaal is weliswaar onhaalbaar maar men moet het altijd blijven nastreven. Het ontwerp van het gyro-stabilisatie systeem, als beschreven in dit rapport is nog niet in de laatste fase van implementatie; verbeteringen en uitbreidingen blijven mogelijk.
1. A constantly increasing amount of information used by man in his everyday activities demands that existing means of communication should be expanded and new systems should be developed.

2. "To be or not to be, that's the question". The elaboration of independent, small-sized, cheap devices for receiving satellite TV-pictures on board the sea and river vessels appears to be actual at present.

3. "David won Goliath". The mobile antenna post constructed on the same principle as the indicator gyroscopic system of stabilisation and control over the focal antenna axis and the plane of its polarisation in the inertia space appaers to be the most perspective variant.

4. "Knowledge is a street-lamp lighting from behind". A non-traditional approach towards constructing the stabilisation system as a combination of a two-axes gyrostabiliser with a horizontal correction contour is most likely to meet the requirements imposed on functional and operational properties of mobile post as well as to provide their autonomy.

5. "The smallest boy always carries the greatest fiddle". Unirotor vibrational gyroscopes operating in the mode of two-component angular velocity sensors as well as pendulous accelerometers provide the required metrological characteristics for gyrostabilisers at a minimal cost.

6. Nothing is more practical than a sound theory. The linearised mathematical model, the methods and the results of structural and parametrical synthesis and the expressions used for error calculations prove to be very convenient tools for designing systems.

7. Practice is truth criterion. Experiments finally prove whether or not technical and design decisions were right.

8. Ideal is inconceivable, but one should always try to attain it. The design of the gyro-stabilising post, described in this report, is not yet completely finished; improvements and extensions remain possible.
Gyrostabiliser
for Mobile Antenna Post

Irina POPOVA
Gyrostabiliser for Mobile Antenna Post

Proefschrift

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Prof.Y.B.Vlassov heeft als begeleider in belangrijke mate aan het totstandkomen van het proefschrift bijgedragen.

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October 7, 1959 (6.30 by Moscow time) is the birthday of cosmic television; it is the day when the phototelevisional apparatus “Yenisei”, on board the automatic interplanetary station “Luna-3”, began taking photos of the Moon’s far side. This station was the first not only to take photos of the Moon’s far side which could hardly be seen from the Earth, but it also transmitted these photographs to the Earth. Despite the fact that historically Russia has been the leader in conquering the outer space and in launching the Earth’s artificial satellites, at present, major events in the sphere of transmitting information which is of vital importance to the public by means of satellites and the development of corresponding techniques and technologies occur abroad. The reasons are not only economic ones, but political as well. Russia has been isolated from the entire world for a long time. And this fact still remains to be a serious obstacle for information spread in Russia though communicational technologies are rapidly changing the pace and the direction of scientific and technical progress, they are wiping interstate boundaries thus influencing the people’s perception of the surrounding world.
Long before I started my scientific research for my thesis I had already had some theoretical and practical experience in elaborating the indicator systems of stabilisation and control over the visual line in optico-electronic systems based on rotor vibrational rate gyroscopes. I had been working under the supervision of Prof. Yuri Vlassov who had always been and will always be my first teacher in the sphere of gyroscopic instrumentation. I will always be deeply and sincerely grateful to him for knowledge and experience he has been teaching me during the long eight years of our mutual collaboration and when discussing various technical problems. The idea to develop a mobile antenna post for receiving satellite television on board the mobile sea objects appeared in 1991 during the discussion on Russian industry conversion in the Scientific-Research Laboratory of the Leningrad Institute of Aviation Instrumentation. This laboratory was headed by Prof. Vlassov and I worked as the researcher in it. A year later this idea was reported about at the First International Congress "Space Technologies in Russia" and then it was developed in the discussions with Dr Hans Martin Braun, Director General Raumfahrt Systemtechnik RST AG, and I am sincerely grateful to him for the attention paid and for his participation in further co-operation. In the definition of problems and in finding the ways of their solution this idea was concerned with investigations which had been conducted in GYROOPTICS Co. Ltd. under my supervision. The effort to translate this idea into life required to devise a number of theoretical and practical questions ranging from constructional principles selection to experimental prototype tests, and they were used as a basis for my thesis.

When working at my thesis I was helped and supported by many people. And, first of all, I would like to thank my promoters Prof. ir. Ger Honderd and Dr. ir. Wim Jongkind for their attention, fruitful discussions and helpful advice concerning different aspects of my thesis. I would gladly express my thanks to all researchers and engineers of GYROOPTICS Co. Ltd. for the constant help in working out the digital simulation and in conducting experiments. It is a great pleasure for me to thank Mr Wim De Peuter for his sustaining interest in my work and sufficient support. I am thankful to Mrs Irina Gromovaya for correcting the English text and I am thankful to all my family for their keen and sympathetic attitude and their everyday support.

Irina Popova
Satellite television information systems are being developed and widely applied nowadays. The urgency of such systems elaboration is conditioned, among other factors, by the increasing necessity to receive television pictures transmitted by satellite relay stations not only in steady-state circumstances but on board the various mobile objects: sea and river vessels, yachts, oil platforms, trains and auto-transport. It is especially actual for sea vessels as they can quickly receive the weather situation picture from meteorological satellites together with satellite television programmes and for fishing fleet because additional information about fishing situation can be received from special satellites accomplishing the Earth sounding. That is the reason why Russia and some other foreign countries began investigating and developing mobile satellite systems (MSS) of communication in the early 1990s, especially those which are supposed to employ intermediate transmission on geostationary orbits by means of satellites. The urgency of such investigations was emphasised in the Proceedings of the 2nd Russia’s Forum “The electronic communications
technology” - “TEC-92” and in “The doctrine of Russia’s space communications during the period up to the year 2000”.

1.1 History and Future

The analysis of contemporary MSS shows that at present, highly reliable, fast, two-way MSS for receiving and transmitting voice, telex and fax messages, PC digital data and modems both in digital and analogue forms are successfully employed. The latest exhibition, such as the 33rd International Exhibition “INTERBOOT-94” in Germany and the 6th International Exhibition “INTERFISHINDUSTRY-95” in St-Petersburg, have demonstrated the achievements of some popular firms, such as Japan Radio Co. Ltd, FURUNO Electronic Co. Ltd, Thrane&Thrane A/S, Denmark; Scientific Atlanta Inc., USA; STN ATLAS ELEKTRONIK, Western Germany with the INMARSAT stations of “A”, “B” and “C” generations, working in this area. Systems of this type use force stabilisation in the form of gyrodynes or indirect gyroscopic stabilisation and they work in complex with the built-in GPS or they possess an interface with on-board navigation equipment. Such systems can not carry out the function of receiving and transmitting the television picture because of a number of reasons, one of them being a rather great error of the focal antenna axis (FAA) and the antenna polarisation planes positioning and holding as well as control limitations.

When receiving and/or transmitting television pictures there exists the necessity of a more accurate FAA positioning in three mutually orthogonal planes with the error which depends on both the MSS antenna directional pattern width measured by dozens of minutes of arc when the spectrum of external effects is wide and on the control angles which form the upper semi-sphere. The requirements mentioned could be met in two ways. One of them is to utilise controlled phasing arrays (FA). FA existing today are developed on the basis of the military-industrial complex technology and are mainly intended for the military and space markets. They are characterised by high prices and can hardly be used in the civil market.
The second way is to employ a special gyroscopic stabiliser which can perform the functions of the FAA stabilisation and control in the satellite direction. The electro-mechanical systems of this type have been developed and are being successfully employed on military objects, on vessels, in particular. They are rather complex and expensive. As a rule, these systems comprise an interface with a vessel navigation complex and a central control terminal. It is rather difficult to utilise such systems with civil objects without significant modifying which often causes their general view changing. It is necessary to have a particular interface for each particular communication with different on-board navigation equipment in each particular case, and their technical parameters excess does not justify their cost in the civil market. The example is an advertised gyrostabiliser antenna post for receiving satellite television picture on board the cruise passenger vessel developed by the German firm Dornier GmbH. Further elaboration carried out by this firm in this direction are unknown at present.

Among Russian enterprises dealing with similar systems the Central Scientific Research Institute “Electropribor” is known to produce a vessel satellite television receiving station “Nord” on the basis of technology developed. The station comprises the system of indirect stabilisation from its own vertical gyro reference with additional position indication from the on-board gyrocompass during the vessel motion and its manual hand setting (fixation) when the vessel stops. The station is not autonomous and possesses significant mass and dimensions properties which only narrow the spheres of its applications, and cannot be employed on yachts or on small-tonnage vessels. The station installation and maintenance is also difficult because of the necessity to organise the interface and the navigation equipment.

The analysis of the results in the sphere of MSS elaboration shows that the task of producing an independent, simple in maintenance, low laborious and low cost mobile antenna post (MAP) for receiving satellite television pictures on board the sea and river vessel of different classes still exists. It could be settled through investigating the ways of producing a special gyrostabiliser for MAP satellite television. And it also requires some
scientific and technical tasks of both theoretical and applied character to be settled.

1.2 Theme and Scientific Goals

The theme of the thesis is theoretical and experimental investigation of the MAP gyrostabiliser for receiving satellite television picture on board the sea and river vessels based on the theoretical analysis and synthesis with the subsequent optimisation of technical characteristics in accordance with modern requirements.

The scientific goals of this paper are as follows:

- Analysis of possible ways of constructing the MAP gyrostabiliser for receiving satellite television picture on board the sea and river vessels, the selection of its rational schemes and operational algorithms.
- Elaboration of the MAP gyrostabiliser mathematical model.
- MAP gyrostabiliser synthesis.
- Elaboration of the MAP gyrostabiliser mathematical model of errors and the ways of their decreasing.

The investigation is conducted in the following basic directions:

- Elaborate recommendations for choosing the constructive and functional scheme and the types of sensitive elements for MAP gyrostabilisers for receiving satellite television picture on board the sea and river vessels.
- Elaborate functional and structural schemes for MAP gyrostabilisers.
- Elaborate the procedure of choosing basic MAP gyrostabiliser parameters.
- Elaborate the requirements to the MAP gyrostabiliser elements and units.
- Elaborate technical decisions for decreasing the MAP gyrostabiliser errors.

The investigation of the MAP gyrostabilisers for receiving satellite TV-pictures on board the sea and river vessels is based on the methods of
analytical mechanics, the theory of automatic control, the optimisation theory and mathematical simulation. The task of providing the required gyrostabiliser errors to conduct steady and high-quality TV-picture reception is solved by means of the theory of automatic control, the error and the optimisation theory.

The investigation results in defining the algorithms of the gyrostabiliser operational models in general, as well as in compiling the mathematical models and establishing theoretical relations which describe the operation of the levelling, search, auto-acquisition and tracking subsystems for the maximum of the satellite TV-signal received. The choice of sensitive elements for the gyroscopic stabilisation subsystem and the subsystem for constructing artificial level is given proof of. Analytical expressions to estimate the gyrostabiliser channel errors are obtained. The procedure for decreasing the gyrostabiliser error values influencing the quality of the satellite TV-picture reception if the evolution forms of the given objects vary is proposed. Experimental research and the MAP gyrostabiliser pilot tests have been conducted.

As a result of theoretical and experimental investigation, we put forward the perspective variant for producing the MAP gyrostabiliser to receive satellite TV-pictures on board the sea and river vessels based on the unirotor vibrational rate gyroscopes and the principle of autonomous indicator stabilisation system supplied with contour of horizontal levelling and the extreme system.

The following points are submitted for defence:

- Principle of constructing the independent system of indicator stabilisation and operation based on the rotor vibrational rate gyroscope with the built-in horizontal correction contour as it best of all meets modern requirement to MAP for receiving satellite TV-pictures.
- Gyrostabiliser mathematical models in general, as well as the subsystem of levelling, search, auto-acquisition and tracking the satellite signal level.
- Gyrostabiliser errors models developed on the basis of motion equations and the ways of reducing them.
- Results of digital simulation of subsystems search, auto-acquisition and tracking of the satellite signal level received.
- Results of experimental tests with the MAP demonstrator and its pilot models.

1.3 Scientific and Applied Aspects

The interconnection of scientific and applied thesis aspects are shown in Fig. 1.1. The MAP gyrostabiliser for receiving satellite TV-pictures consists of an electromechanical unit (Part 1); the “Human-Machine” interface (Part 2) and a TV-system (Part 3). The electromechanical unit represents the system of stabilisation, levelling and FAA operation in accordance with the elevation angle based on gyroscopic, acceleration and torque sensors; it provides the modes of stabilisation, levelling, search, auto-acquisition and tracking the level of the received satellite signal by means of corresponding subsystems operation. The MAP gyrostabiliser is handled by the operator with the help of special software for IBM PC compatible computer and the standard RS-232 interface. The geographical position co-ordinates of the place where the signal is received and the co-ordinates of the Earth satellite point of observation on the geostationary orbit represent the staring information for fulfilling the operational cycle by the MAP gyrostabiliser in an independent mode. The quality of the received picture and the sound are controlled by the user and in actual practice is provided automatically by the use of feedback as an extreme system in accordance with TV-signal envelope level. The thesis focuses on investigating the process of receiving a high-quality satellite TV-picture on board the sea and river vessels through the proposed gyrostabiliser type and the MAP configuration, Part 1, Fig. 1.1.

1.4 Basic Sections

In the first and second chapters of the thesis the tasks connected with the MAP gyrostabiliser for receiving satellite TV-pictures on board the sea and river vessels are studied. The conditions for carrying out reliable and high-quality reception of satellite TV-signals on board the sea and river
Fig. 1.1. Interconnection of scientific and applied aspects
vessels are specified. The requirements for MAP receiving satellite TV-signals are analysed.

It is possible to obtain the required characteristics for perspective MAP only through producing a special MAP gyrostabiliser. Having observed modern states and tendencies in instrumentation development we could recommend to construct such a gyrostabiliser in accordance with the scheme of an independent system of indicator gyrostabilisation on the basis of rotor vibrational gyroscopes (RVG).

Possible electro-kinematic schemes for producing MAP gyrostabilisers are studied. The combination of single- and two-axes gyrostabilisers allows to construct such a MAP which meets modern requirements best of all and thus solves all the complex of tasks accompanying the production of the most promising MSS systems.

The third chapter is devoted to the MAP gyrostabilisers linear theory. Basic operational modes and the succession of their change is investigated in accordance with the MAP functions. The gyrostabiliser generalised functional scheme is given. Linear mathematical models of the gyrostabiliser subsystems in the form of differential equations of the generalised scheme motion comprising all possible scheme decisions are obtained. The equations are presented in the operator form and they can be written down in relation to any measuring system of co-ordinates by use of simple modifications. The choice of the operators parameters and some assumptions are justified thus making it possible to simplify mathematical models of both subsystems and the gyrostabiliser in general.

The fourth chapter describes the MAP gyrostabiliser subsystems synthesis on the basis of schemes which are given preference to in the previous chapter. Proofs are given for utilising the method of dynamic synthesis of linear continuous automatically regulated systems for the gyrostabiliser levelling subsystems in the mode accurate and approximate adjustment. Basic criteria for the subsystems synthesis in each operational mode are defined. It is found necessary to utilise correction contours and to justify such structure and parameters choice which could provide the satisfactory
quality of the transition process with the time required for transferring the MAP platform and the error of its keeping in the horizon plane.

To perform the modes of the satellite TV-signal acquisition and tracking an extreme system, i.e. a non-linear subsystem of search and keeping the FAA directioning to the maximum satellite signal received, is included in the MAP gyrostabiliser azimuth channel structure. The number of assumptions adopted in the second chapter for the gyrostabiliser mathematical model linearisation can also be used for the analysis and synthesis of the levelling subsystem with the satisfactory degree of accuracy, but they are rather approximate when used in the extreme system. There arises the necessity to produce a tool for checking and correcting the methods and results of the analysis for the subsystems of search, acquisition and tracking with the help of the digital mathematical modelling method. To synthesise these subsystems an algorithm is elaborated and a software is written in Pascal. The software is based on corresponding equations of dynamics in which the starting values of the linearized model and the disturbing effects in actual exploitation practice are given. To solve the equation the Merson five-stage method of the fourth order of accuracy is used. Error calculations are estimated by use of the Runge method. Thus the optimisation procedure for the subsystems of search, acquisition and tracking the maximum of the satellite TV-signal is elaborated according to the criterion of minimising the time period for keeping the FAA position in the satellite direction with a required error in case of real external disturbances.

In the fifth chapter, the MAP gyrostabiliser errors divided into two large groups, i.e. procedural and instrumental, are described. The major procedural error is that of the accelerometers of the levelling subsystem caused by the acceleration of the transfer motion when the vessel exercises rolling. The thesis gives the analysis of this error to make it possible to minimise it through the dynamic synthesis procedure. To scrutinise the procedure error for the mode of the platform accurate adjustment into the horizon its motion equations are formulated and the influence of the angular velocity of the Earth’s rotation, the rate gyroscope zero drift and external disturbances on the levelling process are estimated.
Instrumental errors are caused by the inaccuracy accompanying the production, assembling and adjustment of the details and units as well as the gyrostabiliser itself. The MAP gyrostabiliser mechanical part contains two main channels: the channel of the FAA elevation angle and the FAA azimuth angle channel. That is why the influence of technological errors in their production is studied separately and the way of decreasing these errors are investigated.

The sixth chapter is devoted to the experimental studying of the demonstrator and to the pilot models test. To confirm the results of the theoretical research and to treat the proposed technical decisions for producing the MAP gyrostabiliser for promising MSS there were conducted experimental investigations and laboratory-stand tests of the MAP gyrostabiliser demonstrator with the antenna diameter of 120 cm by the Joint-stock company GYROOPTICS and the German firm RST Raumfahrt Systemtechnik GmbH. The MAP pilot models with the antenna diameter of 60 cm have been constructed. Experimental investigations completely confirmed the basic theoretical conclusions and the recommendations arising from them, and the tests allowed to conduct constructive and technological processing of the MAP gyrostabiliser elements and units.

In the Conclusions the major results of the investigations performed are formulated.

In Fig. 1.2 the structure and the alignment of the thesis main sections are given.

1.5 Verifications

The main principles and the results were reported about and discussed at the IIInd All-Union Conference “Gyroscopic Systems and Their Elements” (The Polytechnic Institute, Tula, 1989), the VIIth Intersectoral Scientific and Technical Conference commemorated to N.N.Ostryakov, (The “Azimuth” Scientific Productive Amalgamation, St.Petersburg, 1990), the VIIIth Scientific and Technical Conference (The Higher Artillery Engineering School, Tula, 1991), the Sectional Scientific and Technical Conference (The
Fig. 1.2. Alignment of the thesis basic sections

The results of investigation are reflected in 11 articles and papers published; among them is the author’s certificate to the invention, one patent, two priority references to the invention. There are also 7 articles published and 5 scientific research reports.

The materials of the thesis are used and adopted at the GYROOPTICS Co. Ltd., JSC “EDB Temp”, JSC LOMO enterprises and in the Russian scientific-research centre “The State Optic Institute named after Vavilov”. The adoption results are corroborated by corresponding statements.
Principles of Structure

The Earth's artificial satellites on the geostationary orbit play a leading role in organising satellite communication systems. As the possibilities of increasing the geostationary orbit capacity are limited, further development of satellite communication systems with narrow bands and numerous repetitions of working frequencies, the utilisation of frequencies of higher bands and the installation of a satellite cluster or a large orbit platform in the same orbit position would provide a more complete employment of its resources in the nearest future [1, 2]. Working Earth's stations and those ones which are being designed use frequency ranges from 4 up to 6 GHz, or from 10 up to 14 GHz, and from 20 up to 30 GHz, and among them medium frequencies from 10 up to 14 GHz with linearly polarised signals are employed most often. The frequency range from 20 up to 30 GHz is considered to be a perspective one as it allows to use small-sized antennas with a large amplification factor, and such antennas can not be used for the frequency band of 4 to 6 GHz because a comparatively wide radiation pattern causes mutual interference with other communication systems.
2.1 Peculiarities of Satellite TV-Signal Reception on Board Sea and River Vessels

The artificial satellite position in space in respect to the Earth is unstable because of the Earth's non-sphericity, the inaccuracy of placing the satellite on the orbit as well as because of the varying influence of the Moon and the Sun gravitational forces on it. The satellite performs complicated annual and daily fluctuations, which look like a changing "eight" from the Earth. The instability of satellite position on the orbit is regulated by international conventions. At present, the instability of ±0,1° is considered to be a permissible one, and on the geostationary orbit it corresponds to space fluctuations within 150 km. This peculiarity is to be taken into account when designing MSS.

As MSS operate mostly in the centimeter wave band, parabolic antennas with antenna feeds of various constructions are utilised, and lately even planar antennas have been used. The areas of such antennas determine their amplification factor $G$. For parabolic antennas $G$ can be calculated according to the formula:

$$G = \left( \frac{\pi D}{\lambda} \right)^2$$  \hspace{1cm} (2.1)

where $D$ is an effective antenna diameter measured in cm and $\lambda$ is the wave length in cm.

When designing MAP the antenna radiation pattern (side and major lobes) and cross-polarisation properties are the most important parameters, one of the reasons being the availability of neighbouring satellites on the orbit working in the overlapping channels and the use of varied polarisation on the same satellite relay station to economise the frequency spectrum. The width of the major lobe of the parabolic antenna radiation pattern on the signal attenuation (-3dB) is defined with the formula:
\[ \Theta \approx \frac{\lambda}{D}. \] (2.2)

However, it is possible to determine the values of \( G \) and \( \Theta \) more precisely only experimentally, as they greatly depend on the accuracy of the antenna shape, its working surface irregularities and the antenna feed type. To estimate the sensitivity of the receiving units the trend is to utilise the antenna amplification factor in ratio to complete noise temperature, measured in Kelvin degrees, for it defines the quality of the receiving equipment. Noises conditioned by the space, the atmosphere and the Earth are taken account of in the centimeter wave band. External noises received by the antenna refer to its properties and they are equivalent to antenna noises.

The territory subjected to satellite TV-casting is usually displaced from the equator and is "egg-shaped" or has a more complicated form. The level of the useful signal lowers as the distance from the centre of the satellite relay station aiming on the Earth's surface increases, and demands are made on the size of the receiving antenna useful area (Fig. 2.1).

Because of the influence of local meteorological conditions, the relief and of some other factors, there is no direct dependence between the size of the receiving antenna useful area and the theoretical distribution of the signal useful power. For example, the signal received by the parabolic antenna with the effective dish area of 120 cm can be best of all described with the help of the standardised linear function which has been received experimentally in Central Europe:

\[ F(x) = \frac{V_o \cdot 2,15 \cdot \sin \left( \frac{\pi \cdot x}{1,55^\circ} \right)}{\pi \cdot x \cdot 1,55^\circ}, \] (2.3)
Fig. 2.1. Dependence of the receiving parabolic antenna dish diameter on the change of the EUTELSAT II-F3 signal level

where: $\chi$ is FAA position in respect to the direction to the satellite measured in minutes of arc, $V_o$ is a constant characterising electric properties of the amplifying converting path of the satellite signal received, measured in voltage units. The function chart when $V_o = 2V$ is given in Fig. 2.2.

The chart peak value in Fig. 2.2 corresponds to the exact FAA direction to the satellite. To receive a satellite TV-picture of a high quality the FAA position is to correspond to that part of the chart which is higher than (-3dB) and the antenna polarisation surface is to coincide with the corresponding polarisation surface of the signal from the satellite relay station.
Fig. 2.2. Dependence of the received satellite signal amplitude on the FAA position in relation to the satellite direction

In case the polarisation surfaces mentioned do not coincide on $\delta$ angle, one can observe the received signal power lowering, it is characterised by the loss cosine (cos$\delta$) and can be defined through the expression:

$$\cos^2 \delta \approx \frac{P_1}{P_2} \approx \frac{E_1^2}{E_2^2}, \quad (2.4)$$

in which $E_1, P_1$ correspond to the electric field intensity and the power of the signal received, $E_2, P_2$ correspond to the maximum intensity of the electric field and the power of the relay station signal. If the polarisation surfaces mismatch up to $\pm30^\circ$ the level of the received signal lowering (losses) would be - 1.25 dB, the expression runs:
\[ \Delta = 10 \lg \cos^2 \delta. \] (2.5)

If satellite signals are received on board the sea and river vessels possessing limitations on rolling and pitching up to \( \pm 30^\circ \), losses resulting from polarisation planes mismatch do not significantly affect the TV-picture quality in those regions which are close to the point of the satellite relay station aiming; however, they become really prominent on the edges of the enclosure spot, where the level of the received useful signal becomes commensurable with the loss level. In some cases this source of losses can be compensated by the increase of the useful area of the receiving antenna.

Permissible errors in FAA orientation in the satellite direction depend on the diameter of the receiving parabolic antenna mirror (formula 2.2), they are given in Table 2.1.

<table>
<thead>
<tr>
<th>( \lambda ), cm (Hz)</th>
<th>D, cm</th>
<th>( \Theta ), arc</th>
<th>Permissible errors of FAA orientation ((3\sigma)), arc</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7 - 2.1 (10 -14)</td>
<td>60</td>
<td>2.58</td>
<td>((\pm)1.0)</td>
</tr>
<tr>
<td>2.7 - 2.1 (10 -14)</td>
<td>100</td>
<td>1.55</td>
<td>((\pm)0.8)</td>
</tr>
<tr>
<td>2.7 - 2.1 (10 -14)</td>
<td>120</td>
<td>1.29</td>
<td>((\pm)0.6)</td>
</tr>
<tr>
<td>2.7 - 2.1 (10 -14)</td>
<td>300</td>
<td>0.52</td>
<td>((\pm)0.2)</td>
</tr>
<tr>
<td>2.7 - 2.1 (10 -14)</td>
<td>500</td>
<td>0.31</td>
<td>((\pm)0.1)</td>
</tr>
</tbody>
</table>

Table 2.1. FAA orientation errors dependence on the antenna diameter

FAA angular orientation is defined in two ways: by the angle of place \( \phi \) and the angle of elevation \( \beta \). Both angles depend on the geographical position of the presupposed place of reception on the Earth's surface and on the longitude of the satellite aiming point on the geostationary orbit and they can be determined with formula [3]:
\[ \beta = \arctg \frac{\cosh - 0.15105}{\sinh \frac{\tan(S - L)}{\sin B}} \]  
(2.6)

\[ \varphi = 180^\circ + \arctg \frac{\tan(S - L)}{\sin B} \]  
(2.7)

where \( h = \arccos[\cos(S - L) \cdot \cos B] \).

S is the longitude of the satellite aiming point on the geostationary orbit measured in the minutes of arc, L and B are the longitude and the latitude of the pre-supposed reception place of the satellite TV-signal measured in the minutes of arc. The angle of the place is reckoned from the North clockwise. If the satellite is above the Eastern hemisphere the longitude of its aiming point on the geostationary orbit is with a negative sign.

To determine the angles of the FAA place and elevation quickly special diagrams and tables computed for large populated areas on the territory subjected to satellite telecasting are used. For most European satellites these angles vary within 15° to 50° [4]. Thus, if the place of reception changes so must change the FAA angular orientation according to the expression (2.6) which is defined by the difference between the satellite S and the object L geographical longitude values and the value of latitude of the reception place B. Each of these parameters can be represented as a sum of the ideal value \( B_0, L_0, S_0 \) and the error of its measurement \( \Delta B, \Delta L, \Delta S \):

\[ B = B_0 + \Delta B, \]

\[ L = L_0 + \Delta L, \]  
(2.8)

\[ S = S_0 + \Delta S. \]

The expressions (2.6) used to determine the values of angles \( \beta \) and \( \varphi \) are the functions of three parameters B, L and S, which with regard to expression (2.8) after expansion into a multiple Taylor series and neglect the remainder, will look like this:
\[ \varphi(S_o + \Delta S, L_o + \Delta L, B_o + \Delta B) = \varphi(S_o, L_o, B_o) + \frac{\partial \varphi}{\partial S_o} \cdot \Delta S + \frac{\partial \varphi}{\partial L_o} \cdot \Delta L + \frac{\partial \varphi}{\partial B_o} \cdot \Delta B, \]

\[ \beta(S_o + \Delta S, L_o + \Delta L, B_o + \Delta B) = \beta(S_o, L_o, B_o) + \frac{\partial \beta}{\partial S_o} \cdot \Delta S + \frac{\partial \beta}{\partial L_o} \cdot \Delta L + \frac{\partial \beta}{\partial B_o} \cdot \Delta B. \] (2.9)

The results of the proceeding modification allow to make up the expression for the total error of the FAA location in the azimuth \( \Delta \varphi \) as well as the expression for the total error of the FAA elevation error \( \Delta \beta \) to the satellite:

\[ \Delta \varphi = \varphi(S_o + \Delta S, L_o + \Delta L, B_o + \Delta B) - \varphi(S_o, L_o, B_o) = \]

\[ = \frac{\partial \varphi}{\partial S_o} \cdot (\Delta S + \Delta L) + \frac{\partial \varphi}{\partial B_o} \cdot \Delta B = \]

\[ = \frac{\sin B_o}{1 - \cos^2 B_o \cdot \cos^2(S_o - L_o)} \cdot (\Delta S + \Delta L) - \]

\[ + \frac{\cos B_o \cdot \sin(S_o - L_o) \cdot \cos(S_o - L_o)}{1 - \cos^2 B_o \cdot \cos^2(S_o - L_o)} \cdot \Delta B, \] (2.10a)
\[ \Delta \beta = \beta(S_o + \Delta S, L_o + \Delta L, B_o + \Delta B) - \beta(S_o, L_o, B_o) = \]
\[ = \frac{\partial \beta}{\partial S_o} \cdot (\Delta S + \Delta L) + \frac{\partial \beta}{\partial B_o} \cdot \Delta B = \]
\[ = \frac{1}{(1,023 - 0,302 \cdot \cos(S_o - L_o) \cdot \cos B_o)} \times \]
\[ \times \frac{1}{\sqrt{1 - \cos^2(S_o - L_o) \cdot \cos B_o}} \times \]
\[ \times (-\cos B_o \cdot \sin(S_o - L_o) \cdot (1 + 0,15105 \cdot \cos B_o \cdot \cos(S_o - L_o))) \times \]
\[ \times (\Delta S + \Delta L) + \sin B_o \cdot \cos(S_o - L_o) \times \]
\[ \times (1 - 0,15105 \cdot \cos B_o \cdot \cos(S_o - L_o)) \cdot \Delta B). \]

According to (2.10) the total error of the FAA elevation angle \( \Delta \beta \) includes both the longitudinal \( (\Delta S + \Delta L) \) and the latitudinal \( \Delta B \) components with there weight coefficients \( |K_{\Delta B}^{\Delta \beta}| \) and \( |K_{(\Delta S+\Delta L)}^{\Delta \beta}| \):

\[ K_{(\Delta S+\Delta L)}^{\Delta \beta} = -\frac{\cos B_o \cdot \sin(S_o - L_o)}{(1,023 - 0,302 \cdot \cos(S_o - L_o) \cdot \cos B_o)} \times \]
\[ \times \frac{(1 + 0,15105 \cdot \cos B_o \cdot \cos(S_o - L_o))}{\sqrt{1 - \cos^2(S_o - L_o) \cdot \cos B_o}}, \]  
(2.11)

\[ K_{\Delta B}^{\Delta \beta} = \frac{\sin B_o \cdot \cos(S_o - L_o)}{(1,023 - 0,302 \cdot \cos(S_o - L_o) \cdot \cos B_o)} \times \]
\[ \times \frac{(1 + 0,15105 \cdot \cos B_o \cdot \cos(S_o - L_o))}{\sqrt{1 - \cos^2(S_o - L_o) \cdot \cos B_o}}. \]  
(2.12)

The dependencies of weight coefficients on the longitudinal \( |K_{(\Delta S+\Delta L)}^{\Delta \beta}| \) and latitudinal \( |K_{\Delta B}^{\Delta \beta}| \) errors on the geographical latitude of the place where the
satellite signal $|B_o|$ is received and on the differences between the satellite longitude value and the reception place longitude value $|S_o - L_o|$ is shown in Fig. 2.3 and Fig. 2.4. For instance, the coverage area of the ASTRA 1A satellite (11,20 GHz - 11,45 GHz), ASTRA 1B (11,45 GHz - 11,70 GHz) located on 19,2°E lies between 25°W and15°E, 35°N and 65°N. This reception area with the level of 42 dBW is drawn on Fig. 2.3 and Fig. 2.4 for each of the weight coefficients. From these figures one could see the dominant influence of the error longitudinal component when forming the FAA elevation angle total error. For example, for $|B_o| = 65°$ and $|S_o - L_o| = 5°$ the weight coefficient of the $K^{Δφ}_{(AS+DL)}$ latitudinal error is 20,5 as large as the $K^{Δφ}_{ΔB}$ longitudinal error weight coefficient.

The total error $Δφ$ of the FAA direction to the satellite in the azimuth corresponding to (2.10) comprises both the latitudinal $ΔB$ and the longitudinal $(ΔS + ΔL)$ components with their weight coefficients $K^{Δφ}_{ΔB}$ and $K^{Δφ}_{(ΔS+ΔL)}$:

$$K^{Δφ}_{ΔB} = \frac{-\cos B_o \cdot \sin(S_o - L_o) \cdot \cos(S_o - L_o)}{1 - \cos^2 B_o \cdot \cos^2(S_o - L_o)}.$$ (2.13)

$$K^{Δφ}_{(ΔS+ΔL)} = \frac{\sin B_o}{1 - \cos^2 B_o \cdot \cos^2(S_o - L_o)}.$$ (2.14)

The dependencies of weight coefficients of longitudinal $K^{Δφ}_{(ΔS+ΔL)}$ and $K^{Δφ}_{ΔB}$ errors on the geographical latitude of the $|B_o|$ satellite signal reception place and on the differences between the longitude orbit and the reception place longitude $|S_o - L_o|$ are given in Fig. 2.5 and Fig. 2.6. Fig. 2.5 and Fig. 2.6 show the dominant influence of the longitudinal error component in comparison to the latitudinal one when forming the total error of the FAA direction to the ASTRA satellite in the azimuth.
Fig. 2.3. Weight coefficients for the longitude and latitude components composing the FAA elevation angle total error and depending on the satellite signal reception place latitude.
Fig. 2.4. Weight coefficients for the longitude and latitude components composing the FAA elevation angle total error and depending on the difference between the reception place longitude and that of the satellite.
Fig. 2.5. Weight coefficients for the latitude and longitude components composing the FAA azimuth angle total error and depending on the difference between the reception place longitude and that of the satellite.
Fig. 2.6. Weight coefficients for the latitude and longitude components composing the F4A azimuth angle total error and depending on the satellite signal reception place latitude.
For instance, for $|B_o| = 65^\circ$ and $|S_o - L_o| = 5^\circ$ the weight coefficient of the longitudinal error $K_{(\Delta S + \Delta L)}^{\Delta \phi}$ is 22 times as much as the weight coefficient of the latitudinal one $K_{\Delta \beta}^{\Delta \phi}$.

The values of the longitudinal and latitudinal components of the total error $\Delta \phi$ of the FAA direction to the satellite in the azimuth are to satisfy the condition:

$$\Delta \phi_{\text{max}} > \sqrt{\left(K_{\Delta \beta}^{\Delta \phi}\right)^2 \cdot (\Delta B)^2 + \left(K_{(\Delta S + \Delta L)}^{\Delta \phi}\right)^2 \cdot (\Delta S + \Delta L)^2}, \quad (2.15)$$

where $\Delta \phi_{\text{max}}$ is the maximum permissible error of the FAA orientation $(3\sigma)$.

The values of the longitudinal and latitudinal components of the total error of the FAA elevation angle on the satellite $\Delta \beta$ should satisfy the condition:

$$\Delta \beta_{\text{max}} > \sqrt{\left(K_{\Delta \beta}^{\Delta \beta}\right)^2 \cdot (\Delta B)^2 + \left(K_{(\Delta S + \Delta L)}^{\Delta \beta}\right)^2 \cdot (\Delta S + \Delta L)^2}, \quad (2.16)$$

where $\Delta \beta_{\text{max}}$ is the maximum permissible error of the FAA orientation $(3\sigma)$.

As given in Table 2.1 the value of the permissible error comes to $\Delta_{\text{max}} < 40^\circ$ for the parabolic antenna with the dish diameter of 120 cm. If to assume that in (2.15) there exists the possibility of precise determination of the place latitude where the signal from ASTRA is received, when, for example, $\Delta B = 0$ for the point $|B_o| = 35^\circ, |S_o - L_o| = 5^\circ$, and to neglect the satellite fluctuations on the geostationary orbit, when $\Delta S = 0$, then $\Delta \varphi_{\text{max}} < 40^\circ$, $|K_{(\Delta S + \Delta L)}^{\Delta \varphi}| = 1.7$ and $\Delta L < 23.5^\circ$. In case it is possible to determine precisely in (2.16) the longitude of the similar place of receiving the signal from ASTRA, when $\Delta L = 0$, and to neglect the satellite fluctuations on the
geostationary orbit, when $\Delta S = 0$, then $\Delta \beta_{\text{max}} < 40'$, $|K_{\Delta \beta}^{\Delta S}| = 1,125$ and $\Delta B < 36'$. If $\Delta L = \Delta B$, i.e. when errors in determining the geographical latitude and the longitude of the similar place where the ASTRA signal is received are equal, and the satellite fluctuations on the geostationary orbit $\Delta S = 0$ are neglected, then $\Delta B < 20'$ and $\Delta L < 20'$.

If to take account of the fact that the satellite positioning instability on the geostationary orbit is of the order of $\pm 6'$, then the permissible errors in determining the geographical longitude and latitude values for the similar satellite signal reception place will be 2' less and they will come to $\Delta B < 18'$, $\Delta L < 18'$, accordingly. That is why in order to provide the required FAA angular orientation as well as the antenna polarisation plane on board the sea and river vessels, it is necessary to possess information about the current location of the object with the error less than $\pm 0,3'$. As a rule, such a kind of information is available for navigation tasks solving.

If MAP is installed on board the sea and river vessels, it is necessary to isolate FAA from external disturbances from the base in relation to the geographical system of co-ordinates with errors, less then those given in Table 2.1. The angular position of the object of such type is characterised with the relative bearing $\varphi_k$, the trim $\nu$ and the heeling $\vartheta$ angles in the geographical system of co-ordinates $\zeta \eta \xi O$ in which, as given in Fig. 2.7, the $O \zeta$ axis is in line with the location vertical, and the $O \xi$ axis is at a tangent to the reception place parallel from West to East, $g$ is the gravitational force acceleration, $\Omega_v$ is the vertical and $\Omega_h$ is the horizontal components of the angular velocity of the Earth rotation and $j_{X_0}, j_{Y_0}, j_{Z_0}$ are the projections of linear accelerations of the base resulting from its motion.

The values and properties of the basic external factors when MAP is employed on board the sea and river vessels as the overdeck equipment are given in Table 2.2. The task of controlling the FAA relative angular position and its isolation from the base angular motion can be solved by fitting the receiving antenna in the gimbal mount. Single-, two- and three- axes mounts
can be used to suit the type of the object and the permissible FAA orientation error. The analysis of all possible kinematic schemes of such a mount with regard to the base motion peculiarities and the constructive realisation is given in the following chapter.

Fig. 2.7. The angular orientation of the object with MSS and the FAA in the geographical system of co-ordinate
<table>
<thead>
<tr>
<th>The external factor</th>
<th>The properties of the external factor</th>
<th>The value of the external factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sinus vibration</td>
<td>Acceleration amplitude, m/s²(g)</td>
<td>9.81 (1) 4-33</td>
</tr>
<tr>
<td></td>
<td>Frequency range, Hz</td>
<td></td>
</tr>
<tr>
<td>2. The mechanical impact of a single effect (the wave impact)</td>
<td>The peak impact acceleration, m/s²(g) The duration of the impact acceleration effect, ms</td>
<td>2 (0.2) - along the longitudinal and transverse axes 4.9 (0.5) - along the vertical axis 0.5 - 2.0</td>
</tr>
<tr>
<td>3. Motion:</td>
<td>Motion amplitude, arc Period, s</td>
<td>±30 (The maximum tan acceleration 0.5g) 8</td>
</tr>
<tr>
<td>- rolling</td>
<td></td>
<td>±15 (The maximum tan acceleration 0.5g) 6</td>
</tr>
<tr>
<td>- pitching</td>
<td>Motion amplitude, arc Period, s</td>
<td></td>
</tr>
<tr>
<td>4. Slopes (in motion):</td>
<td>The maximum angle of slope, arc</td>
<td>15</td>
</tr>
<tr>
<td>- long</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- short (up to 3 min)</td>
<td>The maximum angle of slope, arc</td>
<td>30</td>
</tr>
<tr>
<td>5. Yawing</td>
<td>Amplitude, arc Period, s</td>
<td>±8 50</td>
</tr>
</tbody>
</table>

*Table 2.2. The basic factors influencing the MSS on board the sea and river vessels*
2.2 Gyrostabilisers Electro-Kinematic Schemes

2.2.1 Single-Axis Gyrostabilisers

Let us study one of the possible ways of solving the task of controlling the FAA position in the satellite direction and its isolation from the basement angular motion by installing the antenna in the single-axis gimbal mount with the vertical frame position as is shown in Fig. 2.8.

![Diagram of single-axis gimbal mount](image)

*Fig. 2.8. Kinematic scheme of the antenna single-axis gimbal mount with a vertical disposition of the frame*

In so doing we will connect the antenna and the $O'_aY'_aZ'_aX'_a$ co-ordinate system so that the $O'_aY'_a$ axis direction might coincide with the FAA direction. In this case the FAA positioning in the co-ordinate system, which is connected with the gimbals mount frame positioning $O'_pY'_pZ'_pX'_p$ and which coincides with the object co-ordinate system $O_oY_oZ_oX_o$ from the
outset, can be determined with the angle of the actual azimuth $\varphi'$ and that of the actual elevation $\beta' = \beta$, the latter being set equal to the rated angle with the accuracy determined by the instrumental error for a definite region of the satellite signal reception. The actual elevation angle $\beta'$ can be regulated in accordance with the object geographical position changes, however, it can not be controlled in accordance with the object dynamics. The transformation of the $O_p'Y_p'Z_p'X_p'$ co-ordinate system into that of the $O_a'Y_a'Z_a'X_a'$ can be represented by the actual matrix $L = [l_{ik}]$, $i=k=3$ looking like the following:

$$
L = \begin{bmatrix}
\cos \beta' \cdot \cos \varphi' & \cos \beta' \cdot \sin \varphi' & -\sin \beta' \\
-\sin \varphi' & \cos \varphi' & 0 \\
\sin \beta' \cdot \cos \varphi' & \sin \beta' \cdot \sin \varphi' & \cos \beta'
\end{bmatrix}.
$$

(2.17)

To analyse the kinematic scheme of a single-axis gimbal mount and to obtain an expression determining the law of controlling the frame of a single-axis gimbal mount when the basement is disturbed, it is necessary to obtain the matrix $A = [a_{ik}]$, $i,k=3$ which describes the transition from the $O_oY_oZ_oX_o$ co-ordinate system connected with the object to the co-ordinate system connected with the antenna $O_a'Y_a'Z_a'X_a'$. The transition from the object co-ordinate system $O_oY_oZ_oX_o$ to the one which is connected with the antenna $O_a'Y_a'Z_a'X_a'$ described with the help of matrix $A$ can be represented by the following matrix expression:

$$
A = L \cdot D.
$$

(2.18)

In this case the matrix $D = [d_{ik}]$, $i,k=3$ characterises the transition from the geographical co-ordinate system $O_\eta \xi \zeta$ to the one connected with the mobile object $O_oY_oZ_oX_o$, as shown in Fig. 2.7, and it has the following view:
\[
D = \begin{bmatrix}
\cos \varphi \cdot \cos \varphi_k & \cos \varphi \cdot \sin \varphi_k & -\sin \varphi \\
\sin \varphi \cdot \sin \varphi_k & \sin \varphi \cdot \sin \varphi_k + \cos \varphi \cdot \cos \varphi_k & \cos \varphi \cdot \sin \varphi \\
+ \cos \varphi \cdot \sin \varphi_k & + \cos \varphi \cdot \cos \varphi_k & \cos \varphi \cdot \cos \varphi_k \\
\cos \varphi_k \cdot \cos \varphi & \\
+ \sin \varphi \cdot \sin \varphi_k & \\
& \cos \varphi \end{bmatrix}
\]

(2.19)

Matrix \( C = [c_{ik}] \), \( i, k = 3 \), by means of the azimuth angle \( \varphi \) and the elevation angle \( \beta \), describes the resulting transition from the geographical co-ordinate system \( O\eta\xi\zeta \) to the \( O_aY_aZ_aX_a \) system connected with the parabolic receiving antenna mounted on an immobile basement so that the \( O_aY_a \) axis direction should coincide with the FAA direction, as it is shown in Fig. 2.7. It looks like:

\[
C = \begin{bmatrix}
\cos \beta \cdot \cos \varphi & \cos \beta \cdot \sin \varphi & -\sin \beta \\
-\sin \varphi & \cos \varphi & 0 \\
\sin \beta \cdot \cos \varphi & \sin \beta \cdot \sin \varphi & \cos \beta 
\end{bmatrix}
\]

(2.20)

Matrixes \( D = [d_{ik}] \) and \( L = [l_{ik}] \) are square ones of the third order \( i, k = 3 \) and when inserting (2.19) and (2.17) into (2.18) we shall obtain an expression for matrix \( A = [a_{ik}] \) (2.18) the elements of which can be calculated through solving the system of nonhomogeneous linear equations by means of the undetermined coefficient methods.

The law of controlling the single-axis gimbal mount frame results from the requirement of transforming the \( O_aY_a' \) axis into the \( O_aY_a \) one and from fulfilling the condition of equality of the elements of the matrixes \( A \) and \( C \) first lines:

\[
\begin{align*}
\begin{cases}
a_{11} = c_{11}, \\
a_{12} = c_{12}, \\
a_{13} = c_{13},
\end{cases}
\end{align*}
\]

(2.21)

where:
\[ c_{11} = \cos \beta \cdot \cos \varphi; \]
\[ c_{12} = \cos \beta \cdot \sin \varphi; \]
\[ c_{13} = -\sin \beta; \]
\[ a_{11} = \cos \beta' \cdot \cos \varphi' \cdot \cos \psi \cdot \cos \varphi_k + \]
\[ + \cos \beta' \cdot \sin \varphi' \cdot (\sin \vartheta \cdot \sin \psi \cdot \cos \varphi_k - \sin \varphi_k \cdot \cos \vartheta) - \]
\[ + \sin \beta' \cdot (\cos \varphi_k \cdot \cos \vartheta \cdot \sin \psi + \sin \vartheta \cdot \sin \varphi_k); \]
\[ a_{12} = \cos \beta' \cdot \cos \varphi' \cdot \cos \psi \cdot \sin \varphi_k + \]
\[ + \cos \beta' \cdot \sin \varphi' \cdot (\sin \vartheta \cdot \sin \psi \cdot \sin \varphi_k + \cos \vartheta \cdot \cos \varphi_k) - \]
\[ + \sin \beta' \cdot (\cos \vartheta \cdot \sin \psi \cdot \sin \varphi_k - \sin \vartheta \cdot \cos \varphi_k); \]
\[ a_{13} = -\cos \beta' \cdot \cos \varphi' \cdot \sin \psi + \]
\[ + \cos \beta' \cdot \sin \varphi' \cdot \cos \psi \cdot \sin \vartheta - \sin \beta \cdot \cos \vartheta \cdot \cos \psi. \]

The \( \gamma \) angle between two directed in space sections, i.e. the \( O_a Y_a \) axis (Fig. 2.7) and the \( O'_a Y'_a \) one (Fig. 2.8) corresponding to true and actually realised FAA positioning accomplished with the help of the single-axis gimbal mount whose direction is determined by triples of elements of the matrixes A and C (2.21) first lines, is a control error and it is calculated with the following formula:

\[ \cos \gamma = a_{11} \cdot c_{11} + a_{12} \cdot c_{12} + a_{13} \cdot c_{13}. \] (2.22)

After substituting the first elements of the A and L matrixes first lines, the expression for the kinematic error will look like this:

\[ \cos \gamma = \cos \beta \cdot \cos \varphi \cdot (\cos \beta' \cdot \cos \varphi' \cdot \cos \psi \cdot \cos \varphi_k + \]
\[ + \cos \beta' \cdot \sin \varphi' \cdot (\sin \vartheta \cdot \sin \psi \cdot \cos \varphi_k - \sin \varphi_k \cdot \cos \vartheta) - \]
\[ + \sin \beta' \cdot (\cos \varphi_k \cdot \cos \vartheta \cdot \sin \psi + \sin \vartheta \cdot \sin \varphi_k)) + \]
\[ + \cos \beta \cdot \sin \varphi \cdot (\cos \beta' \cdot \cos \varphi' \cdot \cos \psi \cdot \sin \varphi_k + \]
\[ + \cos \beta' \cdot \sin \varphi' \cdot (\sin \vartheta \cdot \sin \psi \cdot \sin \varphi_k + \cos \vartheta \cdot \cos \varphi_k) - \]
\[ + \sin \beta' \cdot (\cos \vartheta \cdot \sin \psi \cdot \sin \varphi_k - \sin \vartheta \cdot \cos \varphi_k)) - \]
\[ + \sin \beta \cdot (\cos \beta' \cdot \sin \varphi' \cdot \cos \psi \cdot \sin \vartheta - \]
\[ + \cos \beta' \cdot \cos \varphi' \cdot \sin \psi - \sin \beta' \cdot \cos \vartheta \cdot \cos \psi). \] (2.23)
To conduct further analysis as well as trigonometric transformation of the (2.23) expression, let us consider the relative bearing of the object $\varphi_k$ as the sum of two components, $\varphi_{k_0}$ and $\Delta \varphi_k$. The first component $\varphi_{k_0}$ represents the relative bearing between the longitudinal axis of the MAP object and the direction to the North. This component can be regarded either as a constant for a more prolonged time period. The second component $\Delta \varphi_k$ represents a changing in time variable which is identical to the yawing angle. In this case the expression for the object relative bearing can be represented like the following:

$$\varphi_k = \varphi_{k_0} + \Delta \varphi_k.$$  \hfill (2.24)

On the basis of 2.2 and the expression (2.6) used for calculating the $\varphi_k, \varphi, \varphi', \vartheta, \psi, \beta, \beta'$ the demarcation lines of possible changes can be determined as:

$$\varphi, \varphi' = \pm 360^\circ; \ \vartheta, \psi = \pm 45^\circ; \ \beta = \beta' \in \left[ +10^\circ \ldots +90^\circ \right].$$  \hfill (2.25)

Assuming that the object is not disturbed along the axes of rolling, trimming and yawing, i.e. $\psi = \vartheta = \Delta \varphi_k = 0$, the error expression will look as follows:

$$\cos \gamma = \cos^2 \beta \cdot \cos (\varphi - (\varphi' + \varphi_{k_0})) + \sin^2 \beta.$$  \hfill (2.26)

Using the possibility of unlimited controlling and operating the frame of a single-axis gimbal mount along the azimuthal axis, the condition of minimising the kinematic error $\gamma$ can formulated like this:

$$\lim_{\gamma \to 0} \cos \gamma = 1.$$  \hfill (2.27)

(2.27) results in the requirement of operating the frame of a single-axis gimbals mount in the azimuth:

$$\varphi' = \varphi - \varphi_{k_0}.$$  \hfill (2.28)
Accounting for the dynamic error $\Delta \varphi_k \neq 0$ when operating the frame of a single-axis gimbal mount in the azimuth and the requirement resulting from (2.28), the expression (2.26) can be represented as:

$$\cos \gamma = \cos^2 \beta \cdot \cos \Delta \varphi_k + \sin^2 \beta. \quad (2.29)$$

Having expended the function $f(x) = \cos \Delta \varphi_k$ in a convergence set $|\Delta \varphi_k| < \infty$ into a Taylor series while making use of only first two elements of this expansion and accounting for the order of smallness of the value $x = \Delta \varphi_k$, the kinematic error can be described with the expression:

$$\gamma = \arccos(1 - \cos^2 \beta \cdot \frac{\Delta \varphi_k^2}{2}). \quad (2.30)$$

The dependence of the antenna suspension kinematic error $\gamma$ on the dynamic error $\Delta \varphi_k$ of the control system in the azimuthal channel is shown in Fig. 2.9. When analysing the charts given in Fig. 2.9, it is possible to make a conclusion that the value (quantity) of the kinematic error of the MAP single-axis gimbal mount increases together with the increase of the value of the dynamic error of the mount frame controlling system in the azimuth if the value of the FAA elevation angle to the satellite is constant and if there are no disturbance effects on the axes of roll and trim on the part of a mobile basement. At the same time, the value of the kinematic error of a single-axis gimbal mount also increases when the FAA elevation angle to the satellite decreases. For instance, the kinematic error $\gamma$ for elevation angles $\beta$ between $0^\circ$ and $50^\circ$ for MAP with the dish diameter of 120 cm peaks maximum permissible value of the order of $40'$ if the dynamic error value corresponds to the object angle of yawing between $40'$ and $60'$ correspondingly, and if disturbances coming from the basement in the roll and trim channels are not taken into consideration.
Fig. 2.9. Dependence of gimbal mount kinematic error $\gamma$ on dynamic error of control system in azimuth channel $\Delta \varphi_k$
If the antenna elevation angle $\beta = \beta' = 90^\circ$, the kinematic error of a single-axis gimbal mount tends to zero irrespective of the value of the control system dynamic error in the azimuth and that of the FAA elevation angle to the satellite, but such a situation is possible only theoretically as in actual practice the satellite relay stations aiming point is shifted from the equator.

The kinematic error equation for the MAP single-axis gimbal mount with the frame positioned vertically, when the basement is disturbed in the trim channel, if $\psi = \Delta \psi, \beta = \beta', \vartheta = 0, \varphi = \varphi' + \varphi_k$, looks like this:

$$
\cos \gamma_{\Delta \psi} = \cos^2 \beta \cdot \cos^2 (\varphi - \varphi_k) \cdot \cos \Delta \psi + \\
+ \cos^2 \beta \cdot \sin^2 (\varphi - \varphi_k) + \sin^2 \beta \cdot \cos \Delta \psi.
$$

(2.31)

Analysing the expression (2.31) one can arrive at the conclusion that the kinematic error of the MAP single-axis gimbal mounts for any value of the FAA elevation angle to the satellite regardless of the geographical co-ordinates of the pre-set reception place, comes to its maximum value $\gamma = \Delta \psi$, when the object relative bearing $\varphi_k$ coincides with the designed angle $\varphi$ and determines the FAA direction to the satellite in the azimuth, or when it differs from it by the $\pi$-fold angle, i.e. $\varphi - \varphi_k = \pi \cdot n, n = 0,1,2$.

The equation of the kinematic error of the single-axis gimbal mount for MAP with a vertical frame positioning when the basement is disturbed in the roll channel, when $\vartheta = \Delta \vartheta, \beta = \beta', \psi = 0, \varphi = \varphi' + \varphi_k$, obtains the following view:

$$
\cos \gamma_{\Delta \vartheta} = \cos^2 \beta \cdot \sin^2 (\varphi - \varphi_k) \cdot \cos \Delta \vartheta + \\
+ \cos^2 \beta \cdot \cos^2 (\varphi - \varphi_k) + \sin^2 \beta \cdot \cos \Delta \vartheta.
$$

(2.32)

Analysing the expression (2.32) one can arrive at the conclusion that the kinematic error of the MAP single-axis gimbal mount for any value of the FAA elevation angle to the satellite, irrespective of the pre-set reception place geographical co-ordinates, comes to its maximum $\gamma = \Delta \vartheta$, when the object relative bearing $\varphi_k$ determining the FAA direction to the satellite in
the azimuth, differs from the designed angle value $\varphi$ by the value multiple to $\frac{1}{2} \cdot \pi$, i.e. $\varphi - \varphi_k = \frac{1}{2} \cdot \pi \cdot n, n = 0,1,2$.

The fact that the given kinematic scheme contains no control over the FAA elevation angle imposes significant restrictions on the MAP use on board the mobile object, as for sea and river vessels, the values of disturbance effects $\Delta \theta, \Delta \varphi, \Delta \psi$ in real practice come to values of the order of minutes of arc units and thus exceed the FAA orientation permissible error given in Table 2.1. Judging by the analysis accomplished it is possible to draw a conclusion that the single-axes gimbal mount kinematic scheme does not meet all the requirement imposed on MAP, its usage is rather limited and that's why it is excluded from further consideration because it cannot serve for the purpose of solving the task of controlling the FAA positioning in the satellite direction as well as the task of its isolating from the basement angular motion.

2.2.2 Two-Axes Gyrostabilisers

The second possible way of solving the task of the FAA positioning to the satellite and its isolation from the basement angular motion is to install the antenna in the two-axes gimbal mount. In so doing there exist two possible variants of positioning the mount frame in relation to the basement. One of these variants is the kinematic scheme horizontal plane. At the expense of appearing the second degree of freedom, the problem of controlling the FAA positioning in the satellite direction subjected to the effect of the disturbed basement and in case the MAP object-carrier changes the geographical coordinates of the pre-set satellite signal reception place can be solved. Unfortunately, there appears an error angle $\delta$ between the MAP receiving antenna polarisation planes and the satellite relay station, and this angle changes when the object relative bearing changes. This fact effects the quality of the satellite signal receiving and even causes the picture breakdown, because the object relative bearing $\varphi_k$ varies greatly in accordance with the expression (2.25). This variant of the gimbal mount kinematic scheme is not very widely used, nevertheless it can be employed on MAP.
with circular polarisation, or in the receiving antenna converter with the polarisation plane being controlled with the electronic equipment over a wide range; or if the polarisation plane position is steady and the range of the object relative bearing change is limited, it will be determined with the permissible fall level of the satellite signal received, in accordance with (2.5).

The second variant of the two-axes gimbals mount kinematic scheme is that with the vertical positioning of the mount external frame and the horizontal positioning of the internal frame control axis, as it is shown in Fig. 2.10.

*Fig. 2.10. Kinematic scheme of a two-axes gimbal mount with vertical disposition of external frame and horizontal disposition of internal one*
In this case it is desirable to connect the antenna and the $O'_a Y'_a Z'_a X'_a$ co-ordinate system so that the $O'_a Y'_a$ axis direction might coincide with the FAA direction. The FAA position in the co-ordinate system is connected with the $O'_p Y'_p Z'_p X'_p$ mount frame position, which primarily coincides with the object co-ordinate system $O'_o Y'_o Z'_o X'_o$, and can be determined by the actual azimuth angle $\varphi'$ and the current elevation angle $\beta'$, which, in distinction to the single-axis gimbal mount, can be operated in accordance with the object dynamics and the change of the map object geographical position. Matrix $L = [I_{ik}]$, $i = k = 3$ for a two-axes gimbal mount describing the transition of the $O'_p Y'_p Z'_p X'_p$ co-ordinate system into that of the $O'_a Y'_a Z'_a X'_a$ one is identical to the matrix for a single-axis gimbal mount (2.17). Further steps in conducting the analysis and in obtaining expressions for the law of mount frames operating when the basement is disturbed fully coincide with the analysis given in Section 2.2.1. When solving the system of linear equations (2.21) we get expressions describing the laws of operating the gimbal mount frames, which look like:

\[
\begin{align*}
\varphi' &= \arctg \left( \frac{\cos \beta \cdot \sin \vartheta \cdot \sin \psi \cdot \cos(\varphi - \varphi_k)}{\cos \beta \cdot \cos \vartheta \cdot \cos(\varphi - \varphi_k) + \sin \beta \cdot \sin \psi} + \right) \\
&\quad \left( \frac{\cos \beta \cdot \cos \vartheta \cdot \sin(\varphi - \varphi_k)}{\cos \beta \cdot \cos \vartheta \cdot \cos(\varphi - \varphi_k) + \sin \beta \cdot \sin \psi} - \right) \\
&\quad \left( \frac{\sin \beta \cdot \sin \vartheta \cdot \cos \psi}{\cos \beta \cdot \cos \vartheta \cdot \cos(\varphi - \varphi_k) + \sin \beta \cdot \sin \psi} \right) \\
\beta' &= \arcsin \left( \frac{-\cos \beta \cdot \cos \vartheta \cdot \sin \vartheta \cdot \cos(\varphi - \varphi_k) +}{+ \cos \beta \cdot \sin \vartheta \cdot \sin(\varphi - \varphi_k) + \sin \beta \cdot \cos \vartheta \cdot \cos \psi} \right). 
\end{align*}
\]

The operation of the two-axes gimbal mount in accordance with the expression (2.33) over the azimuth $\varphi'$ and elevation $\beta'$ provides, in principle, retaining the FAA position in the satellite direction under the disturbed basement conditions. Nevertheless, there is an obvious drawback in this gimbals mount scheme which results in the error angle between the
MAP receiving antenna polarisation planes and the satellite relay station. The value of this angle increases with the increase of the FAA elevation angle to the satellite, and the sphere of its possible use narrows. The second disadvantage of this scheme is the necessity to operate the gimbal mount external frame steadily and it also results in a significant increase of the required rated power and the torque of referring the azimuthal controlling channel, especially if the FAA elevation angle to the satellite is large.

2.2.3 Three-Axes Gyrostabilisers

For objects with a practically unlimited radius of action subjected to significant angular disturbances, such as sea vessels, the task of controlling the FAA relative position and its isolation from an object angular motion in the geographical system of co-ordinates can best be solved when using the three-axes gimbal mount. In this case, FAA is specifically oriented in the inertial system of co-ordinates which does not coincide with that of the geographical one because of the Earth’s daily rotation. Thus the satellite position on the geostationary orbit is determined in the geographical co-ordinate system, while FAA is to be oriented in the satellite direction with a permissible error, and that is the reason why there exists a necessity to make the inertial system of co-ordinates coincident with the geographical one. In connection with this, there are two possible variants of the kinematic scheme for constructing a three-axes gimbal mount: the first is when the external mount axis is situated in the vertical plane, and the intermediate and the internal ones in the horizontal one, respectively, and the second is when the external and the intermediate axes are situated in the horizontal plane, while the internal one is in the vertical plane respectively. In both cases, in order to control the FAA elevation angle in accordance with the object’s changing its location in the geographical co-ordinates system it is possible to use an extra axis in respect to which this angle can be regulated [5].

The first variant of the kinematic scheme for a three-axes gimbal mount is shown in Fig. 2.11. The scheme is assumed to organise a very complicated law for controlling all the three axes of the gimbal mount to compensate the horizontal and the vertical components of the Earth’s rotation angular
velocity vector. Besides, it is possible to lose one degree of freedom if to put together the gimbal mount frames when the FAA elevation angle is significant.

![Diagram of a three-axes gimbal mount with vertical disposition of external frame]

Fig. 2.11. Kinematic scheme of a three-axes gimbal mount with vertical disposition of external frame

The second variant of the gimbals mount construction scheme is given in Fig. 2.12. In this scheme the horizontal component of the vector of the
Earth’s rotation angular velocity is compensated through operating the external and the intermediate gimbal mount frames which are situated in the horizontal plane, and the vertical component of this vector can be compensated through the corresponding operation of the internal frame.

Fig. 2.12. Kinematic scheme of a three-axes gimbal mount with vertical disposition of internal frame

Matrix $L \equiv [l_{i k}], i = k = 3$ for a three-axes antenna gimbals mount, which describes the $O_p'Y_p'Z_p'X_p'$ co-ordinates system transition into that of the $O_a'Y_a'Z_a'X_a'$, looks like:
\[
\begin{pmatrix}
\cos \varphi' \cdot \cos \beta' \\
+ \cos \varphi' \cdot \sin \beta' \times \\
\times \sin \gamma'
\end{pmatrix}
\begin{pmatrix}
\sin \varphi' \cdot \cos \gamma' + \\
\times \cos \gamma'
\end{pmatrix}
\]

\[
L = 
\begin{pmatrix}
- \sin \varphi' \cdot \cos \beta' \\
+ \sin \varphi' \cdot \sin \beta' \times \\
\times \sin \gamma'
\end{pmatrix}
\begin{pmatrix}
\cos \varphi' \cdot \cos \gamma' - \\
+ \sin \varphi' \cdot \sin \beta' \times \\
\times \cos \gamma'
\end{pmatrix}
\]

(2.34)

Both variants of the three-axes gimbal mount can be realised in accordance with the gyroscopic stabilisation concept which provides isolation of the FAA angular position from the object’s motion even if it is intensively disturbed and isolates it with the help of three gyroscopic sensors, from the inner disturbance torque effects in the gimbal mount axes as well as the unbalanced mass torque.

"To relate" the gyrostabilisation (inertial) system to the geographical system of co-ordinates it should possess the contour of horizontal correction obtained through accelerometric sensitive elements as well as the azimuthal angle correction, the latter being accomplished to the level of this signal after acquisition the satellite signal. The classical scheme of constructing such a gyroscopic stabilisation system intends to install gyroscopes and accelerometers directly on the stabilised platform shown in Fig. 2.11 and Fig. 2.12 in grey where the level of disturbances is the lowest. Additional difficulties concerning the increase of the disturbing moments values caused by a large number of electrical connections in the gimbal mount internal frame occur; these difficulties can also result from the necessity to modify the co-ordinates to make the sensors measurement axes coincident with the gimbal mount operating axes. The disadvantages mentioned could be partly excluded or reduced if to use a non-traditional approach for the antenna gimbal mount scheme which is a combination of a two-axes gyrostabiliser with a horizontal correction from accelerometers and a single-axis
gyrostabiliser with a vertically oriented frame and external correction with the azimuthal angle. Construction peculiarities, the sensors choice and the kinematic scheme description for an antenna combined gimbal mount are discussed in the following subsection.

2.2.4 Combination of Single- and Two-Axes Gyrostabilisers

As the stabilisation system and the FAA control in the inertial space are intended to maintain stable functioning of the satellite communication channel when being employed on a mobile basement, such a system is to perform the following tasks:

- to search the required geostationary satellite,
- “to acquire” the satellite signal,
- to preserve the FAA direction to the satellite with a required accuracy.

In accordance with the tasks mentioned the electro-kinematic scheme for designing the system of stabilisation and FAA operating and control is to provide three operational modes: FAA search, acquisition and its preserving the direction of the satellite signal maximum. To insure the required FAA angular orientation and the antenna polarisation plane the information about the actual mobile object location and its angular orientation on the geographical system of co-ordinates is to be available. This information containing this or that error is on board to solve navigation tasks, that is why it allows to realise an indirect system of antenna operation and stabilisation conceptually; by means of such a system it is possible to arrange communication with the vessel navigational system through the interface. The functioning of an indirect stabilisation system of a similar type under actual operating conditions appears to be problematic even with an insignificant level of the object disturbances, when an unsatisfactory system speed breaks down the mode of acquisition or that of preserving the direction to the satellite: here the effect of the FAA “knocking out” occurs, as for example, with characteristic waves impacts. Besides, the indirect stabilisation system possesses additional disadvantages characteristic of systems of this type which are connected with the inaccuracy occurring when setting the axes of the on-board navigation system and that of indirect
stabilisation; other disadvantages are connected with preserving the achieved accuracy of setting during its exploitation. Indirect stabilisation systems with their own heading and attitude gyro system and an additional positional and heading indication from the on-board gyrocompass during the object motion somewhat reduce these errors, but they do not eliminate them completely. The cost and the operational complexity of such systems increase greatly.

The alternative variant for solving the tasks formulated is to design an independent gyroscopic indication system of stabilisation and FAA operation and control as a combination of a two-axes gyrostabiliser with the horizontal correction contour and a single-axis gyrostabiliser with a correction system in the azimuth installed on it.

The key problem in designing the indicator gyrostabilisers is the selection of the element base, the gyroscopic sensitive elements in particular. “Free” gyroscopes, such as balanced gyroscopes in the gimbal mount, two-degrees-of-freedom floated gyroscopes, gyroscopes in the electromagnetic suspension as well as angular velocity sensors can be regarded as examples of gyroscopic sensitive elements. All these types of “free” gyroscopes are complex enough and their price is rather high. Their use in such systems requires to employ highly accurate tracking systems. As an alternative, angular velocity sensors could be utilised, and their selection depends on the requirements to control velocities, frequency band, their own noises and the FAA permissible drift. The analysis of the present-day situation with gyroscopic sensors showed that the best suited devices are angular velocities sensors designed in accordance with the scheme for single-rotor vibration gyroscopes working in the two-component sensor mode [6]. Gyroscopes like these possess the required technical characteristics under the pre-set operational conditions, low cost price and sufficient reliability.

The second reliable factor determining the characteristics of the gyroscopic stabilisation systems is the use of performance elements. They mainly include electrical machines creating controlling and stabilising moments along the suspension axes. To achieve high accuracy in the indicator
gyroscopic stabilisation systems it is necessary to increase the frequency band width; thus the use of the reduction gear drive and AC motors should be neglected.

To obtain information about the FAA angular position in the basic system of co-ordinates or the parameters of the object oscillation motions, angle data sensors installed on the corresponding suspension axes can be used. There exist elaborations for sensors of various types, such as capacitive, differential transformer, variable-induction, moving-coil, optic-electronic ones, etc. Their selection depends on the requirements for measurements accuracy, mass and dimensions characteristics, on the price as well as on the type of performance elements. Among the precision data-angle sensors the most popular ones today are contactless rotating transformers.

Accelerometers can be used as sensitive elements of the horizontal correction contour [7]. The error and the bandwidth requirements make it possible to use widely spread nowadays pendulous accelerometers which also possess admissible mass, dimensions and cost characteristics.

The electro-kinematic scheme of a three-axes gyroscopic system of FAA stabilisation is shown in Fig. 2.13. The first gyroscope, given in the figure under number 8, works in the two-axes gyrostabiliser; it is installed on the gimbal mount intermediate frame so that its sensitivity axes coincide with the OZ and OY axes of horizontal stabilisation channels. During the first stage of the satellite signal search the switching on of the two-axes stabilisation occurs and a rough levelling of the instrumental horizon plane takes place.

The FAA position stabilisation relative to the OX axis is accomplished by means of a single-axis gyrostabiliser using the signal from the corresponding outlet of gyroscope 4. This gyroscope is installed on the gimbal mount internal frame so that one of its sensitivity axes is collinear to the OX axis. The signal from gyroscope 4 is transmitted to drive 6 after the process of integrating in the signal stabilisation mode.

The signal search in the azimuth can be realised in two ways. According to the first one the stabiliser azimuthal channel works in the mode
Fig. 2.13. Electro-kinematic scheme of combined type.
of "electric spring" during the rough horizontal levelling, i.e. the relative angle in the suspension azimuthal axis is preserved equal to zero in accordance with signals from angle-data sensor 10. The object relative bearing from its attitude and heading system is to be transmitted into the computer which produces a signal proportional to the difference between the object relative bearing and the angle of elevation (azimuth) of the chosen satellite in accordance with the corresponding algorithm.

After finishing rough levelling the stabiliser switches to the mode of accurate levelling into the horizontal plane, when this difference signal is transmitted to drive 6. If there is no attitude and heading system on the object, then a gyrostabiliser is to be provided with such a system. In this case the stabiliser attitude and heading system can be an autonomous one, or it can employ signals from gyroscope 8 to determine relative bearing.

The search mode is completed when the FAA direction and the direction to the satellite differ by the angle providing the switch of "the acquisition" mode in accordance with a certain level of the satellite signal received. An accurate levelling into the horizon continues to work in the acquisition mode. In the azimuth channel the mode of "electric spring" switches off and the extreme system switches on, and this system turns FAA through a correction angle round the azimuthal axis by the criterion of maximum value of signal 5 received from the satellite. For objects with high velocities and for nonstationary satellites an extreme system by the elevation angle must work by means of the corresponding platform deflection from the horizon plane or through controlling the FAA elevation angle in relation to axis 3.

When working with geostationary satellites it is possible to realise the second way of the satellite signal search without knowing the object relative bearing through FAA circular rotation in relation to the azimuthal axis and through further selecting the signal from the required satellite via its frequency selection in the tuner. The extreme system performance begins simultaneously with a synchronous switch of the mode of circular rotation after completing the mode of rough levelling and setting the designed FAA elevation angle. To do it in the simplest manner harmonic oscillations in the
X axis with a pre-set frequency and amplitude are given. These oscillations are gained by transmitting the electric signal from the generator to the inlet of the summator of drive 6. When FAA enters the satellite zone, the signal is taken from the tuner and after being demodulated, amplified and properly modified it enters the integrator along arrow 5. The search is completed after the signal received from the satellite is generated in the feedback circuit by the FAA positioning in the azimuth and enters the integrator inlet; the relation between the values of a useful signal and noise should be sufficient for switching the acquisition mode on. After demodulating the satellite signal value is proportional to FAA positioning in relation to true satellite direction. After integrating this signal is used to control the FAA positioning in the azimuth in the order to gain its maximum in concrete reception conditions.

Having completed tuning to the satellite signal maximum, the mode of tracking the maximum is realised. The performances of the extreme system, the contour of horizontal correction and the systems of two-axes and single-axis stabilisation continue. If there is an extreme system by the elevation angle, the contour of horizontal correction may be switched off in the tracking mode, and it allows to reduce errors from linear acceleration acting on MAP in the place of its instalation above the object’s centre of swaying. The stabilisation system ensures the FAA isolation from the disturbances of the mobile basement and the extreme system and the system of horizontal correction produce controlling and correcting signals which provide continuous FAA tracking in the satellite direction.

2.3 Conclusions

Investigations conducted in Chapter 2 can result in the following basic conclusions.

- At present, there exists a tendency to widen the sphere of MAP employment, especially those ones which work on board the mobile objects of different types. And the requirements to their metrological,
functional and exploitation characteristics also heighten although they cannot be complied with the elaborations existing.

- The FAA gyroscopic stabiliser is considered to be a very important MAP component as it ensures its metrological, functional and exploitation properties. Those systems of indirect stabilisation which have been previously employed cannot meet many of the requirements imposed on perspective MAP.

- The indicator gyroscopic stabilisation with a correction contour in accordance with the FAA angle of elevation (azimuth) in the geostationary satellite direction can be regarded as an appropriate basic concept for designing and constructing FAA gyroscopic stabilisers for perspective MAP. It allows to provide stabilisation accuracy on the level of minutes of arc when realising functional characteristics of a wide range in order to achieve constructive decisions highest flexibility.

- Unirotor vibrational gyroscopes operating in the mode of a two-component sensor of absolute angular velocities suit to the requirements imposed on basic sensitive elements for perspective MAP best of all. They allow to ensure necessary metrological characteristics in a wide range of designed functional characteristics under varied operational conditions. Among analogue gyroscopes these ones appear to be the smallest in size and the cheapest. Brushless DC motors can be employed as performance elements. General requirements to angle-data sensors can be realised through using differential transformer sensors. To realise specific requirements, an individual approach to their design and construction concept is necessary.

- To design a bearing co-ordinate system in the MAP stabiliser connected with the horizon plane, a horizontal correction contour is built into it. Pendulous accelerometers can be used as sensitive elements for this contour. They make it possible to realise the static error in determining the instrumental horizon plane at the level of
minutes of arc, besides, they are smaller and cheaper as compared to identical sensors of a similar class.

• To construct such a MAP stabiliser which would possess metrological characteristics ensuring receiving satellite TV-picture of high quality on board the mobile objects, it is necessary to accomplish the mathematical analysis and the parametrical synthesis to optimise the subsystems of search, acquisition and tracking the satellite signal maximum by minimising the time of obtaining a TV-picture of high quality and preserving the FAA satellite direction with a required error if real external disturbances occur.
3 Mathematical Model

To write down the equation for antenna motion, the antenna being rigidly attached to the gyrostabilised three-axes gimbal mount platform, we use the system of co-ordinates related to the mount elements:

- $OY'_A Z'_A X'_A$ relates to the antenna co-ordinates system, the $OX'_A$ axis of which is directed along the internal mount axis, while the $OY'_A$ axis coincides with the FAA;
- $OY''Z''X''$ relates to the intermediate gimbal mount frame,
- $OY'Z'X'$. relates to the external gimbal mount frame,
- $OY'_p Z'_p X'_p$ relates to the object.

Mutual arrangement of all these co-ordinates systems can be determined by relative angles $\gamma', \beta', \varphi'$ shown in Fig. 3.1.
3.1 Equations for Antenna Motion in Search Mode

Absolute angles of the platform turning in relation to its initial position in the inertial space are marked with $\gamma_p, \beta_p, \alpha_p$, correspondingly and specified in accordance with Fig. 3.1.

Fig. 3.1. Absolute angles of gyrostabilised platform in relation to its initial position in the inertial space

The task of synthesising the indicator gyrostabilised platform (GSP) channels is solved in such researches as [8], [9], the platforms being constructed on the rotor vibrational rate gyroscopes. The separator
stabilisation channel in the region of significant frequencies can be described in the operator form with the help of the linearised equation:

\[ \left( T_i^2 p^2 + 2 \xi_i T_i p + 1 \right) \cdot \alpha_i = K_{0i} \cdot M_i, i = Y, Z, X, \]  \hspace{1cm} (3.1)

where \( \alpha_x = \alpha_p, \alpha_z = \beta_p, \alpha_y = \gamma_p; M_i \) are moments acting along the stabilisation axes; \( K_{0i} \) is the gain factor of the closed separator stabilisation channels.

When installing the first gyroscope and two accelerometers on the gimbal mount intermediate frame, their sensitivity axes coinciding with the horizontal stabilisation channels axes Y and Z, GSP would represent a combination of a two-axes gyrostabiliser and a horizontal correction contour on which a one-axis gyrostabiliser with the second gyroscope and an azimuthal correction contour are mounted. During the first phase of the satellite signal search mode, i.e. during rough adjustment into the horizon plane, GSP operates in the two-axes gyrostabiliser mode. If, in this case, the stabilisation channels are constructed as it has been recommended in [10], the cross correlation between channels will be negligibly small.

Signals controlling the horizontal correction contour are the signals from accelerometers whose sensitivity axes coincide with OY' and OZ'. By using Fig. 2.7, we can estimate linear accelerations projections on the accelerometers sensitivity axes in the place of MAP installation. In this case, these linear accelerations projections on the accelerometers sensitivity axes could be described through the expressions:

\[
\begin{align*}
    j_{y''} &= -\cos \gamma' \cdot \sin \beta' \cdot j_x^0 + \cos \beta' \cdot j_y^0 + \sin \gamma' \cdot \sin \beta' \cdot j_z^0 + \\
    &+ \left[ \cos \psi \cdot \sin \beta' \cdot \cos (\phi + \gamma') + \sin \psi \cdot \cos \beta' \right] \cdot g, \\
    j_{z''} &= \sin \gamma' \cdot j_x^0 + \cos \gamma' \cdot j_y^0 - \cos \psi \cdot \sin (\phi + \gamma') \cdot g.
\end{align*}
\]  \hspace{1cm} (3.2)

The angles between the accelerometers sensitivity axes and the horizon plane would be:
\[ \Delta \alpha_Y = \arcsin[\cos \psi \cdot \sin \beta \cdot \cos(\vartheta + \gamma') + \sin \psi \cdot \cos \beta'], \]
\[ \Delta \alpha_Z = -\arcsin[\cos \psi \cdot \sin(\vartheta + \gamma')]. \]  

(3.3)

If to make the \( OY_1Z_1X_1 \) and \( O\eta'\xi'\zeta' \) co-ordinates systems coincident and to neglect the rate of the Earth revolution we could obtain the following expressions:

\[ \cos \psi \cdot \sin \beta' \cdot \cos(\vartheta + \gamma') + \sin \psi \cdot \cos \beta = \sin \beta_p, \]
\[ \cos \psi \cdot \sin(\gamma' + \vartheta) = -\cos \beta_p \cdot \sin \gamma_p. \]  

(3.4)

As the process of adjustment into the instrumental horizon plane begins from the dislocking, the initial conditions have the following view:

\[ \alpha^0_Z = \psi_0, \alpha^0_Y = -\vartheta^0, \dot{\alpha}^0_Z = \dot{\beta}^0_p = \psi^0, \dot{\alpha}^0_Y = \dot{\gamma}^0_p = -\dot{\vartheta}^0. \]  

(3.5)

Taking into consideration everything mentioned above the equations for the accelerometers motion in the rough adjustment mode can be written down like:

\[ \left( T^2_A p^2 + 2 \xi_A T_A p + 1 \right) U^Y_A = K_A \cdot \begin{bmatrix} g \cdot \sin \Delta \alpha_Y \\ + j^0_Y \cdot \cos \gamma' \cdot \sin \beta' + \\ + j^0_Y \cdot \cos \beta' + \\ + j^0_Y \cdot \sin \gamma' \cdot \sin \beta' + j^0_Y \end{bmatrix}, \]
\[ \left( T^2_A p^2 + 2 \xi_A T_A p + 1 \right) U^Z_A = K_A \cdot \begin{bmatrix} g \cdot \sin \Delta \alpha_Z + j^0_Y \cdot \sin \gamma' + \\ + j^0_Z \cdot \cos \gamma' + j^0_Z \end{bmatrix}. \]  

(3.6)

where \( j^0_Y, j^0_Z \) are accelerometers errors reduced to equivalent linear accelerations; \( U^Y_A, U^Z_A \) are signals on the accelerometers outlets; \( T_A \) is the accelerometers time constant; \( \xi_A \) is the accelerometers damping factor and \( K_A \) is the accelerometer outlet signal steep. In case the basement is fixed signals from accelerometers are proportional to the platform deflection
angles in relation to the horizontal plane with the precision of their errors. To position the platform in the horizon plane these signals are transferred to the inlets of integrators $K^i_j(p)$ of corresponding stabilisation channels through the amplifying-transforming unit. Signal transformation is accomplished in accordance with the operators $W_A^{Ci}(p)$, the view and the parameters of which are chosen when using the desired characteristics of the adjustment process:

$$U_A^{Ci} = W_A^{Ci}(p) \cdot U_A^i, i = Y, Z,$$  \hspace{1cm} (3.7)

where $U_A^{Ci}$ are control signals along the horizontal correction channels on the integrators inlets.

After passing through integrators and after being transformed by the corresponding sections of the stabilisation contour, the control signals enter the torque motors and they look like:

$$U_M^i = \frac{K^i_i}{p} \cdot W_R^{ii}(p) \cdot U_A^{Ci}, i = Y, Z,$$  \hspace{1cm} (3.8)

where $W_R^{ii}(p)$ is the operator transforming the integrator outlet signals into those ones on the torque motors inlets in the stabilisation contour.

If DC motors without reduction gears are employed, the transformation of $U_M^i$ inlet signals into torques applied to the GSP gimbal mount axes is fulfilled in accordance with the equation:

$$(T_M^i p + 1) \cdot M^C_i = K_M^i \cdot U_M^i, i = Y, Z,$$  \hspace{1cm} (3.9)

where $T_M^i$ is the torque motor electromagnetic constant, $K_M^i$ is the torque motors gain factor.
The system of equations (3.1), (3.6), (3.7), (3.8) and (3.9) under initial conditions (3.5) describes the GSP operation during rough adjustment to the horizon as a first approximation.

Rough adjustment is over either after a lapse of a fixed time period after on-switching, this time period being determined on a priori knowledge of the time dependence of the process parameters, or on the basis of criterion elaborated in accordance with the accelerometers signals for each type of objects.

The phase of accurate adjustment to the horizon plane is characterised by insignificant GSP deflection angles from the horizon plane as well as by small absolute velocities of the platform motion along the horizontal channels. The structure and the parameters of the amplifying-transforming unit in this case change so as to provide the required filtration of linear accelerations caused by the object motion. A constant signal providing the antenna rotation in the azimuth in the mode of panoramic observation is transmitted on the GSP azimuthal axis. Linearised equations for movement along the azimuthal axis can be written down like this:

\[
\left(T_x^2p^2 + 2\xi_xT_xp + 1\right) \cdot \alpha_p = K^0_x \cdot (M_X - M^C_X),
\]

\[
\Delta \varphi = \alpha_p - \alpha^0_x - \frac{1}{p} \cdot \Omega_v,
\]

\[
M^C_X = \frac{K^X_i}{p} \cdot W^X_R(p) \cdot W^X_M(p) \cdot U^0.
\]

When accomplishing accurate adjustment it is necessary to account for a change in the instrumental horizon plane position in the inertial space resulting from the Earth revolution in the right-hand parts of equations of motion along horizontal channels (3.6). The GSP deflection angles from the horizon plane being small, it is possible to think that \( \sin \beta_p \approx \beta_p, \sin \gamma_p \approx \gamma_p, \cos \beta_p \approx 1 \), the accuracy degree being sufficient enough. Besides, it is possible to consider \( \beta' = -\psi, \gamma' = -\varphi \) with the accuracy up to the GSP coincidence with the horizon plane error. One
should be aware of the fact that there exist cross correlation of the GSP centrifugal moments of inertia and the moments of the torque [11].

Taking into consideration everything described in this section the generalised structural scheme of GSP in the mode of the satellite signal search can be represented as it is shown in Fig. 3.2.

Fig. 3.2. Generalised structural scheme of gyrostabilised platform in the search mode
The search mode is over when a signal, the level of which is sufficient for starting the satellite signal acquisition system operating, is produced on the TV-receiver outlet.

3.2 Equations for Gyrostabilised Platform Motion in Acquisition and Tracking Modes

When operating in the acquisition and tracking mode, the GSP horizontal channels are to provide tracking the horizon plane with the error not exceeding the permissible error of the FAA deflection from the satellite direction in respect to the elevation angle. As a rule, this error does not exceed 1°. That is why it is possible to write down the accelerometers motion equations precisely enough:

\[
\begin{align*}
\left \{ \begin{array}{l}
    g \cdot \left( \beta_p - \frac{1}{p} \cdot \Omega_H \cdot \sin \varphi_K \right) - \\
    \left( T_A^p p^2 + 2 \xi_A T_A p + 1 \right) \cdot U_A^Y = K_A \cdot \\
    \left[ + j_0^x \cdot \cos \gamma' \cdot \sin \beta' + j_0^y \cdot \cos \beta' + j_0^z \cdot \sin \gamma' \cdot \sin \beta' + j_1^y \right]
\end{array} \right.
\end{align*}
\]  

\[
\begin{align*}
\left \{ \begin{array}{l}
    g \cdot \left( \gamma_p - \frac{1}{p} \cdot \Omega_H \cdot \cos \varphi_K \right) - \\
    \left( T_A^p p^2 + 2 \xi_A T_A p + 1 \right) \cdot U_A^Z = K_A \cdot \\
    \left[ + j_0^x \cdot \sin \gamma' + j_0^z \cdot \cos \gamma' + j_1^z \right]
\end{array} \right.
\]  

(3.11)

where $\beta_p \approx \Delta \alpha_Y, \gamma_p \approx \Delta \alpha_Z$. In this case the channels operation is the same as in the accurate adjustment mode.

In acquisition and tracking modes the platform internal axis $X$ is gyrostabilised and isolated from the basement motion. Linearised equation for the internal frame movement in relation to the azimuthal axis is also described with the expression (3.1). To accomplish the satellite signal acquisition and tracking on the level not less than it is required, the GSP azimuthal channel is switched into the extreme system operational mode as
the $U_{TV}$ signal is produced on the TV-receiver outlet. The dependence of this signal level on the angle determining the FAA positioning in relation to the original direction to the satellite in azimuth (i.e. error angle) can be described with the expression similar to (2.3), the latter possessing a distinct extreme. The error $\Delta \varphi$ is formed by the initial error angle $\alpha_x^0$, the actual angle $\alpha_p$, and that of the geographical co-ordinates system turning in relation to the vertical axis:

$$\Delta \varphi = \alpha_x^0 - \alpha_p - \frac{1}{p} \Omega_v,$$

$$\alpha_p = K_X(p) \cdot \Delta M,$$

$$\Delta M = M_X + M^C_X + M_G. \tag{3.12}$$

To minimise the error angle $\Delta \varphi$ and to compensate the gyroscope drift and the vertical component of the velocity vector of the Earth revolution a correcting contour built on the principle of the extreme system is used. The satellite signal extreme (maximum) estimation is provided through search motion which in fact harmonic oscillations from the master:

$$M_G = A \cdot \sin \omega t. \tag{3.13}$$

The search motion amplitude is restricted by the permissible dynamic error of the FAA stabilisation as well as by the power of the stabilisation drive along the gimbal mount azimuthal axis, the latter restricting the frequency maximum for the search motion.

As the initial error angle $\alpha_x^0$ is estimated for the moment when GSP is switched from the search mode into the acquisition one and as its value is insignificant, the expression for describing the signal on the receiver outlet after expansion into a power series and neglecting the terms of the large order of smallness can be approximated like the following:

$$U_{TV} = B_1 - B_2 \cdot \Delta \varphi^2. \tag{3.14}$$
The error angle consists of a slowly changing component and a search motion harmonic one. When demodulating the receiver outlet signal by means of the reference frequency, which equals the double master generator frequency $2\omega$, and harmonic components filtration the frequencies of which are divisible by the $\omega$ master generator frequency, the $U_F$ signal proportional to a slowly changing component is produced:

$$U_{DM} = B_1 \cdot \sin(\omega t + f) - B_2 \cdot \Delta \varphi^2 \cdot \sin(\omega t + f),$$
$$U_F = W_F(p) \cdot U_{DM}. \quad (3.15)$$

This signal is transmitted to a correcting contour $W_R^E(p)$, the parameters of which are chosen in accordance with the permissible error $\Delta \varphi'$ resulting from the Earth rotation and the gyroscope drift. The equation describing the dependence of the $M_X^C$ moment on the $U_E^C$ control signal is similar to the last member of the equation system (3.9):

$$M_X^C = \frac{K^C}{p} \cdot W_R^X(p) \cdot W_M^X(p) \cdot U_E^C,$$
$$U_E^C = W_R^E(p) \cdot U_F,$$  \quad (3.16)

$$M_X^C = W_F(p) \cdot W_R^E(p) \cdot \frac{K^X}{p} \cdot W_R^X(p) \cdot W_M^X(p) \cdot U_{DM}.$$

The equations presented are in fact non-linear ones and that is the reason why their further analysis is rather difficult. The method of harmonic linearisation has been used for them linearisation. As there is a harmonic signal $U_G$ in the azimuthal channel inlet and this signal masters the antenna motion, it is possible to assume that the signal on the azimuthal channel outlet $\Delta \varphi$ can be represented as Fourier series for frequencies divisible by the master generator frequency:
\[ \Delta \varphi = \Delta \varphi + \sum_{m=1}^{\infty} \Delta \varphi_m \cdot \sin(\omega t + f_m). \]  \hfill (3.17)

The signal on the demodulator outlet then will have the view:

\[ U_{DM} = \Delta \varphi^2 \cdot \sin(\omega t + f) + 2\Delta \varphi \cdot \sin(\omega t + f) \times \]
\[ \times \sum_{m=1}^{\infty} \Delta \varphi_m \cdot \sin(m \omega + f_m) + \]
\[ + \sum_{m=1}^{\infty} \sum_{l=1}^{\infty} \Delta \varphi_m \cdot \Delta \varphi_l \cdot \sin(m \omega + f_m) \cdot \sin(l \omega + f_l) \cdot \sin(\omega t + f). \]  \hfill (3.18)

If the band-pass filter provides reliable suppression of harmonics beginning with the first one, the expression for \( U_{DM} \) can be written down like the following:

\[ U_{DM} = \Delta \varphi_1 \cdot \Delta \varphi, \]  \hfill (3.19)

where \( \Delta \varphi_1 \) is the amplitude of the antenna search motion. The system of equations (3.1), (3.11), (3.12), (3.13), (3.14), (3.15), (3.16) and (3.19) under the condition that the initial error angle is estimated as \( \alpha^0_x \), describes the GSP operation in the mode of the satellite signal acquisition and tracking as a first approximation. Having taken into account everything mentioned above the generalised and linearised structural schemes of the GSP azimuthal channel in the acquisition and tracking mode is presented in Fig. 3.3a and Fig. 3.3b correspondingly.
3.3 Conclusions

The results of investigations presented in Chapter 3 allow to draw the following conclusions:
• Linear mathematical model describes the GSP generalised model motion in the modes of the satellite signal maximum search, acquisition and tracking. This model is a combined scheme comprising the horizontal correction contour and the extreme system in the azimuthal channel. The linear mathematical model is represented as a system of linear equations in the operational form.

• Such an analysis done with the help of the corresponding mathematical apparatus is based on a number of assumptions, e.g. linearisation of the system separate non-linear elements and neglect the values of a higher order of smallness, thus making it possible to simplify the mathematical model of the whole system and its separate subsystems.

• The satellite signal search mode could be provided in two ways. One of them is realised when transmitting a DC signal into the controlling contour of the gimbal mount azimuthal axis. As a result the antenna revolves in azimuth with a constant angular velocity in the panoramic observation mode.

In the second approach, an azimuthal channel drive controls the gimbal mount internal frame, the axis of which is coinciding with the place vertical with the accuracy up to the levelling contour error, by means of signals from the relative turning data-angle transmitter in a feedback of an “electric spring” type. In this case the structural scheme of the GSP azimuthal channel differs from the first variant by the error angle signal composition and the availability of the operator transforming the data-angle transmitter and the attitude-and-heading system signals into the control signal on the integrator inlet. The error angle signal is then proportional to the difference between the object relative bearing and the pre-set FAA azimuth angle within the geographical co-ordinates system. The structure and the parameters of the transformation operator are chosen in accordance with the required quality of the system transition process. Errors occurring when defining the error angle components are constituents of the total error of this system. This total error should not exceed the maximum permissible error
angle value when the minimum value of the satellite signal received is sufficient enough for switching into the search mode. As the second way is much more complicated from the viewpoint of its technical realisation, the results of synthesising the auto-acquisition and tracking system with the utilisation of the "electrical spring" mode are given in the following chapter.
4

Synthesis

There exists a large number of works devoted to synthesising optimal in speed systems [12], [13], [14]. However, the use of their results for synthesising the GSP adjustment system with a mobile basement makes it possible to realise rather complex technical decisions. As the requirements imposed on the MAP readiness time are not strict, it makes sense to employ a simpler decision which is based on the method of dynamic synthesising linear continuous systems of automatic control [15].

4.1 Levelling System

4.1.1 Rough Adjustment Subsystem

Rough adjustment system is intended for preliminary GSP levelling. The major criterion for this system synthesis is the duration of the transition process. When accomplishing rough adjustment the change of the horizon plane position in the inertia space appears to be negligible as compared to the levelling error and thus could not be taken into account. If the gyrostabilisation system is available the levelling error is primarily
evaluated through linear accelerations \( j^0_Y, j^0_Z \) caused by GSP motion in the point of its attachment on the object.

As the initial angles of the GSP deflection from the horizon plane are equal to the object swaying angles, the latter being significantly limited (not more than 30°, as a rule), the approximation
\[
\sin \Delta \alpha_Y \approx \Delta \beta_p, \sin \Delta \alpha_Z \approx \Delta \gamma_p, \Delta \beta_p \approx \psi^0 - \beta_p, \Delta \gamma_p \approx -\sigma^0 - \gamma_p
\]
is accurate enough. The gyrostabilisation channel described with the equation (3.1) could be regarded the system invariable element. The medium frequency region for the levelling system in this case will be \( \omega_i \leq \frac{1}{T_i}, i = Y, Z. \) Thus the accelerometers and torque motors sluggishness as well as dynamic elements describing filters in the transfer \( W^i_R(p), i = Y, Z \) could also be neglected. The open transfer function of the levelling channel would look like this then:

\[
W^i_{OH}(p) = \frac{K_i}{T_i^2 p^2 + 2 \xi_i T_i p + 1} \cdot g \cdot K_A \cdot \frac{K^i}{p} \times \\
\times K^i_R \cdot K^i_M \cdot \left( \sqrt{2} \cdot T_i p + 1 \right) \cdot W^i_A(p); \\
i = Y, Z. 
\]

By choosing the phase and amplitude steadiness margin which characterises the transmission process quality as a criterion for adopting correction it is possible to obtain expressions for transfer functions \( W^i_A(p) \):
where i=Y, Z and $K^i_g$ is the gyroscope gain factor from the measured angular velocity up to the input signal on the integrator. The equation describing the adjustment process with the system structure and parameters chosen looks as the following:

$$
\left(T_i^2 p^2 + 2\xi_i T_i p^2 + p + \frac{r}{T_i}\right) \cdot \Delta \alpha_i = p \cdot \left(T_i^2 p^2 + 2\xi_i T_i p + 1\right) \cdot \Delta \alpha_i^0. \tag{4.3}
$$

Now let the Laplace standardised operator $\tilde{s} = sT_i$ be introduced. Equation (4.3) in the Laplace transform becomes:

$$
\left(\tilde{s}^3 + 2\xi_i \tilde{s} + \tilde{s} + r\right) \cdot \Delta \alpha_i(\tilde{s}) = \tilde{s} \cdot \left(\tilde{s}^2 + 2\xi_i \tilde{s} + 1\right) \cdot \Delta \alpha_i^0(\tilde{s}). \tag{4.4}
$$

If initial angles correspond to jump-like disturbances, its transform could be written in a form $\frac{\Delta \alpha_i^0}{\tilde{s}}$. Then the solution of equation (4.4) written in the Laplace transform looks as the following:

$$
\Delta \alpha_i(\tilde{s}) = \frac{1}{r} \cdot \frac{\tilde{s}^2 + 2\xi_i \tilde{s} + 1}{(\tau_1 \tilde{s} + 1) \cdot (\tau_2 \tilde{s}^2 + 2\xi_2 \tau_2 \tilde{s} + 1)} \cdot \Delta \alpha_i^0. \tag{4.5}
$$

Values $\tau_1, \tau_2, \xi$ are determined by the chosen "r" value which should always be less than one. In Fig. 4.1 one can see diagrams of these values dependence on "r", if $\xi_i = 0,707$:

- $r = 0,10 \Rightarrow \tau_1 = 8,33; \tau_2 = 1,086; \xi_2 = 0,69$;
- $r = 0,25 \Rightarrow \tau_1 = 2,22; \tau_2 = 1,320; \xi_2 = 0,63$;
- $r = 0,50 \Rightarrow \tau_1 = 1,11; \tau_2 = 1,350; \xi_2 = 0,337$. 

Fig. 4.1. Amplitude and frequency characteristics of the closed system of rough adjustment with various “r”.

On changing from the Laplace transform to the original one can obtain an expression with the help of which the process of the platform adjustment into the horizon plane is described:
\[
\Delta \alpha_i = \frac{1}{r} \left\{ \frac{P}{\tau_1} \cdot \ell \cdot \tau_1 + \frac{Q}{\tau_2} \cdot \ell \cdot \tau_2 \cdot x \right\} \Delta \alpha_i^0, \quad (4.6)
\]

\[
P = \frac{1 + \tau_1^2 - 2 \xi_1 \tau_1}{\tau_1^2 + \tau_2^2 - 2 \xi_2 \tau_2 \tau_1},
\]

where \( Q = \frac{\tau_1 \cdot (1 - \tau_2^2) + 2 \xi_1 \tau_2^2 - 2 \xi_2 \tau_1}{\tau_1^2 + \tau_2^2 - 2 \xi_2 \tau_2 \tau_1}, \)

\[
R = -1 + \tau_2^2 + 2 \xi_1 \tau_1 - 2 \xi_2 \tau_2 \tau_1
\]

and \( \tau = \frac{t}{T_i} \) is pure number.

A consequence of (4.6) is the fact that the platform motion to the horizon plane contains both non-periodic and harmonic components. If "r" is large (approximating 1), the second component is prevailing. For instance, when r=0.5 the oscillatory index is approximating M=1.5. If "r" reduces, the adjustment process is characterised with a non-periodic component and becomes non-periodic as well.

The steadiness phase margin tends to \( \frac{\pi}{2} \), and the adjustment time largely depends on \( \tau_1 \) value and can be approximately calculated with the formula:
\[ T' \approx -T_1 \tau_1 \ln \left( k \cdot r \cdot \frac{\tau_1 - 2 \xi \tau_2}{\tau_1 - 2 \xi} \right), \quad (4.7) \]

in which \( k \) is the required adjustment accuracy in fractions from initial deflection. For instance, for \( r=0.1 \) and \( \xi = 0.707 \) the platform adjusting into the horizon plane with the error not exceeding 1% from the initial deflection with \( T_i = 0.5\pi \) takes place during the time period not exceeding \( T' = 1.6 \)s.

It is necessary to estimate the torques which must be produced by stabilising motors in order to realise the non-periodic process of the platform adjusting into the horizon plane. Maximum torques for stabilising motors should exceed maximum inertia moments which occur at the initial moment of the adjustment \( t=0+ \):

\[ M_i^c > I_p \frac{A}{r \tau_1^3} \frac{1}{T_i^2} \Delta \alpha_i^0. \quad (4.8) \]

For instance, for adjusting the platform from the initial angle \( \Delta \alpha_i^0 = 45^\circ \) with error not exceeding 1% during the time period of 1,6s when \( T_i = 0.5\pi (s) \) the stabilising motors should develop maximum torques not less than \( 8,5 \cdot I_p, \) [g-cm].

A consequence of (4.7) and (4.8) is the fact that when \( T_i \) increases the adjustment time \( T' \) also increases in accordance with the linear law, while the maximum torque decreases in inverse proportion to the square of \( T_i \).

The error of adjusting the platform into the horizon plane will be mainly determined by \( j_i^E \) signal, i.e. by equivalent acceleration on the accelerometer inlet if its sensitivity axis is positioned in the horizon plane. This signal is caused by linear accelerations of the point of the antenna attachment on the mobile object. Dependence between error and linear acceleration \( j_i^E \) looks like:
\[ \Delta \alpha_i = \frac{1}{\sqrt{2} \tau_i \bar{p} + 1} \cdot \frac{1}{\tau_1 \bar{p} + 1} \cdot \frac{1}{\tau_2 \bar{p}^2 + 2 \xi_2 \tau_2 \bar{p} + 1} \cdot \frac{\dot{\bar{J}}_i^E}{g}. \] (4.9)

The relation of linear acceleration to free fall acceleration allows to estimate the error of the platform adjustment into the horizon plane if harmonic changes of linear acceleration of the platform suspension point are registered. It is obvious that \( \tau \) and \( T_i \) decrease improves the filtrating properties of the system. Significant influence of the system filtrating properties on the adjustment error manifests itself with frequencies larger \( \frac{1}{\tau_1} \).

### 4.1.2 Accurate Adjustment and Retaining Subsystem

The mode of accurate adjustment and retaining the GSP in the horizon plane is characterised by small angles of the platform deflection from the horizon plane and their maximum is determined by its error in the rough adjustment mode. Linear oscillations of the GSP point of attachment on the object and the gyroscopes errors in the horizontal stabilisation channels significantly influence the accuracy of the platform in the horizon plane. That is why the motion equations for these channels can be written like this:

\[
\begin{align*}
\Delta \alpha_Y &= K_H^Y(p) \cdot \\
&\left[ \Omega_H \cdot \sin \varphi_K \cdot \frac{1}{p} + \frac{1}{g} \cdot W_{OH}(p) \cdot \dot{j}_Y^0 + \\
&\frac{K_i^Y}{p} \cdot K_R^Y \cdot K_M^Y \cdot K_Y(p) \cdot \dot{U}^0_Y + K_Y(p) \cdot M_Y \right], \\
\Delta \alpha_Z &= K_H^Z(p) \cdot \\
&\left[ \Omega_H \cdot \cos \varphi_K \cdot \frac{1}{p} + \frac{1}{g} \cdot W_{OH}(p) \cdot \dot{j}_Z^0 + \\
&\frac{K_i^Z}{p} \cdot K_R^Z \cdot K_M^Z \cdot K_Z(p) \cdot \dot{U}^0_Z + K_Z(p) \cdot M_Z \right].
\end{align*}
\] (4.10)
where $W_{OH}^i(p) = g \cdot K_A \cdot \frac{K_i}{p} \cdot K_r \cdot K_M \cdot K_i(p) \cdot W_A^c(p)$ is the transfer function of an open levelling channel,

$$K_H^i(p) = \frac{1}{1 + g \cdot K_A \cdot \frac{K_i^i}{p} \cdot K_r \cdot K_M \cdot K_i(p) \cdot W_A^c(p)}$$

is the transfer function in accord with the error of tracking the horizon plane of the closed levelling channel and $U_{g}^{i0}$ is the gyroscope error reduced to the integrator inlet of the stabilisation channel. As before, the range of significant frequencies in the levelling system is much smaller than the stabilisation frequency proper. That is why in (4.10) it is possible to assume that:

$$K_i(p) \approx \frac{1}{K_g \cdot K_i \cdot K_r \cdot K_M}$$

(4.11)

where $K_g^i$ is the gyroscope gain factor from the angular velocity measured up to the signal on the integrator inlet. Steady state error of the levelling system can be described in expressions:

$$\Delta \alpha_Y \approx \frac{1}{p \rightarrow 0} \cdot \frac{1}{K_g^Y \cdot W_A^c(p)} \cdot \Omega_H \cdot \sin \varphi_K + \frac{1}{g} \cdot j_Y^0 + \frac{1}{g \cdot K_A^Y} \cdot \frac{1}{W_A^c(p)} \cdot U_{g}^{Y0} +$$

$$\frac{p}{g \cdot K_A^Y \cdot K_i^Y \cdot K_r^Y \cdot K_M^Y} \cdot \frac{1}{W_A^c(p)} \cdot M_Y,$$

$$\Delta \alpha_Z = \frac{1}{p \rightarrow 0} \cdot \frac{1}{K_g^Z \cdot W_A^c(p)} \cdot \Omega_H \cdot \cos \varphi_K + \frac{1}{g} \cdot j_Z^0 + \frac{1}{g \cdot K_A^Z} \cdot \frac{1}{W_A^c(p)} \cdot U_{g}^{Z0} +$$

$$\frac{p}{g \cdot K_A^Z \cdot K_i^Z \cdot K_r^Z \cdot K_M^Z} \cdot \frac{1}{W_A^c(p)} \cdot M_Z,$$

(4.12)
A consequence of (4.12) is the fact that for excluding static errors in tracking the horizon plane caused by the Earth’s revolving, the gyroscope zero signal drift and the disturbing moments in transfer function \( W^c_{A} (p) \) should contain an integrating element. To choose the horizontal correction contour structure and its parameters it is necessary to employ the dynamic synthesis [16]. Taking into account the simplicity of the contour realisation, its structure could be determined by the transfer function:

\[
W^c_i (p) = K^c_i \cdot \frac{T_A^c \cdot p + 1}{p} \cdot \frac{1}{T_f^2 \cdot p^2 + 2 \xi_f T_f \cdot p + 1}.
\]

(4.13)

Recognising the permissible value of the error coefficient \( C^i_2 \) as the initial requirement, it is necessary to take into account that this value, with consideration for a second exponent of astatic system, equals the value inverse to the open system gain factor:

\[
\frac{1}{2} C^i_2 = \frac{1}{K_i} = \left[ \frac{K^c_i \cdot g \cdot K^i_A}{K^i_g} \right]^{-1} = \frac{K^i_g}{K^c_i} \cdot \frac{1}{g \cdot K^i_A}.
\]

(4.14)

The permissible value \( C^i_2 \) for low-manoeuvring objects should be chosen on the condition that the platform deflection from horizon plane is not to exceed this permissible value when the object turns round the vertical axis with the maximum speed. It is clear that the maximum levelling error occurs when the stabilisation axis deflects from the meridian plane. This error can be estimated precisely enough with the expression

\[
\Delta \alpha_i = \frac{1}{2} \cdot C^i_2 \cdot \Omega_H^i \cdot \omega_K = \frac{K^i_g}{K^c_A} \cdot \frac{1}{g \cdot K^i_A} \cdot \Omega_H^i \cdot \omega_K,
\]

(4.15)

where \( \omega_K \) is the constant angular velocity of the object turning round its vertical axis. The gain factor of the open system in this case is to meet the requirement
\[ K^i \geq \frac{\Omega_H^i \cdot \omega_K}{\Delta \alpha'} \]  

(4.16)

In Fig. 4.2 one can see corresponding regions of permissible values \( K \) depending on the permissible error \( \Delta \alpha' \) with different \( \omega_K \) values.

**Fig. 4.2. Corresponding regions of permissible values \( K \)**

If \( K \) is known, basis frequency \( \omega_B \) could be obtained, and at this frequency the amplitude-frequency characteristic of the non-corrected open system is to cross the null decibel axis:

\[ \omega_B = \sqrt{K}. \]  

(4.17)

For a chosen structure of the correction contour the maximum phase redundancy can be obtained at the frequency:
\[ \omega = \frac{1}{T_F} \sqrt{\frac{1}{2} \left( 1 - \frac{\xi_F'}{\xi_F} \right) \left( 1 + \frac{\xi_F' \cdot \tau_F'}{\tau_F} \right) - \frac{\xi_F^2}{\xi_F^2 + 2\xi_F' + 1}} \]

where \( \tau_F' = \frac{T_F}{T_A} \).

This frequency depends on \( \xi_F \), the \( \xi_F' \) value and the length of the section with the inclination \(-20 \text{dB/dec}\) of the open system amplitude-frequency characteristic. If this frequency is regarded as a cut-off frequency of the open system \( \omega_C \), then the parameters of the correction contour are calculated from the formulas:

\[ \omega_C = \frac{K}{\omega_C} \cdot \frac{T_F}{\tau_F}, T_A = \omega_A = \frac{K}{\omega_C} \cdot \frac{\tau_F'}{T_F}, T_F = \tau_F' \cdot T_A. \]  

The magnitudes of dimensionless values \( \tau_F', \xi_F' \) are chosen on the basis of the desired transmission process quality through realising the required phase and amplitude steadiness margin. For example, if the choice is \( \xi_F = 0.707, \tau_F' = 0.1 \), the system will possess the phase steadiness margin of \( \phi_s \approx 52^\circ \) and the amplitude steadiness margin of \( A_s \approx 5 \text{dB} \). The ratios of the correction contour parameters will approximately be as: \( \omega_C = 2.236\sqrt{K}, T_A = \omega_A = 0.2\omega_C, T_F = \omega_F = 10\omega_A \).

4.2 Extreme System

At present, methods for determining the structure and the parameters for the automatic control system by the requirement that can be imposed on them
and concern their accuracy in dynamics are developed rather fully. One of the best developed methods of engineering synthesis, which is taken as a basic one in our further discussion, is the method of log-log frequency characteristics (LFC) [17]. Synthesising the system by means of the LFC method is the simplest way to estimate its stability margin through oscillation index $M$. In this case, one can determine the system structure and parameters on the basis of its frequency properties. For type $M = \left| K^E_C(p) \right|_{\text{max}}$ astatic systems the oscillation index equals the relative value of the amplitude frequency peak in the closed system. For spatial systems of automatic control the oscillation index amounting to $M = 1, 2, \ldots 1, 7$ is considered to be acceptable. The phase frequency characteristic of the system, in this case, must not overlap the so called restricted area, the maximum phase margin of the system amounting to:

$$\varphi_s = \arcsin \frac{1}{M}.$$  \hspace{1cm} (4.20)

This area is determined by the type of the amplitude frequency characteristic near the cut-off frequency $\omega_C^E$, i.e. the frequency where LFC y-co-ordinate equals zero. The cut-off frequency determines the system band width and the transition process duration and is the smaller, the greater is $\omega_C^E$. Opening the control loop one can obtain the transfer function in the open loop of the non-corrected extreme system (Fig. 3.3-b) as the product:

$$K^E_O(p) = K^X(p) \cdot \Delta \varphi_1 \cdot W^E_R(p) \cdot \frac{K^X_R(p)}{p} \cdot W^X_R(p) \cdot W^X_M(p),$$  \hspace{1cm} (4.21)

where $K^X(p) \cdot \frac{K^X_R(p)}{p} \cdot W^X_R(p) \cdot W^X_M(p)$ is the immutable part of the extreme system which is determined by requirements to the stabilisation system along X-axis, and $W^E_R(p) \cdot W^E_R(p)$ is the corrected part, and changing its structure and parameters one can improve the extreme system quality.
Following the works [18], it is possible to investigate the extreme system LFC overlapping the axis of the zero dB with the slope of -20dB/dec. Such a slope on $\omega = \omega_C^E$ corresponds to the aperiodic unit properties and provides the smallest oscillation of the transition process in the closed system. The value of the extreme system cut-off frequency must be, at least, by an order less than the frequency of the searching motion $\omega_G$ generated and the stabilisation system frequencies proper:

$$\omega_C^E \approx 0,1 \omega_G,$$

(4.22)

thus ensuring steady filtration of harmonic components on the demodulator $U_{DM}$ outlet. To increase the astatic system type number order an additional integrating factor of an electronic type is introduced into the control system thus lessening the error influence at low frequencies, the error being proportional to the zero signal on the gyroscope outlet (equivalent to angular velocity $\omega_E$ in Fig. 3.3b). That is why, LFC length with a slope of -20dB/dec. will be, on the left, limited by another length, with a slope of -40dB/dec. The expression for transfer function of the extreme system controller will take the following view:

$$W_R^E(p) = \frac{T_R^E \cdot p + 1}{p},$$

(4.23)

where $T_R^E$ is the time constant the value of which should not be small as it can cause the decrease of the system stability margin. The following expression can be used as a preliminary estimation of its permissible value:

$$T_R^E \geq \frac{2 \cdot \left( M^2 - M \cdot \sqrt{M^2 - 1} \right)}{\omega_C^E \cdot (M^2 - 1)}.$$  

(4.24)

To obtain the pre-determined oscillation index $M$, $h$, being the smallest extent of the LFC length with a slope of -20dB/dec., should correspond to the expression:
\[ h = \frac{M + 1}{M - 1}. \] (4.25)

From the view point of the simplicity of the extreme system technical decision it makes sense to obtain its required properties making "h" length extent the smallest.

To increase the system filtration properties it is possible to use the filter of the second order with transfer function \( W_f(p) \) looking like this:

\[ W_f(p) = \frac{1}{T_f^2 \cdot p^2 + 2 \cdot \xi_f \cdot T_f \cdot p + 1}, \] (4.26)

where \( T_f \) is the time constant of the extreme system filter and \( \xi_f \) is the attenuation parameter. To obtain the pre-determined oscillation index of the system, for which the LFC cut-off frequency is known, it is necessary to get the filter time constant which can be calculated from the relation:

\[ T_F = \frac{T_R^E}{h}. \] (4.27)

The attenuation parameter \( \xi_f \) is to be chosen on the condition that \( 0 < \xi_f < 1 \), because if \( \xi_f \geq 1 \), the unit becomes aperiodic of the second order, and if \( \xi_f \rightarrow 0 \), a "hump" appears on the amplitude characteristic and it approaches infinity. With values \( 0.5 \leq \xi_f < 1 \) LFC looks like a polygonal line. In such calculations an additional stability margin could be foreseen, if there are small time constants which were not taken into consideration yet and the sum of which is less than the time constant \( T_F \) which is estimated from formula (4.27). Transfer function of the corrected extreme system, when open, is described with the following expression having regard to (4.26) and (4.23):
\[ K_0^E(p) = \frac{K_1^E \cdot (T_R^E \cdot p + 1)}{p^2 \cdot (T_F^2 \cdot p^2 + 2 \cdot \xi F \cdot T_F \cdot p + 1)}, \]  

(4.28)

where \( K_1^E \) is the gain factor of the open system. The parameters of transfer function in the open extreme system can be chosen on the basis of permissible error \( \Delta \varphi' \) caused by the Earth's rotation and the gyroscope drift. The former component imposes restriction on the gain factor of the open system:

\[ K_1^E > \frac{\Omega y}{\Delta \varphi'}, \]  

(4.29)

while the latter one imposes restriction on the gain factor of the circuit contour from the error angle \( \Delta \varphi \) to the integrating factor inlet \( U_E^C \) (Fig. 3.3b):

\[ K_1^E' > \frac{\omega_E}{\Delta \varphi'}. \]  

(4.30)

As an example, let us calculate the extreme system in which searching motion frequency \( \omega_E = 4 \text{Hz} \), oscillation index \( M=1,2 \) and attenuation parameter \( \xi_F=0,5 \); in this case \( \omega_C^E=0,4 \text{Hz} \) and the parameters of the extreme system correcting unit will have the following values with \( h=11 \):

\( T_R^E = 10 \text{s}, \omega_R^E = 0,1 \text{s}^{-1}, T_F = 0,9 \text{s}, \omega_F = 1,1 \text{s}^{-1}, A_s \approx 5 \text{dB} \). The system phase stability margin makes up \( \varphi_s \approx 22^\circ \) and can be calculated with the formula:

\[ \tan \varphi_s = \frac{2 \cdot \xi_F \cdot T_F \cdot \omega_C^E}{1 - T_F^2 \cdot \omega_C^2}. \]  

(4.31)

The analysis of the results obtained showed that the extreme system with the filter of the second order, where \( \varphi_s \approx 20^\circ \), possesses the greater phase
stability and more intensive filtration properties than the similar one with
the filter of the first order.

The reliability of the results of the extreme system synthesising, their
optimisation and the correctness of the assumptions accepted were checked
through the method of mathematical simulation described in the following
section.

4.3 Azimuth Channel Control System

Three-axes gyrostabiliser of the combined type is a non-linear and non-
stationary system with a variable structure. Some assumptions have been
considered in the system analysis by means of suitable mathematical
apparatus. The linearisation of the system separate non-linear factors and the
neglect of values of a higher order of smallness are among these
assumptions. It has allowed to simplify the whole system mathematical
model as well, as some separate subsystems. This approach is acceptable for
the levelling system analysis and synthesis. However, the distinctive
singularity of the azimuth channel control system is its pure non-linearity,
which results from the operation modes sequence, such modes as search,
acquisition and tracking of the satellite TV-signal.

With respect to the extreme system approximate analysis and synthesis
adduced above, a tool is to be elaborated to check and to correct methods
applied and results obtained. By means of Pascal, one of the most
widespread algorithmic languages (compiler of Turbo Pascal, Borland), the
program "Extreme Search" (ES) has been developed, which could be used
as such a tool. The algorithm and text of the SE program are adduced in A
and B correspondingly.

As it was mentioned above, among the applications of the gyrostabilised
antenna employed for satellite TV-signal reception are various river and sea
vessels. Therefore, the disturbances used in the program have been chosen
from normative papers (standards) determining the equipment operation
environments [19], [20], [21], [22].
The program structure is based on the most complex gyrostabiliser operation cycle, i.e. by using the "electrical spring" mode described above intended to give final recommendations of its best application.

Search mode constitutes antenna harmonic oscillations when rotating around the stabiliser azimuth axis; it begins right once after completing the platform rough levelling and adjusting the FAA specified elevation angle. These oscillations occur as electrical signals in the sinus form transferred from the generator to the corresponding inlet of the azimuth channel control system, in accordance with arrow 5 in Fig. 2.13. The oscillation frequency is nominated one decade higher than the cut-off frequency of the SE system. The oscillation amplitude is chosen to provide a compromise between the motor power limitation in the stabiliser azimuth channel and the accuracy required for retaining FAA direction to the satellite. Taking into consideration the stabiliser specified structure the amplitude were chosen equal to 5" and the frequency equal to 3 Hz.

In the "electrical spring" mode, a signal proportional to the angle between the vessel heading and direction towards a satellite in the azimuth is fed to the output of the relative turn angular sensor (shown with 10 in Fig. 2.13) in the azimuth channel. The value of vessel heading can be set manually from a stabiliser control desk with respect to indications of onboard visual devices, or can be received from an external heading system as mentioned above. The satellite direction is calculated in accordance with the algorithm using the longitude and latitude data of the vessel actual position which can either be set manually from the stabiliser control desk or received from onboard navigation equipment. The algorithm accuracy of the FAA positioning in azimuth should provide an acquisition of the satellite signal after completing the "electrical spring "mode.

The signal received from the satellite comes through the demodulator and after being filtered it is transformed into a signal the value of which is to be proportional to the FAA position related to the true satellite direction. After integration this signal controls the FAA position, the latter depending on antenna actual position in azimuth. The system is astatic in relation to all
disturbances, such as gyro drift and disturbing moments along the gimbal mount axes occurring on the integrator outlet in the auto-acquisition contour. Therefore, resulting errors of the whole system comprise methodical errors in the search mode and system dynamic errors. On completing transition, FAA positioning fluctuates in the neighbourhood of the satellite true direction. To get a TV-picture of a high quality these fluctuations should correspond to the portion of the curve which is higher than -3 dB level in Fig. 2.2.

Corresponding equations for search and acquisition motions are shown below. One of the Runge-Kutta methods, namely, the five-staged Merson method of the fourth order of accuracy has been applied for solving these equations. The Runge method has been applied to calculate errors.

The GSP differential equation in the azimuth channel is described with the following equation:

\[ I_p^X \cdot \dot{\alpha}_p + \mu_p^X \cdot \dot{\alpha}_p \Delta = M_X, \]  

(4.32)

where \( I_p^X \) is the platform inertia moment relative to the corresponding mount axis \( X \), \( \mu_p^X \) is the damping factor relative to the corresponding platform mount axis \( X \), \( \alpha_p \) is the absolute angle of a platform turn, \( \Delta M_X \) is the summary moment acting relative to the corresponding platform mount axis \( X \).

The differential equation for a gyroscope looks like:

\[ T_g^X \cdot \ddot{U}_g^X + U_g^X = K_g^X \cdot \dot{\alpha}_p, \]  

(4.33)

where \( T_g^X \) is the time constant of the gyroscope in the azimuth channel, \( K_g^X \) is the gyroscope transfer factor and \( U_g^X \) is the signal on the gyroscope outlet.

The integrator differential equation is as follows:
\[ \dot{U}_i^X = K_i^X \cdot \left( T_i^X \cdot \dot{U}_g^X + U_g^X \right) + U_E^C, \tag{4.34} \]

where \( T_i^X \) is the time constant of an integrator, \( K_i^X \) is the transfer factor of an integrator, and \( U_E^C \) is the control signal on the integrator inlet in the modes of "electrical spring", auto-acquisition and tracking.

\[ U_E^C = K_{R'}^E \cdot \left( T_R^E \cdot \dot{U}_{es} + U_{es} \right), \text{ if } F(\alpha_p) < U_{TV}', \]
\[ U_E^C = K_{R'}^E \cdot \left( T_R^E \cdot \dot{U}_{DM}' + U_{DM}' \right), \text{ if } F(\Delta \varphi) \geq U_{TV}', \tag{4.35} \]

where \( U_{TV}' \) is the threshold level of the TV-receiver, \( K_{R'}^E \) is the correction unit transfer factor in the "electrical spring" mode, \( K_{R'}^E \) is the correction unit transfer factor in auto-acquisition and tracking modes, \( U_{es} \) is the control voltage in the "electrical spring" mode, the expression for the latter looking like:

\[ U_{es} = K_{es} \cdot \Delta \varphi, \tag{4.36} \]

where \( K_{es} \) is the transfer factor of the FAA relative position feedback.

\[ F(\Delta \varphi) = U_{TV}, \tag{4.37} \]

where \( U_{TV} \) is the signal from the TV-receiver outlet.

The FAA relative position is determined as follows:

\[ \Delta \varphi = \alpha_p - \left( \alpha_X^0 - \varphi_k \right) - \left( \varphi_y - \varphi \right), \tag{4.38} \]

where \( \varphi_y \) is the angle of yaw.

The demodulator equation in acquisition and tracking modes looks like this:
\[ U_{DM} = U_t \cdot \sin(\omega t + f_m), \]
\[ U_{DM}' = U_{DM} + U^x_g, \] (4.39)

where \( U_t \) is the voltage on the filter outlet in auto-acquisition and tracking modes.

The equation for a filter in the acquisition contour is the following:
\[ T_r \cdot \dot{U}_t + U_t = 10 \cdot K_r \cdot T_f \cdot \dot{U}_{TV}, \] (4.40)

where \( T_f \) is the filter time constant, \( K_r \) is the filter transfer factor.

The filter differential equation in the azimuthal stabilisation channel looks like:
\[ T^x_r \cdot U^c_x + 2 \cdot \xi^x_r \cdot T^x_r \cdot U^c_x + U^c_x = K^x_f \cdot (T^x_i \cdot \dot{U}^x_i + U^x_i), \] (4.41)

where \( T^x_r \) is the time constant of the filter in the azimuthal stabilisation channel, \( \xi^x_r \) is the dimensionless damping factor of the filter in the azimuthal stabilisation channel, \( K^x_f \) is the transfer factor of the filter in the azimuthal stabilisation channel, \( T^x_i \) is the time constant of the correction unit in the azimuthal stabilisation channel, \( U^c_x \) is the voltage actual value on the stabilising motor outlet in the azimuthal channel.

The equation for the stabilising motor is the following:
\[ M^C_x = K^x_M \cdot U^c_x \] (4.42)

where \( K^x_M \) is the transfer factor of the stabilising motor along the platform gimbal mount axis.

In all cases of simulation the vessel actual heading introduction is assumed only at the initial stage. Basis values of the system parameters are borrowed
from the system linear model. In all charts given below, the "B" point position shows the transfer from the "electrical spring" mode to the acquisition mode and consequently to the TV-signal received tracking.

In a case the vessel heading is constant and the initial mismatch between the FAA position in azimuth and the direction towards the satellite is about 15°, the satellite TV-signal search and acquisition process can be represented as shown in Fig. 4.3.

The portion from zero to point "B" corresponds to the transition process of the gyrostabiliser operation in the "electrical spring" mode. In point "B" the system is switched from the "electrical spring" mode to the acquisition one. In this case the static error is missing and transition is close enough to the one described with the linear model given above.

![Diagram](image)

**Fig. 4.3. Process of the satellite TV-signal search and acquisition when the vessel heading is constant**

Let us consider the influence of the vessel heading variation on the satellite signal search and acquisition process. The satellite signal search and
acquisition process, when the vessel heading is changed with a rate up to 0,1°/s, its direction coinciding with the antenna rotation in azimuth towards the satellite, is shown in Fig. 4.4. Thus, the time of the satellite TV-signal search is reduced by means of the antenna rotation direction and the vessel movement in azimuth coincidence. Assuming that the vessel is making the heading change with the rate up to 0,1°/s in the direction opposite to the antenna rotation towards the satellite, it could be seen in Fig. 4.5, that the time of the satellite TV-signal search and acquisition increases as compared to the previous case when the vessel and antenna movements coincide. The reliable acquisition of the satellite TV-signal is provided when the vessel heading is changed with the rate not exceeding 0,1°/s. The increase of the rate of the vessel heading change causes essential variation of the process of the satellite TV-signal search and acquisition.

Fig. 4.4. Process of the satellite TV-signal search and acquisition when the directions of the vessel movement with the rate in the order of 0,1°/s and the antenna rotation towards the satellite in azimuth are coincident
Fig. 4.5. Process of the satellite TV-signal search and acquisition when the directions of the vessel movement with the rate in the order of 0.1°/s and the antenna rotation towards the satellite in azimuth are opposite

When the vessel heading is changed with the rate in the order of 0.5°/s in the same direction as the FAA rotation towards the satellite, it could be seen in Fig. 4.6 that the time of the transition process of the satellite TV-signal search and acquisition modes is less than in the case shown in Fig. 4.4.

The satellite signal is not acquired if the vessel changes its heading with the rate in the order of 0.5°/s in the direction opposite to antenna rotation towards the satellite; with the result that the system operational speed for "electric spring" mode is not sufficient enough. Such a process is shown in Fig. 4.7.

In actual practice, it is possible to change the vessel heading with the rate up to 6°/s. In this case, it is necessary to check the possibility to acquire the satellite TV-signal as the vessel and the antenna movement directions coincide. Transition process for cases like this one corresponds to Fig. 4.8.
Fig. 4.6. Process of the satellite TV-signal search and acquisition when the directions of the vessel movement with the rate in the order of 0.5°/s and the antenna rotation towards a satellite in azimuth are coincident.

Fig. 4.7. Process of the satellite TV-signal search and acquisition when the directions of the vessel movement with the rate in the order of 0.5°/s and the antenna rotation towards the satellite in azimuth are opposite.
Fig. 4.8. Process of the satellite TV-signal search and acquisition when the directions of the vessel movement with the rate in the order of 6°/s and the antenna rotation towards the satellite are coincident in azimuth

The chart in Fig. 4.8 shows the reliable acquisition of the satellite TV-signal within a shorter time as compared to cases when the rate of the vessel heading change is less.

Analysing these early results of simulation it should be mentioned that:

- The system has insufficient operational speed in the "electrical spring" mode if the antenna movement to the satellite is opposite to the vessel direction in azimuth and the vessel heading changes with the rate exceeding of 0,1°/s.

- The transition process duration of the satellite TV-signal search and acquisition modes reduces when the directions of the antenna and vessel movements in azimuth are coincident.
The first circumstance imposes some restrictions on such a system application. To remove these restrictions the system operation algorithm should be changed. It could be done in two ways.

1. The antenna mount axis in azimuth should be locked prior to the search mode start. In this case, one of the gyros measures the direction of the vessel rate vector in azimuth. The direction of the FAA search rotation towards the satellite is to be coincident with the direction of the vessel heading change in azimuth. However, these requirements fulfilment will cause to the satellite signal search and acquisition algorithm complication and even the search and acquisition time increases in some instances.

2. The absolute value of the antenna search rotation rate must be limited as it was mentioned above. Thus, the control signal should be transmitted to the corresponding inlet of the antenna position control system in azimuth irrespective of the module and direction of the vessel heading change vector. The time of the satellite TV-signal search and acquisition can be occasionally increased. However, there is an opportunity of the autonomous search and acquisition system operation when data of the vessel actual heading are not needed. Moreover, the vessel actual heading can be precisely calculated by the data of the angular sensor in the gyrostabiliser azimuth channel after the satellite TV-signal acquisition. Relative bearing data can be used for navigation tasks, as instance, in emergencies.

It is important for the search and acquisition system designing to limit the motor torque in the azimuth channel. To estimate the influence of the torque limitation on search and acquisition modes, the limited value of the motor torque in the order of 10000 gcm has been taken into consideration. The satellite signal search and acquisition transition with limited motor torque in the order of 10000 gcm is shown in Fig. 4.9 and Fig. 4.10 (the latter is presented with the enlarged time scale along the abscissa co-ordinate axis).
Fig. 4.9. Process of the satellite TV-signal search and acquisition when the directions of the vessel movement and antenna rotation towards the satellite in azimuth are coincident and the motor torque in the azimuthal channel is limited by 10000 gcm

While analysing simulation results, the FAA additional fluctuations in the neighbourhood of the satellite true direction have been found. These fluctuations are caused by the "saturation" mode of the motor, so the time of the satellite signal search and acquisition tends to increase. It should be mentioned that the acquisition system with specified parameters has a tendency towards non-acquiring the satellite TV-signal and it seems result from limitation on the motor torque value. Therefore, sufficient influence of the motor torque limitation on the satellite TV-signal search and acquisition should be taken into consideration when designing similar systems. In practice, a typical vessel movement in azimuth is yaw, i.e. momentary changes of the vessel general heading caused by outer disturbances. The influence of yaw on the satellite TV-signal search and acquisition is shown in Fig. 4.11, Fig. 4.12 and Fig. 4.13.
Fig. 4.10. Process of the satellite TV-signal search and acquisition when the directions of the vessel movement and antenna rotation towards the satellite in azimuth are coincident and the motor torque in the azimuthal channel is limited by 10000 gcm, the time scale of the abscissa co-ordinate axis being enlarged.

The vessel yaw with the amplitude up to 2° practically does not modify the process of the satellite TV-signal search and acquisition. In sufficient disturbances the acquisition system tracks the vessel swaying, thus causing corresponding time increase of the satellite TV-signal search and acquisition. Hence, the harmonic vessel yaw variations do not disturb the satellite TV-signal acquisition.
Fig. 4.11. Influence of the vessel yaw with the amplitude in the order of 2° and time period of about 7s on the process of the satellite TV-signal search and acquisition

Fig. 4.12. Influence of the vessel yaw with the amplitude in the order of 5° and time period of about 7s on the process of the satellite TV-signal search and acquisition
Fig. 4.13. Influence of the vessel yaw with the amplitude in the order of $10^\circ$ and time period of about 7s on the process of the satellite TV-signal search and acquisition

4.4 Conclusions

Results of investigations conducted in Chapter 4 allow to draw the following conclusions:

- The method of dynamic synthesis for linear continuous system of automatic control was substantiated for the levelling system synthesis. The duration of the transition process was chosen the major criterion for the rough levelling system synthesis, the levelling error was the major criterion for the accurate levelling system synthesis and the oscillation index was the major criterion for the extreme system synthesis. When choosing the correction structure and parameters, amplitude and phase stability margins were used as criteria. The transfer function of the correcting unit for the rough adjustment system was determined with expression (4.2), with expression (4.13) the transfer function for the accurate adjustment system was calculated
• and the same function for the extreme system was estimated in accordance with expressions (4.23) and (4.26).

• With the rough adjustment system structure and parameters chosen expressions (4.6) and (4.7) were obtained and they describe the process of rough adjustment into the instrumental horizon plane and the dependence of the system transition process duration on the correction contour parameters correspondingly. Amplitude-frequency characteristics of the closed system of rough adjustment, given in Fig. 4.1, make it possible to vary optimally the correction contour parameters to improve the quality of the transition process in the system. To ensure aperiodic process in the system of rough levelling expression (4.8) was obtained which allowed to calculate the maximum torque of stabilising motors required. To estimate the errors of the system of the platform rough adjustment into the horizon plane with the structure and the parameters chosen, expression (4.9) could be used with a sufficient degree of accuracy, if harmonically changing linear acceleration affect the point of the platform suspension over the centre of the object swaying.

• Preliminary engineering synthesis of the extreme system could be accomplished in accordance with the linearised simplified model (4.21). To exclude static errors in the system of accurate levelling an integrating factor was introduced into the correction contour structure. Maximum error in the system of accurate levelling occurs if the stabilisation axis deflects from the meridian plane and its value could be estimated through expression (4.15) with a sufficient degree of correctness. On the basis of permissible errors of levelling the minimum gain factor in the open system could be determined by the curves given in Fig. 4.2, the object constant angular velocity in the azimuth varying.

• To provide steady filtration of harmonic components on the demodulator outlet it is necessary to provide the difference of at least one decade between the frequency of the master oscillator and the
extreme system cut-off frequency. To lessen the influence of the gyroscope equivalent angular velocity on the system errors, this angular velocity being transferred to the stabilisation contour integrator inlet, it is necessary to raise the astatic system type number of the extreme system by introducing an additional integrating factor into the control contour. The parameters of the transfer function in the open extreme system could be estimated from expressions (4.29) and (4.30), accordingly, judging by the permissible error caused by the Earth rotation and the gyroscope drift. Introducing the filter of the second order into the correcting unit structure it is possible to improve the intensity of the extreme system filtration properties and enlarge the phase stability margin.

- Refinements of the simplified linearised extreme system model developed can be accomplished with the method of digital simulation in accordance with the model elaborated and with complete motion equations, non-linearity and real disturbances taken into consideration. On the basis of the results analysed it is possible to state that assumptions adopted for linearising the extreme system are substantiated and they can describe the system dynamics for all possible object’s evolutions in azimuth with a sufficient enough degree of accuracy. The mathematical model elaborated, as well as methods of structural and parametrical synthesis, can be employed for engineering design of similar systems both for the purpose of optimising the choice of separate elements and for optimising the system as a whole in accordance with the criteria of permissible errors and the minimum time for the satellite signal search and acquisition.
5

Errors

The error of retaining the required FAA orientation and the antenna polarisation plane, caused by linear accelerations in the point of its suspension, appears to be the dominating one in the structure of the MAP GSP total error. This error results from accelerated translation motion of the object as well as from its angular oscillations, if the antenna suspension point does not coincide with the pole around which they occur.

5.1 Influence of Object Different Forms of Motion on System Errors

5.1.1 Horizontal Correction System Error Caused by Object Angular Oscillations

If the projections of the antenna suspension point accelerations on the coordinate system axes are $j_x^0, j_y^0, j_z^0$, the axes being connected with the object, acceleration projections on GSP axes could be calculated with relation:
\[
\begin{bmatrix}
\mathbf{j}_x^0 \\
\mathbf{j}_y^0 \\
\mathbf{j}_z^0
\end{bmatrix} = \begin{bmatrix}
cos \gamma' \cdot cos \beta' & sin \beta' & -sin \gamma' \cdot cos \beta' \\
(-cos \gamma' \cdot sin \beta' \cdot cos \phi' +) & cos \beta' \cdot cos \phi' & (cos \gamma' \cdot sin \phi' +) \\
(+sin \gamma' \cdot sin \phi' & cos \gamma' \cdot sin \beta' \cdot cos \phi' & +sin \gamma' \cdot sin \beta' \cdot cos \phi')
\end{bmatrix} \times
\begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix}
\]

(5.1)

Neglecting the distance between the antenna suspension point and the places of the accelerometers installation on the platform one could get acceleration projections on their sensitivity axes:

\[
\begin{align*}
\mathbf{j}_y^p &= (-cos \gamma' \cdot sin \beta' \cdot cos \phi' + sin \gamma' \cdot sin \phi') \cdot \mathbf{j}_x^0 + \\
&+ cos \beta' \cdot cos \phi' \cdot \mathbf{j}_y^0 + \\
&+ (cos \gamma' \cdot sin \phi' + sin \gamma' \cdot sin \beta' \cdot cos \phi') \mathbf{j}_z^0, \\
\mathbf{j}_z^p &= (cos \gamma' \cdot sin \beta' \cdot sin \phi' + sin \gamma' \cdot cos \phi') \cdot \mathbf{j}_x^0 - \\
&+ cos \beta' \cdot sin \phi' \cdot \mathbf{j}_y^0 + cos \gamma' \cdot cos \phi' \cdot \mathbf{j}_z^0.
\end{align*}
\]

(5.2)

If accelerometers are installed on the internal frame of the GSP suspension, \( \phi' = 0 \) in expressions (5.2) and these expressions take the view of:

\[
\begin{align*}
\mathbf{j}_y^p &= -cos \gamma' \cdot sin \beta' \cdot \mathbf{j}_x^0 + cos \beta' \cdot \mathbf{j}_y^0 + sin \gamma' \cdot sin \beta' \cdot \mathbf{j}_z^0, \\
\mathbf{j}_z^p &= sin \gamma' \cdot \mathbf{j}_x^0 + cos \gamma' \cdot \mathbf{j}_y^0.
\end{align*}
\]

(5.3)

The linear acceleration of the antenna suspension point during angular oscillations of the object can be calculated by this acceleration vector determined with the formula:

\[
\mathbf{j}_F = \bar{\mathbf{e}}_F \times \bar{r} \times \bar{\omega}_F \times (\bar{\omega}_F \times \bar{r}),
\]

(5.4)

where \( \bar{r} \) is the radius-vector of the antenna suspension point in relation to the point around which oscillations take place (poles), \( \bar{\omega}_F \) is the angular
velocity of the basement oscillations and \( \ddot{\varepsilon} \) is the angular acceleration of basement oscillations. The co-ordinates system being connected with the object, vector \( \vec{J}_F \) projections on its axes take the view of:

\[
\vec{j}_F^x = -\left[ \left( \dot{\phi} \cdot \sin \theta \cdot \cos \psi - \dot{\theta} \cdot \sin \psi \cdot \sin \theta + \dot{\psi} \cdot \cos \theta \right)^2 + \right] \cdot x + \\
\left\{ \left( \dot{\theta} - \dot{\phi} \cdot \sin \psi \right) \cdot \left( \phi \cdot \cos \psi \cdot \cos \theta - \right) + \dot{\phi} \cdot \sin \theta \cdot \cos \psi - \dot{\psi} \cdot \sin \theta + \right\} \cdot y + \\
\left\{ \left( \dot{\theta} - \dot{\phi} \cdot \sin \psi \cdot \phi \cdot \psi \cdot \cos \theta \right) + \right\} \cdot z,
\]

(5.5a)
\[ J_x^F = \begin{bmatrix} \ddot{\phi} \cdot \sin \theta \cdot \cos \psi - \dot{\theta} \cdot \sin \psi \cdot \sin \theta + \\
+ \ddot{\psi} \cdot \cos \theta + \phi \cdot \dot{\theta} \cdot \cos \theta \cdot \cos \psi - \dot{\phi} \cdot \dot{\psi} \cdot \sin \theta \cdot \sin \psi - \\
+ \dot{\theta} \cdot \dot{\psi} \cdot (\cos \theta + 1) \cdot \sin \theta - \dot{\theta}^2 \cdot \sin \psi \cdot \cos \theta + \\
+ (\phi \cdot \cos \psi \cdot \cos \theta - \dot{\theta} \cdot \sin \psi \cdot \cos \theta - \\
+ \dot{\psi} \cdot \sin \theta) \cdot (\dot{\theta} - \dot{\phi} \cdot \sin \psi) \end{bmatrix} \cdot x - \\
+ \left[ (\dot{\phi} \cdot \sin \theta \cdot \cos \psi - \dot{\theta} \cdot \sin \psi \cdot \sin \theta + \dot{\psi} \cdot \cos \theta)^2 + \right] y + \\
+ \left[ (\phi \cdot \cos \psi \cdot \cos \theta - \dot{\theta} \cdot \sin \psi \cdot \cos \theta - \dot{\psi} \cdot \sin \theta)^2 \right] \cdot z, \] 

(5.5b)

\[ J_y^F = \begin{bmatrix} -(-\ddot{\phi} \cdot \sin \psi + \ddot{\theta} - \dot{\phi} \cdot \dot{\psi} \cdot \cos \psi) + (\phi \cdot \cos \psi \cdot \cos \theta - \\
+ \dot{\theta} \cdot \sin \psi \cdot \cos \theta - \psi \cdot \sin \theta) \cdot (\phi \cdot \sin \theta \cdot \cos \psi - \\
+ \dot{\phi} \cdot \sin \theta \cdot \sin \psi + \dot{\psi} \cdot \cos \theta) \end{bmatrix} \cdot x + \\
[ \ddot{\phi} \cdot \cos \psi \cdot \cos \theta - \dot{\theta} \cdot \sin \psi \cdot \cos \theta - \\
+ \dot{\phi} \cdot \sin \theta \cdot \sin \psi + \dot{\psi} \cdot \cos \theta \cdot \cos \psi - \dot{\theta} \cdot \sin \psi \cdot \sin \theta - \\
+ \dot{\theta} \cdot \dot{\psi} \cdot \cos \theta \cdot \cos \psi + \dot{\theta}^2 \cdot \sin \psi \cdot \sin \theta + \\
+ (\dot{\theta} - \dot{\phi} \cdot \sin \psi) \cdot (\dot{\phi} \cdot \sin \theta \cdot \cos \psi - \\
+ \ddot{\phi} \cdot \sin \theta \cdot \sin \psi + \dot{\psi} \cdot \cos \theta) \right] y - \\
\left[ (\phi \cdot \cos \psi \cdot \cos \theta - \dot{\theta} \cdot \sin \psi \cdot \cos \theta - \dot{\psi} \cdot \sin \theta)^2 + \right] \cdot z, \] 

(5.5c)
where \( x, y, z \) are the platform suspension point radius-vector projections on the axes co-ordinates system connected with the object.

As the angles, angular velocities and angular accelerations of yaw are usually rather small, they can be neglected. The latter equations become much simpler in this case:

\[
\begin{align*}
\dot{j}_F^x &= \left[ (-\ddot{\vartheta} \cdot \sin \psi \cdot \sin \vartheta + \dot{\psi} \cdot \cos \vartheta)^2 + \dot{\vartheta}^2 \right] \cdot x + \\
&+ \left[ \ddot{\vartheta} \cdot \sin \psi \cdot \sin \vartheta - \ddot{\psi} \cdot \cos \vartheta + \dot{\vartheta} \cdot \dot{\psi} \cdot \cos \vartheta \cdot \sin \vartheta \right] \cdot y + \\
&+ \left[ \frac{1}{2} \dddot{\vartheta} \cdot \sin^2 \psi \cdot \sin 2\vartheta - \frac{1}{2} \dddot{\psi} \cdot \sin 2\vartheta - \ddot{\vartheta} \cdot \dot{\psi} \cdot \cos 2\vartheta \right] \cdot z, \\
\dot{j}_F^y &= \left[ (-\ddot{\vartheta} \cdot \sin \psi \cdot \sin \vartheta + \ddot{\psi} \cdot \cos \vartheta - \dot{\vartheta} \cdot \dot{\psi} \cdot \cos \vartheta \cdot \sin \vartheta \right] \cdot x - \\
&+ \left[ \dddot{\vartheta} \cdot \sin^2 \psi + \dddot{\psi} \cdot \sin^2 \psi \right] \cdot y + \\
&+ \left[ \ddot{\vartheta} \cdot \sin \psi \cdot \cos \vartheta + \dot{\vartheta} \cdot \dot{\psi} \cdot \cos \vartheta \cdot \cos \vartheta \right] \cdot z, \\
\dot{j}_F^z &= \left[ \ddot{\vartheta} + \dddot{\vartheta} \cdot \sin^2 \psi \cdot \frac{1}{2} \cdot \sin 2\vartheta - \\
&+ \frac{1}{2} \dddot{\psi} \cdot \sin 2\vartheta - \ddot{\vartheta} \cdot \dot{\psi} \cdot \sin \vartheta \cdot \cos \vartheta \right] \cdot x + \\
&+ \left[ \ddot{\vartheta} \cdot \sin \psi \cdot \cos \vartheta - \dot{\vartheta} \cdot \dot{\psi} \cdot \cos \vartheta \cdot \cos \vartheta + \dot{\vartheta} \cdot \dot{\psi} \cdot \cos \vartheta \cdot \sin \vartheta \right] \cdot y - \\
&+ \left[ \left( \ddot{\vartheta} \cdot \sin \psi \cdot \cos \vartheta + \dddot{\vartheta} \cdot \sin \vartheta \right)^2 + \dot{\vartheta}^2 \right] \cdot z.
\end{align*}
\]

To estimate linear acceleration projections on the accelerometers sensitivity axes it is possible to neglect stabilisation errors which are much less than the angles, angular velocities and angular accelerations of the object swaying are. It is apparent that the following equations are the case:

\[
\phi' \approx -\phi, \gamma' \approx -\vartheta, \beta' \approx -\psi.
\]

(5.7)
Accounting for (5.7), expressions for $j_Y^p, j_Z^p$ will take the following view:

\[
j_Y^p = \left[ \ddot{\vartheta} \cdot (1 - \cos \psi) \cdot \sin \psi \cdot \sin \vartheta + \dot{\psi} \cdot \cos \vartheta \cdot \cos \psi + \right. \\
\left. \frac{1}{2} \dot{\vartheta}^2 \cdot \cos \vartheta \cdot \sin 2\vartheta - \dot{\psi}^2 \cdot \sin \psi \cdot \cos \vartheta + \right. \\
\left. + \dot{\psi} \cdot \dot{\vartheta} \cdot \sin \vartheta \cdot \left( \sin^2 \vartheta - \cos \psi \cdot \cos \vartheta - 2 \cdot \cos \psi \right) \right] \cdot x + \\
\left[ - \dot{\psi} \cdot \sin \psi \cdot \cos^2 \vartheta - \dot{\vartheta}^2 \cdot \sin^2 \psi \cdot \cos \vartheta - \right. \\
\left. + \dot{\psi}^2 \cdot \cos \psi \cdot \sin \vartheta \cdot \sin 2\vartheta \right] \cdot y + \\
\left[ \ddot{\vartheta} \cdot \sin \psi \cdot \cos \vartheta \cdot (1 - \cos \psi) - \ddot{\vartheta} \cdot \sin \psi \cdot \sin \vartheta - \right. \\
\left. + \dot{\psi}^2 \cdot \sin \psi \cdot \sin \vartheta + \dot{\psi} \cdot \dot{\vartheta} \cdot \cos \vartheta \cdot \cos \psi \right] \cdot z, \tag{5.8}\]

\[
j_Z^p = \left[ - \ddot{\vartheta} \cdot \cos \vartheta + \ddot{\vartheta}^2 \cdot \sin \vartheta \cdot (1 + \sin^2 \psi) - \dot{\vartheta} \cdot \dot{\psi} \cdot \cos \vartheta \right] \cdot x + \\
\left[ - \ddot{\vartheta} \cdot \sin \psi + \ddot{\psi} \cdot \frac{1}{2} \sin 2\vartheta + \dot{\psi} \cdot \dot{\vartheta} \cdot (\cos \vartheta \cdot \cos^2 \psi) \right] \cdot y + \\
\left[ - \ddot{\vartheta} \cdot \sin \vartheta - \ddot{\vartheta}^2 \cdot \cos \vartheta \cdot (1 + \sin^2 \psi) - \dot{\vartheta} \cdot \dot{\psi} \cdot \sin \vartheta \cdot \sin \vartheta \right] \cdot z.
\]

In case of uniplane oscillations in OXZ plane:

\[
j_Y^p = 0,
\]

\[
j_Z^p = - \frac{d^2}{dt^2} (x \cdot \sin \vartheta + z \cdot \cos \vartheta). \tag{5.9}\]

In particular case of uniplane oscillations in OXY plane:

\[
j_Y^p = \frac{d^2}{dt^2} (x \cdot \sin \psi + y \cdot \cos \psi), \tag{5.10}\]

\[
j_Z^p = 0.
\]
Now let us estimate the platform levelling errors if basement oscillations result from the following harmonic law:

$$\psi = \psi_A \cdot \sin(\omega_F \cdot t + f_\psi),$$

$$\vartheta = \theta_A \cdot \sin(\omega_F \cdot t + f_\vartheta).$$

(5.11)

It is known [23], that in this case functions included into (5.11) expressions can be arranged into series:

$$\sin[\theta_A \cdot \sin(\omega_F \cdot t + f_\vartheta)] = 2 \cdot J_1(\theta_A) \cdot \sin(\omega_F \cdot t + f_\vartheta) +$$

$$+ 2 \cdot J_3(\theta_A) \cdot \sin 3(\omega_F \cdot t + f_\vartheta) +$$

$$+ 2 \cdot J_5(\theta_A) \cdot \sin 5(\omega_F \cdot t + f_\vartheta) + \ldots,$$

$$\cos[\theta_A \cdot \sin(\omega_F \cdot t + f_\vartheta)] = J_0(\theta_A) + 2 \cdot J_2(\theta_A) \cdot \cos 2(\omega_F \cdot t + f_\vartheta) +$$

$$+ 2 \cdot J_4(\theta_A) \cdot \cos 4(\omega_F \cdot t + f_\vartheta) + \ldots,$$

$$\sin[\psi_A \cdot \sin(\omega_F \cdot t + f_\psi)] = 2 \cdot J_1(\psi_A) \cdot \sin(\omega_F \cdot t + f_\psi) +$$

$$+ 2 \cdot J_3(\psi_A) \cdot \sin 3(\omega_F \cdot t + f_\psi) +$$

$$+ 2 \cdot J_5(\psi_A) \cdot \sin 5(\omega_F \cdot t + f_\psi) + \ldots,$$

$$\cos[\psi_A \cdot \sin(\omega_F \cdot t + f_\psi)] = J_0(\psi_A) + 2 \cdot J_2(\psi_A) \cdot \cos 2(\omega_F \cdot t + f_\psi) +$$

$$+ 2 J_4(\psi_A) \cdot \cos 4(\omega_F \cdot t + f_\psi) + \ldots,$$

(5.12)

where $J_n(\theta_A), J_n(\psi_A), n = 0, 1, 2, \ldots$, are Bessel’s functions of the first genus. The expressions obtained are used in (5.8) and then in equations (4.10). Final equations (4.10), after corresponding modifications and simplifications, can be used to estimate the levelling system error resulting from linear accelerations of the antenna suspension point during the object harmonic swaying. Preliminary estimation of this error showed that its constant component is the value of large order of smallness. It can be excluded from further consideration, because the requirements to the FAA
orientation errors for MAP of this type are on the level of tens of minutes of arc.

5.1.2 Horizontal Correction System Error Resulting from Random Linear Accelerations Influence

Real linear accelerations of the antenna suspension point on a moving object are random process. They could be regarded as stationary ones possessing normal distribution to a sufficient degree of accuracy. Accounting only for a low frequency region of spectrum (frequencies which are lower than the stabilisation system cut-off frequency), random linear accelerations could in full be characterised by the spectrum density:

\[
S_j(\omega) = \frac{2 \cdot \mu_j \cdot \sigma_j^2 \cdot \omega^2}{\pi \cdot \left[ \left( \omega^2 + \mu_j^2 - \lambda_j^2 \right)^2 + 4 \cdot \mu_j^2 \cdot \lambda_j^2 \right]}, \tag{5.13}
\]

where \( \sigma_j \) is the mean square value of linear accelerations, and \( \lambda \) and \( \mu \) characterise the distribution law. Introducing the standardised pure frequency \( \frac{\omega}{\sqrt{K}} = \nu \), it is possible to obtain the expression for the spectrum density:

\[
S_j(\nu) = \frac{2 \cdot \overline{\mu}_j \cdot \sigma_j^2 \cdot \nu^2}{\pi \cdot \left[ \left( \nu^2 + \overline{\mu}_j^2 - \overline{\lambda}_j^2 \right)^2 + 4 \cdot \overline{\mu}_j^2 \cdot \overline{\lambda}_j^2 \right]}, \tag{5.14}
\]

where: \( \mu_j = \overline{\mu}_j \cdot \sqrt{K} \), \( \lambda_j = \overline{\lambda}_j \cdot \sqrt{K} \).

Under the influence of random linear accelerations the mean square error will be determined with the expression:

\[
\sigma_{\Delta a} = \sqrt{\int_{-\infty}^{\infty} |K_j(\nu)|^2 \cdot S_j(\nu) d\nu}, \tag{5.15}
\]
which, after substituting the expression estimating $K_j$ and (5.14) and further integrating [24], takes the view:

$$\sigma_{\Delta \alpha} = \sigma_j \cdot \sqrt{\mu_j \cdot 2 \cdot \frac{L}{D}},$$

and where

$$D = \frac{1}{l_0} \cdot (\tau_f \cdot l_1 + 2 \cdot \xi_F) \cdot \left( l_0 \cdot 2 \cdot \xi_F \cdot \tau_F + l_1 + \tau_A^C \right) \cdot \left( \frac{l_1}{l_0} + \tau_A^C \right) \times$$

$$\times \left[ \left( \tau_f^2 \cdot l_0 + l_1 \cdot 2 \cdot \xi_F \cdot \tau_F + 1 \right) \left( 1 + l_0 + l_1 \cdot \tau_A^C \right) - 3 \cdot l_0 \cdot \tau_A^2 \right] -$$

$$+ \frac{\tau_f}{l_0} \cdot \left[ \frac{l_1}{l_0} + l_0 \cdot \left( \tau_A^C - 2 \cdot \xi_F \cdot \tau_F \right) + l_1 \cdot \tau_A^C \cdot \left( \frac{l_1}{l_0} + \tau_A^C \right) \right] \times$$

$$\times \left[ \left( \tau_f \cdot l_1 + 2 \cdot \xi_F \right)^2 \cdot \left( 1 + l_0 + l_1 \cdot \tau_A^C \right) + \right]$$

$$+ \frac{\tau_f}{l_0} \cdot \left( \tau_f \cdot l_1 + 2 \cdot \xi_F \right) \times$$

$$\left[ 2 \cdot \left( \frac{l_1}{l_0} + \tau_A^C \right) \cdot \left( \tau_f \cdot l_1 + 2 \cdot \xi_F \right) \cdot \left( \frac{\tau_f^2 \cdot l_0}{l_0} + \right. \right.$$

$$\left. + l_1 \cdot 2 \cdot \xi_F \cdot \tau_F + 1 \right) +$$

$$\left. + \tau_f \cdot \left( \frac{l_1}{l_0} + \tau_A^C \right) \cdot \left( 1 + l_0 + l_1 \cdot \tau_A^C \right) \right]$$

$$+ \left( \tau_f^2 + l_0 + l_1 \cdot 2 \cdot \xi_F \cdot \tau_F + 1 \right) \left( l_0 \cdot 2 \cdot \xi_F \cdot \tau_F + l_1 + \tau_A^C \right) \times$$

$$\times \left[ \tau_f^2 \cdot \left( \frac{l_1}{l_0} + \tau_A^C \right)^2 - \frac{1}{l_0} \cdot \left( l_0 \cdot 2 \cdot \xi_F \cdot \tau_F + l_1 + \tau_A^C \right) \cdot \left( \tau_f \cdot l_1 + 2 \xi_F \right) \right] -$$

$$\left( \frac{l_1}{l_0} + \tau_A^C \right)^2 \cdot \left[ \left( \tau_f \cdot l_1 + 2 \xi_F \right) \cdot \left( \frac{\tau_f^2 \cdot l_0}{l_0} + l_1 \cdot 2 \cdot \xi_F \cdot \tau_F + 1 \right)^2 + \right.$$

$$\left. + l_0 \cdot \tau_f^3 \cdot \left( \frac{l_1}{l_0} + \tau_A^C \right) \right],$$

(5.17a)
\[ L = \tau_A^2 \cdot (\tau_F \cdot l_1 + 2 \cdot \xi_F) \cdot \left( \tau_F^2 \cdot l_0 + l_1 \cdot 2 \cdot \xi_F \cdot \tau_F + 1 \right) \cdot \left( \frac{1}{l_0} + \tau_C^2 \right) - \\
+ \tau_A^2 \cdot \tau_F \cdot \left( l_0 \cdot 2 \cdot \xi_F \cdot \tau_F + l_1 + \tau_C^2 \right) \cdot \left( \frac{1}{l_0} + \tau_C^2 \right) - \\
+ \tau_A^2 \cdot \tau_F \cdot \left( \tau_F \cdot l_1 + 2 \cdot \xi_F \right)^2 + \tau_F^2 \cdot \left( \tau_F \cdot l_1 + 2 \cdot \xi_F \right) \cdot \left( \frac{1}{l_0} + \tau_C^2 \right) + \\
\frac{1}{l_0} \cdot \left( \tau_F \cdot l_1 + 2 \cdot \xi_F \right) \cdot \left( \tau_F^2 \cdot l_0 + l_1 \cdot 2 \cdot \xi_F \cdot \tau_F + 1 \right) \times \\
\times \left( l_0 \cdot 2 \cdot \xi_F \cdot \tau_F + l_1 + \tau_C^2 \right) - \frac{\tau_F}{l_0} \cdot \left( l_0 \cdot 2 \cdot \xi_F \cdot \tau_F + l_1 + \tau_C^2 \right)^2 - \\
+ \frac{\tau_F}{l_0} \cdot \left( \tau_F \cdot l_1 + 2 \cdot \xi_F \right)^2 \cdot \left( 1 + l_0 + l_1 \cdot \tau_C^2 \right), \]

where: \( l_0 = \mu_j^2 + \lambda_j^2, l_1 = 2 \cdot \mu_j \).

If the parameters of the object random swaying are known, through expression (5.16) it is possible to estimate the mean square error of the horizontal correction system resulting from linear accelerations effect in the antenna suspension point.

### 5.1.3 Horizontal Correction System Error Caused by Object Accelerated Translation Motion

The object is assumed to move over the ideal sphere with radius \( R' \), the instrumental horizon plane being adjusted ideally at the starting moment. The levelled platform angular positioning error, when its suspension point moves with acceleration, is estimated through the expression:
\[
\alpha_p = \frac{1}{\tau_F^2 \cdot \ddot{p}^4 + 2 \cdot \xi_F \cdot \tau_F \cdot \ddot{p}^2 + \tau_A^C \cdot \ddot{p} + 1} \times \left[ \frac{\tau_F^2 \cdot \ddot{p}^2 + 2 \cdot \xi_F \cdot \tau_F \cdot \ddot{p} + 1}{K \cdot R'} \right] \cdot \frac{1}{g} \cdot (\tau_A^C \cdot \ddot{p} + 1) \cdot \ddot{V},
\]

(5.18)

where \( \ddot{V} \) is the projection of the object centre of mass velocity on the direction of the corresponding accelerometer sensitivity axis.

A well-known condition of the horizontal correction contour invariance to linear accelerations of the platform suspension point can be derived from (5.18). In fact, it is necessary for \( K = \left( \frac{g}{R'} \right)^{-1}, \tau_A^C = 0, \tau_F = 0 \) to provide complete invariance [25]. Then it becomes clear that the system will be on the stability threshold and it will cause continuous oscillations with Shuller period at non-zero initial conditions. If only the condition \( K = \frac{g}{R'} \) is compiled, the static error will equal zero under the expose of constant linear acceleration. The selection of other system parameters corresponds to above presented methods and provides its inherent oscillations damping. For instance, if \( \lambda = 0.05, \chi = 0.465 \), the transition process with a jump acceleration will be described with the expression:

\[
\frac{g}{\ddot{V}} \cdot \Delta \alpha_p = -2.836 \left[ 0.42 \cdot e^{-0.37 \cdot \tau} - 0.164 \cdot e^{-5.5 \cdot \tau} - 0.48 \cdot e^{-1.67 \cdot \tau} \cdot \sin(4.25 \cdot \tau + 0.56) \right].
\]

(5.19)

The diagram of the transition process is shown in Fig. 5.1. Excessive correction may constitute approximately 1.15 in static deflection of the system, the parameters of which significantly differ from the invariant system \( (K \gg \left( \frac{g}{R'} \right)^{-1}) \). Damping is determined by the first non-periodic component of the transition process. The duration of this process can be estimated with the formula:
\[ \tau \approx -2.7 \cdot \ln(8.4 \cdot 10^{-3} \cdot \chi), \]

where \( \chi \) is the error as a percentage of static deflection (with \( \chi = 1\% , \tau = 13 \)).

\[ \frac{\Delta \alpha_p}{V} = \frac{1}{2} \cdot \tau^2. \]

*Fig. 5.1. Transition process in the horizontal correction contour met with acceleration jump at work if \( \lambda = 0.05 \) and \( \chi = 0.46 \).*

Under real conditions of the object motion the duration of the transition process is incommensurably larger than the duration of linear accelerations effect. That is the reason why real processes are determined by the initial length of the transition process curve, the diagram of which is identical to the inverse ratio of the square-law dependence:

If the object, in this case, gains speed \( V_0 \) at the expense of a single acceleration impulse, the error of the platform positioning in the horizon plane could be estimated from the expression:
\[ \Delta \alpha_p = \frac{1}{2 \cdot g} \cdot V_0 \cdot (2 \cdot \tau - \Delta \tau) \cdot \sqrt{\frac{g}{R'}}. \] (5.22)

The error reduction is very slow (the process lasts during tens of minutes), that is why expression (5.22) for a system installed on manoeuvring object estimates the error of the platform levelling resulting from its speeding up and braking.

### 5.2 Instrumental Errors of Focal Antenna Axis Elevation Angle Adjustment

The choice of the correcting contour structure and its parameters influences the dynamic errors of the levelling system if linear accelerations and the gyroscope dynamic errors are at work. These errors are specified by corresponding transfer functions of the open system. To generalise the results the following pure parameters are introduced as:

\[ \bar{p} = \frac{p}{\sqrt{K}}, \tau_f = T_F \cdot \sqrt{K}, \frac{T_A}{T_F} = \lambda, \tau_A = T_A^c, \omega_c \cdot T_F = \chi. \] The transfer functions of the closed-loop system of accurate adjustment in the instrumental horizon plane with linear accelerations and the gyroscope equivalent angular velocity are at work looks like this:

\[ K_j(\bar{p}) = \frac{\sqrt{\frac{\chi}{\lambda}} \cdot \bar{p} + 1}{(\lambda \cdot \chi) \cdot \bar{p}^4 + 2 \cdot \xi_F \cdot \sqrt{\lambda \cdot \chi} \cdot \bar{p}^3 + \bar{p}^2 + \sqrt{\frac{\chi}{\lambda}} \cdot \bar{p} + 1}, \] (5.23)

\[ K_{Ug}(\bar{p}) = \frac{(\lambda \cdot \chi) \cdot \bar{p}^2 + 2 \cdot \xi_F \cdot \sqrt{\lambda \cdot \chi} \cdot \bar{p} + 1}{(\lambda \cdot \chi) \cdot \bar{p}^4 + 2 \cdot \xi_F \cdot \sqrt{\lambda \cdot \chi} \cdot \bar{p}^3 + \bar{p}^2 + \sqrt{\frac{\chi}{\lambda}} \cdot \bar{p} + 1} \cdot \frac{\bar{p}}{K \cdot K_g}. \]
In Fig. 5.2 corresponding amplitude-frequency characteristics for $\lambda$ and $\chi$ which provide the admissible system phase and amplitude stability margin are presented.

![Amplitude-frequency characteristics](image)

**Fig. 5.2. Amplitude-frequency characteristics of the accurate levelling system with different phase and amplitude stability margins**

A set of curves indicated with numbers “2” in Fig. 5.2 characterise the system with larger phase and amplitude stability margins as compared with the system the characteristics of which are indicated with number “1”. Having analysed these characteristics it is possible to conclude that under the influence of linear accelerations $j^p_z$, $j^p_y$ in the frequency range less than $3\sqrt{K}$ the error of retaining the platform in the horizon plane is in fact equal to the ratio between their amplitude and free fall acceleration. With frequencies higher than $3\sqrt{K}$ filtration properties of the correcting contour
manifest themselves and the error becomes less at the intensity of -60dB/dec as frequency increases.

Harmonic components of the gyroscope zero signal influence on the error is also the largest in the frequency range \(3\sqrt{K}\). This influence decreases at the intensity -20dB/dec as frequency becomes greater or less. Thus, at low frequencies (below the base frequency) the system error is proportional to the gyroscope zero signal, the latter being equivalent to angular acceleration; at high frequencies it is proportional to the zero signal equivalent to the platform turning angle around its corresponding axis. The choice of the correcting contour determines the requirements for the horizontal channels gyroscope zero signal uniquely. It is apparent that harmonic components of the zero signal are to be limited in the following way:

\[
\sqrt{\sum_{i=1}^{n} \left[ \frac{1}{K^i} \left| \omega_E^i(v_1) \cdot \omega_E^{-i}(v_1) \right| \right]^2} < \Delta \alpha \quad (5.24)
\]

where \(\omega_E^i(v_1)\) is the amplitude of the gyroscope zero signal first harmonic reduced to the equivalent angular velocity and "n" is the number of zero signal harmonic components. If it is necessary to obtain significant filtration properties of the contour, this limit might appear to be rather tangible [26]. For instance, if the base frequency chosen equals 0.01 Hz, the harmonic component of the gyroscope zero signal in the frequency range of 0.03 Hz is to satisfy the condition: \(\omega_E^i[\%] < 0.25 \cdot \Delta \alpha \) [minutes of arc]. In this case it is necessary to bear in mind that \(\Delta \alpha\) forms only a part of a permissible error \(\Delta \alpha\), which also comprises errors resulting from:

- equivalent linear acceleration effects in the point of the antenna suspension, this linear acceleration being transferred to the accelerometer inlet along the corresponding axis;

- a random component of the accelerometer instrumental error proper;
• a random component of the instrumental error for the electro-
mecanical unit of the FAA elevation angle control.

The error caused by the equivalent linear acceleration effect was thoroughly
described in the preceding sections; it was determined through the following
components:

• for an object harmonic swaying expression (4.10) was used with
regard to substitutions (5.8) and (5.12);

• for an object random swaying expression (5.16) was used;

• for an object accelerated translation motion expression (5.22) was
used.

The composition and the quantity of the random component of the
accelerometer instrumental error are determined by the type and the class of
the acceleration transducer used and comprises such typical components as
zero signal drift in one triggering, zero signal drift during the life time and
temperature coefficient of zero displacement. The constant component of the
accelerometer zero signal is usually known and is estimated with
the corresponding calibrations for its further compensation in the system by
electronic means. The random component of the instrumental error in the
unit of FAA elevation angle control also depends on concrete realisation of
both this unit and its element base. An instrumental error constant
component of such unit can be calculated or measured by corresponding
means for its further compensation (or to take account of it) in the system
itself. That is why instrumental error constant components of the
accelerometer and the unit of FAA elevation angle control are not
considered within the permissible error $\Delta \alpha_1$.

5.3 Instrumental Errors of Azimuthal Channel

Among typical operational modes of the system of spatial stabilisation and
control the basic ones are the modes with a constant quantity of external
influence, when external influence changes with a constant velocity and
harmonic and free influences. If to consider the azimuth channel maximum autonomous, it is possible to single out the basic types of instrumental errors caused by (Fig. 3.3b):

- external disturbances $M_X$,
- equivalent angular velocity of the gyroscope $\omega^X_F$ attached to the integrator inlet in the stabilisation azimuthal channel,
- vertical component of the Earth’s rotation angular velocity $\Omega_V$ on the accelerometer inlet,
- search motion in the form of harmonic influence.

These errors can be estimated with the help of corresponding transfer functions of the closed system. The transfer function of the closed system with respect to external influence has the view:

$$\begin{align*}
K^X(p) &= \frac{\Delta\varphi}{M_X} = \frac{K_X \cdot p}{K^X \cdot \Delta\varphi_1} \times \\
&\times \frac{T_F^2 \cdot p^2 + 2 \cdot \xi_F \cdot T_F \cdot p + 1}{T_F^2 \cdot \Delta\varphi_1 \cdot p^4 + \frac{2 \cdot \xi_F \cdot T_F}{K^X \cdot \Delta\varphi_1} \cdot p^3 + \frac{1}{K_X \cdot \Delta\varphi_1} \cdot p^2 + T^R \cdot p + 1},
\end{align*}$$

(5.25)

where $K^X = K_X \cdot K_I \cdot K^X_R \cdot K^X_M$ is the gain factor of the open system.

Transfer functions of the closed system with respect to the gyroscope equivalent angular velocity influence as well as to the vertical component of the Earth’s angular velocity look like:
\[ K_{\Omega_x}(p) = \frac{\Delta \phi}{\omega_{\Omega_x}} = \frac{p}{K \cdot \Delta \phi} \times \]
\[ \frac{\left( T_F^2 \cdot p^2 + 2 \cdot \xi_F \cdot T_F \cdot p + 1 \right)}{K \cdot \Delta \phi_1 \cdot p^4 + \frac{2 \cdot \xi_F \cdot T_F}{K \cdot \Delta \phi_1} \cdot p^3 + \frac{1}{K \cdot \Delta \phi_1} \cdot p^2 + T_R^E \cdot p + 1} \]  \hspace{1cm} (5.26)

\[ K_{\Omega_y}(p) = \frac{\Delta \phi}{\Omega_{\Omega_y}} = \frac{p}{K \cdot \Delta \phi} \times \]
\[ \frac{\left( T_F^2 \cdot p^2 + 2 \cdot \xi_F \cdot T_F \cdot p + 1 \right)}{K \cdot \Delta \phi_1 \cdot p^4 + \frac{2 \cdot \xi_F \cdot T_F}{K \cdot \Delta \phi_1} \cdot p^3 + \frac{1}{K \cdot \Delta \phi_1} \cdot p^2 + T_R^E \cdot p + 1} \]  \hspace{1cm} (5.27)

As the polynomial of the numerator in each transfer function of the closed system (5.26) and (5.27) has a zero root, this system would be astatic in respect to disturbing influences \( \omega_{\Omega_x} \) and \( \Omega_{\Omega_y} \), i.e. there will be no static error in this system. These expressions are identical to those of the closed transfer function (5.23) accurate adjustment in the instrumental horizon plane when influenced by the gyroscope equivalent velocity. The procedure for their normalising could be accomplished in the similar way by using, for instance, the corresponding gain factor of the open system. For engineering design of such systems a family of amplitude-frequency characteristics with different phase and amplitude stability margins could be plotted after their normalisation, in accordance with expressions (5.26) and (5.27). The final selection of parameters for a correcting contour would be determined by required system phase and amplitude stability margins and they could be estimated from these diagrams. In this case, limitation on harmonic components of the gyroscope zero signal will take the form analogous to expression (5.24):

\[ \sqrt{\sum_{l=1}^{n} \left[ \frac{1}{K \cdot \Delta \phi} \cdot K_{U_x}^X(v_l) \cdot \omega_{\Omega_x}^X(v_l) \right]^2} < \Delta \phi_{\omega_{\Omega_x}^X}, \]  \hspace{1cm} (5.28)
where $\Delta \varphi_{\omega e}^{\infty}$ represents only partial tolerance for a regulated quantity $\Delta \varphi$ which comprises the amplitude of the harmonic assigning influence $\Delta \varphi_1$. It is worth mentioning that the azimuthal channel total error as compared to that of the FAA elevation angle channel consists of a smaller number of components caused by a smaller amount of external disturbances. Besides, the extreme system is included into the azimuthal channel as far as the regulated value $\Delta \varphi$ is concerned. That is why it is possible to draw a conclusion that expression (5.24) imposes much stricter limitations on gyroscope zero signal harmonic components as compared to expression (5.28). The choice of gyroscopic sensitive elements during engineering designing could be accomplished from the view point of their unification, on the basis of limitations determined by expression (5.24).

5.4 General Recommendations for Permissible Errors Distribution and Estimation

The required zone for spatial orientation of FAA directionning to the satellite is determined by maximum permissible error $\pm \Delta_{\text{max}}$ which depends on the receiving antenna diameter (Table 2.1). This zone has the form of a circle with the radius $R = \Delta_{\text{max}}$ and its centre coincides with point “O”, i.e. the point of the satellite signal reception in the geographical system of coordinates (Fig. 5.3). The maximum permissible error of FAA positional orientation to the satellite $\pm \Delta_{\text{max}}$ is determined by two components:

1. The total error of the azimuthal channel $\Delta \varphi_{\text{max}}$.

2. The total error of the elevation angle channel $\Delta \beta_{\text{max}}$.

In general, such a relationship should be observed:

$$\Delta_{\text{max}} \geq \sqrt{\Delta \varphi_{\text{max}}^2 + \Delta \beta_{\text{max}}^2}.$$  (5.29)

If to assume that tolerances for channels errors are distributed equivalently, these components could be calculated with the formula used for determining ABCD square side through the radius $R = \Delta_{\text{max}}$ of the circle described:
\[ \Delta \beta_{\text{max}} = \Delta \varphi_{\text{max}} = \frac{\Lambda_{\text{max}}}{\sqrt{2}}. \]  

(5.30)

That is why, the requirement imposed on maximum permissible errors of both the azimuthal channel and the channel of the elevation angle could be written as the following:

\[ \Delta \beta \leq \frac{\Lambda_{\text{max}}}{\sqrt{2}}, \quad \Delta \varphi \leq \frac{\Lambda_{\text{max}}}{\sqrt{2}}. \]  

(5.31)

Fig. 5.3. Dependency of the reception spot displacement from the direction of the object motion
Equivalent distribution of permissible errors between the channels could be of practical use only when these channels possess similar structure and parameters. In our case it is possible for both the levelling system and that of stabilisation along axes Y and Z comprised into the FAA elevation angle channel. Hence, the error of the mechanism of the FAA elevation angle adjustment is to be subtracted from the permissible error of the elevation angle channel $\Delta \beta_{\text{max}}$, and the error remainder is to be equivalently distributed between the channels corresponding to axes Y and Z. It is worthwhile to introduce weight coefficients of errors as regards the channels of the FAA elevation angle and the azimuthal channel which would make it possible to distribute maximum permissible errors to impair the requirements towards the elements and some subsystems.

When designing a system with a present maximum permissible error $\pm \Delta_{\text{max}}$, the structure and the parameters of one of the channels controlling the FAA positioning are assumed to be determined first thus allowing to estimate the maximum possible error of this channel. From Fig. 5.3 the coefficient “C” for the relationship between channels errors can be estimated like:

$$tg \delta = \frac{\Delta \beta}{\Delta \varphi} = C.$$  \hspace{1cm} (5.32)

Using expressions (5.29) and (5.32) the expressions for limiting the coefficients of the relationship looks:

- if the initial quantities are $\pm \Delta_{\text{max}}$ and $\Delta \beta_{\text{max}}$:

$$C_{\text{max}} \geq \frac{\Delta \beta_{\text{max}}}{\sqrt{\Delta_{\text{max}}^2 - \beta_{\text{max}}^2}}, \Delta \varphi_{\text{max}} \leq \frac{\Delta \beta_{\text{max}}}{C_{\text{max}}};$$  \hspace{1cm} (5.33)

- if the initial quantities are $\pm \Delta_{\text{max}}$ and $\Delta \varphi_{\text{max}}$:

$$C_{\text{max}} \leq \frac{\sqrt{\Delta_{\text{max}}^2 - \Delta \varphi_{\text{max}}^2}}{\Delta \varphi_{\text{max}}}, \Delta \beta_{\text{max}} \leq \Delta \varphi_{\text{max}} \cdot C_{\text{max}};$$  \hspace{1cm} (5.34)
It could be seen in Fig. 5.3 that it is possible to describe possible combinations of errors distribution between the channels as regards the relationship between the sides of those rectangles which are shown with dashed lines and those ones which are inscribed in the circle with the radius \( R = \Delta_{\max} \). If the rectangle longer side is oriented along the axis \( \Delta \varphi \), the azimuthal channel of the system designed appears to be the "bottle-neck" and it will reserve the largest amount of the total system error. If the rectangle long side is oriented along the axis \( \Delta \beta \), the situation would become exactly the converse.

The analysis given in Sections 5.1 and 5.2 showed that the total error of the FAA elevation angle channel possesses a rather complex structure and a varied interaction of its components. Besides, the absence of the extreme system in this channel imposes certain limitations on the duration of continuous MAP operation without periodic data updating concerning the object’s actual location changes throughout telecommunication with one satellite. That is why, when designing systems like this one and when employing them on various objects, it is worthwhile to estimate the territory, the time period and the MAP continuous operation without preliminary FAA elevation angle correction. The whole time period of the MAP continuous operation, when the elevation angle \( \beta \) is not corrected, could be determined with the expression:

\[
\Delta \beta_* \geq \int_0^T \dot{\beta}(t) \, dt,
\]

(5.35)

where \( \Delta \beta_* \) is a permissible change of the FAA elevation angle towards the satellite within the required zone of spatial orientation if the object moves over the Earth’s surface with a linear velocity \( \ddot{V} \), \( \dot{\beta} \) is the corresponding angular velocity and \( T \) is the time period of the MAP elevation angle correction. In Fig. 5.3 one could see an arbitrarily error distribution in the MAP channels \( \Delta \beta_0 \) and \( \Delta \varphi_0 \) assigned in the form of rectangle A'B'C'D'. For MAP without an extreme system in the azimuthal channel (see Fig. 5.3) the FAA spatial orientation changes in accordance with two co-ordinates, i.e. the elevation angle \( \Delta \beta_* \) and the azimuth angle \( \Delta \varphi_* \), and this change
results from the $\Delta \beta, \Delta \varphi, O$ co-ordinates system going to the $\Delta \beta', \Delta \varphi', O'$ system of co-ordinates. So, $\Delta \beta'$ can be calculated via triangle OO'D' by means of the expression:

$$
\Delta \beta' = \sqrt{\Delta_{\text{max}}^2 - \Delta \beta_0^2 - \Delta \varphi_0^2 - \Delta \varphi_0'^2}.
$$

(5.36)

The change of the FAA spatial orientation in accordance with the azimuth angle can be compensated if to use the extreme system in the MAP azimuth channel; thus, the change of the spatial orientation in accordance with the azimuth angle during free object motion over the Earth’s surface will not take place. In this case, the FAA spatial orientation will change only in accordance with the elevation angle $\Delta \beta''$ (See Fig. 5.3) through transferring the $\Delta \beta, \Delta \varphi, O$ system of co-ordinates into that of the $\Delta \beta'', \Delta \varphi', O''$. Thus, $\Delta \beta''$ can be easily calculated with the chord $|A'B'| = 2 \cdot \Delta \varphi_0$ and the radius of the permissible zone $\Delta_{\text{max}}$ in the expression:

$$
\Delta \beta'' = \sqrt{\Delta_{\text{max}}^2 - \Delta \varphi_0^2 - \Delta \varphi_0''^2}.
$$

(5.37)

The vector of the object linear velocity $\vec{V}$ consists of two components: the vector characterising the change of the object’s longitude by the object itself $\vec{V}_L$ and the vector characterising the change of the object’s latitude also by the object itself $\vec{V}_B$. These components could be determined with the object heading angle (Fig. 5.4) as follows:

$$
\begin{align*}
\vec{V}_B &= V \cdot \cos \varphi_k, \\
\vec{V}_L &= V \cdot \sin \varphi_k.
\end{align*}
$$

(5.38)

Taking into account that the objects linear velocity $\vec{V}$ is connected with its angular velocity $\vec{\omega}^0$ through the Earth’s radius, expressions for corresponding components of the object’s angular velocity when the object moves over the Earth’s surface look like:
\[ \omega^0_B = \frac{V \cdot \cos \varphi_k}{R_E}, \]
\[ \omega^0_L = \frac{V \cdot \sin \varphi_k}{R_E \cdot \cos B}, \]

where \( R_E = (6378,169 \pm 0,008) \) km is the average equatorial radius of the Earth.

![Diagram of velocity vectors and Earth](image)

**Fig. 5.4. Dependence between the components of the linear velocity vector and the object heading angle**

It could be seen from (2.7) that the FAA elevation angle is the function of three variables: S, L and B. The angular velocity of changing the FAA elevation angle can be calculated by means of differentiating expression (2.7):
\[ \beta = \frac{\partial \mathcal{F}}{\partial \dot{B}} \cdot \dot{B} + \frac{\partial \mathcal{F}}{\partial L} \cdot \dot{L}, \] (5.40)

\[ \beta = f(B, L, S), \]

where \( \dot{B} = \omega^0_B, \dot{L} = \omega^0_L. \)

Calculations and transformation resulted in finding out that the angular velocity of the FAA elevation angle could be determined with two components, i.e. \( \dot{\beta}_L, \) which depends on the angular velocity of changing the geographical longitude by the object and \( \dot{\beta}_B, \) which depends on the angular velocity of changing the geographical latitude by the object. If the object’s velocity is constant (\( V = \text{const} \)), this dependence can be written like:

\[ \dot{\beta} = f(S, L, B, \omega^0); \]

\[ \dot{\beta} = \dot{\beta}_L + \dot{\beta}_B; \]

\[ \dot{\beta}_L = K_{\beta} \cdot K_L; \]

\[ \dot{\beta}_B = K_{\beta} \cdot K_B, \] (5.41)

\[ K_{\beta} = \frac{V \cdot (-1 + 0.15 \cdot \cos(L - S) \cdot \cos B)}{R \cdot \left(1,0225 - 0.3 \cdot \cos(L - S) \cdot \cos B\right) \cdot \sqrt{1 - \cos^2(L - S) \cdot \cos^2 B}}, \]

\[ K_B = \sin B \cdot \cos(L - S) \cdot \cos \phi_k, \]

\[ K_L = \sin(L - S) \cdot \sin \phi_k. \]

Actual values of the object’s longitude and latitude during its motion can be obtained from the expressions:
\[ B = \int B \dot{\alpha} = \frac{V \cdot \cos \varphi_k \cdot t + B_0}{R_E}, \]

\[ L = \int L \dot{\alpha} = tg \varphi_k \cdot \ln \left( \frac{tg \left( \frac{V \cdot \cos \varphi_k \cdot t + \pi + B_0}{2 \cdot R_E} \right) + \frac{B_0}{2}}{tg \left( \frac{\pi + B_0}{4} \right)} \right) + L_0. \]  

(5.42)

Expression (5.41), after inserting (5.39) and (5.42) into it, determines the dependence of the angular velocity when changing the FAA angular positioning on the distance covered by the object during its free motion over the Earth’s surface with a constant velocity. Let us analyse two particular cases of the object motion: first, when the vector of the object linear velocity is directed tangentially to the meridian, i.e. \( \varphi_k = 0^\circ \), and second, when the vector of the object linear velocity is directed tangentially to the parallel, i.e. \( \varphi_k = 90^\circ \). In the first case \( L = L_0, B = \frac{V \cdot t}{R_E} + B_0, \beta = K_\beta \cdot K_B \), and in the second \( B = B_0, L = \frac{V \cdot t}{R_E \cdot \cos B_0} + L_0, \beta = K_\beta \cdot K_L \). The time period for the MAP continuous operation without correcting the FAA elevation angle in such cases could be estimated with expressions:

\[ \sqrt{\Delta_{\text{max}}^2 - \Delta \varphi_0^2 - \Delta \beta_0^2} \geq 2 \cdot \left[ \left( 3,4 - \frac{\chi}{0,3} \right) \cdot \arctg \left( \frac{\chi}{2} - 0,3 \right) - \right. \]

\[ + \left. \left( 3,4 - \frac{\chi_0}{0,3} \right) \cdot \arctg \left( \frac{\chi_0}{2} - 0,3 \right) \right] \]  

(5.43)

where: in case \( \varphi_k = 0^\circ \)

\[
\begin{align*}
\chi_0 &= \arcsin \left[ \cos (L_0 - S_0) \cdot \cos B_0 \right], \\
\chi &= \arcsin \left[ \cos (L_0 - S) \cdot \cos \left( \frac{V \cdot t}{R_E} + B_0 \right) \right];
\end{align*}
\]  

(5.44)
and in case $\varphi_k = 90^\circ$

$$
\left\{
\begin{array}{l}
\chi_0 = \arcsin\left[\cos(L_0 - S_0) \cdot \cos B_0\right], \\
\chi = \arcsin\left[\cos\left(\frac{V \cdot t}{R_E \cdot \cos B_0} + L_0 - S\right) \cdot \cos\left(\frac{V \cdot t}{R_E} + B_0\right)\right].
\end{array}
\right.
$$

(5.45)

As an example, let us consider how to estimate the time period of continuous MAP telecommunication with one of the satellites without additional correcting the FAA elevation angle. Assuming that linear vessel velocity equals 30 knots, $\varphi_k = 0^\circ$, $\Delta \beta_1 = 0.5^\circ$, $L_0 = S$; $B_0 = 45^\circ$, $\dot{\beta} = 6 \cdot 10^{-4}\frac{0^\circ}{s}$, $t \approx 14$ min. The calculations conducted allow, on the one hand, to practically estimate how long the vessel can move without correcting the initially set FAA elevation angle if there is no extreme system in the FAA elevation angle channel. On the other hand, these data allow to estimate the required occurrence of data updating concerning the object’s geographical location in order to elaborate requirements to the support equipment from which such information could be received and on the basis of which the FAA elevation angle can be corrected by GPS, for instance.

### 5.5 Conclusions

The error of retaining the required FAA orientation and the antenna polarisation plane in the inertia space by means of an autonomous gyroscopic indicator system of stabilisation and control, if this system is realised as a combination of a two-axes gyrostabiliser supplied with the horizontal correction contour and a single-axis gyrostabiliser with the extreme system in the azimuth installed on the two-axes gyrostabiliser, consists of two major errors: the error of the azimuthal angle adjustment and the error of the FAA elevation angle adjustment in the satellite direction. These errors are, in their turn, determined by the structure of the azimuthal channel and the channel of the MAP elevation angle. The analysis described in Chapter 5 and its results enable us to draw some conclusions concerning these errors estimation.
The elevation angle channel comprises the system of two-axes gyroscopic stabilisation, the axes being positioned horizontally, the system of rough and accurate GSP adjustment in the instrumental horizon plane and the mechanism for the FAA elevation angle adjustment, and taken as a whole they determine the structure of its total error. In sections 5.1 and 5.2, basic errors resulting from linear accelerations of the antenna suspension point influence in diverse forms of object motion and harmonic components of the gyroscope zero signal are investigated. Expressions suitable for estimating errors occurring during the object's harmonic oscillation motion under the influence of equivalent linear accelerations (expression (4.10) in view of (5.8) and (5.12) substitution) as well as during its accelerated translational motion (expression (5.22) and during random oscillation motion (expression (5.16) are obtained. Amplitude frequency characteristics for the system of accurate levelling are drawn on the basis of transfer functions of the closed system of accurate adjustment in the horizon in accordance with linear accelerations influence and the gyroscope equivalent linear velocity (5.23). The analysis of these characteristics proved that with frequencies lower than that of the accurate levelling system basic one the error is proportional to the gyroscope zero signal, the latter being equivalent to angular acceleration, while with higher frequencies it is proportional to the zero signal equivalent to the angle of the GSP turn round its corresponding axis. These errors are dominant in the structure of total error of the elevation angle channel.

Major instrumental errors of the azimuthal channel result from: external disturbances, the gyroscope equivalent angular velocity, the vertical component of the angular velocity of the Earth's revolution and the search motion in the form of harmonic influence. Errors caused by first three disturbances are calculated in accordance with the corresponding transfer functions of the closed system of the single-axis gyrostabiliser (5.25), (5.26) and (5.27). On exposure to these influences the system does not possess a static error. The amplitude of
the harmonic assigning influence is completely comprised in the azimuthal channel total error.

- Expressions (5.24) and (5.28) imposing limitations on harmonic components of the gyroscope zero signals in corresponding channels are obtained. These expressions determine the choice of the gyroscopic sensitive element and they also characterise the system filtrating properties. From the view point of the element base unification in the process of engineering design, expression (5.24) would be the governing one when choosing the type of the gyroscopic sensitive element, for the total error with regard to the elevation angle channel possesses a more complex structure as compared to the azimuthal channel total error.

- Recommendations for distributing permissible error among the channels and subsystems when designing systems similar to MAP could be derived from expression (5.29) in a general way. Expressions (5.33) and (5.34) impose limitations on coefficients of relation between these errors, if initial data varies. The absence of the extreme system in the elevation angle channel reduces the duration of the MAP continuos operation, if not to correct this angle in accordance with the object’s current position changing. To estimate the time and the location where continuous telecommunication is being conducted without accomplishing correction accurately enough, expression (5.35), with due regard to (5.41), (5.39) and (5.42) substitution, could be used with objects moving with constant velocity. Time and location are the functions of several variables, i.e. the satellite longitude, the object’s heading, initial and actual magnitudes of the object coordinates and angular velocity when it moves along the Earth’s surface arbitrarily. The FAA elevation angle correction should be accomplished more often, if the direction of the object linear velocity vector coincides with the satellite directioning. It could be corrected as often as four times during an hour. The ability to estimate how often to renew data about the object actual position in each case when MAP is employed makes it possible to formulate requirements for maintenance equipment from which such information could be
obtained for correcting the FAA elevation angle automatically, without a human help.

- Chapter 5 describes methods of errors estimation and expressions for their calculation, they are presented in the form convenient for engineering calculations when designing similar systems.
As an approbation of theoretical investigations and the scheme proposed for constructing the MAP three-axes gyrostabiliser, a demonstrator of the gyrostabilised antenna post MAP-120 for receiving satellite TV-signals was produced in 1993.

6.1 Experimental Investigations of Demonstrator

6.1.1 Description

The classic scheme for constructing a three-axes system of gyrostabilisation was realised in the demonstrator. The gyrostabiliser comprises:

- Three-axes gimbal mount with a vertically positioned internal gimbal mount frame and horizontally positioned external and intermediate frames.

- Two unirotor vibrational gyroscopes, their specification being described in Table 6.1. One of them is installed on the internal gimbal
mount frame so that the direction of one of its sensitivity axis is coincident with the internal frame turn axis. The second gyroscope is installed on the intermediate frame so that its sensitivity axes are collinear to the external and intermediate frames axes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Zero signal random component independent on linear acceleration, $%_h$, not more than</td>
<td>10</td>
</tr>
<tr>
<td>2. Range of angular velocities measured, $%_s$</td>
<td>90</td>
</tr>
<tr>
<td>3. Stability of scale factor, %, not more than</td>
<td>3</td>
</tr>
<tr>
<td>4. Linear acceleration sensitivity, $%_h/g$</td>
<td>6</td>
</tr>
<tr>
<td>5. Temperature coefficient of zero signal drift, $%_h/oC$, not more than</td>
<td>0,2</td>
</tr>
<tr>
<td>6. Wattage, W, not more than</td>
<td>2,5</td>
</tr>
<tr>
<td>7. Dimensions, mm</td>
<td>$\varnothing 50 \times 60$</td>
</tr>
<tr>
<td>8. Mass, g</td>
<td>450</td>
</tr>
</tbody>
</table>

Table 6.1 Unirotor vibrational gyroscope specification

- Two pendulous accelerometers, their characteristics given in Table 6.2, are installed, in accordance with the classical scheme, on the internal frame, the latter being the GSP with the minimal level of outer disturbances.
- Three DC collector torque motors are installed on each of the gimbal mount axes accordingly and there are three angle-data transmitters of the transformer type. The azimuthal channel angle-data transmitter is a sine-cosine transformer which is used for co-ordinate transformation to match the gyroscopes sensitivity axes and those of the gimbal mount.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Measurements range, g</td>
<td>+(3...100)</td>
</tr>
<tr>
<td>2. Zero signal drift in one triggering, g</td>
<td>±10^{-5}</td>
</tr>
<tr>
<td>3. Instability of rate of change property, %</td>
<td>0,15</td>
</tr>
<tr>
<td>4. Temperature coefficient of rate of change property, (\text{oC}^{-1})</td>
<td>6\cdot10^{-4}</td>
</tr>
<tr>
<td>5. Temperature coefficient of zero displacement, (\text{g/oC})</td>
<td>3\cdot10^{-5}</td>
</tr>
<tr>
<td>6. Sensitivity threshold, g</td>
<td>1\cdot10^{-5}</td>
</tr>
<tr>
<td>7. Frequency:</td>
<td></td>
</tr>
<tr>
<td>• bandwidth on the 3 dB level, Hz, not less than</td>
<td>10...80</td>
</tr>
<tr>
<td>• damping factor</td>
<td>0,5</td>
</tr>
<tr>
<td>8. Dimensions, mm</td>
<td>26\times11\times22</td>
</tr>
<tr>
<td>9. Mass, g</td>
<td>55</td>
</tr>
</tbody>
</table>

Table 6.2. Specification of pendulous accelerometer

- A parabolic antenna with a centred focus and a dish diameter of 120 cm which is installed on the gimbal mount internal axis by means of an additional axis to regulate and fix the FAA elevation angle to the
satellite manually. To adjust the FAA elevation angle to the satellite more accurately, a special displacement signal is used and it is transmitted to the corresponding inlet of the levelling system and makes it possible to measure the FAA elevation angle within the range of ±15° if the geographical position of the vessel changes significantly.

- The electronic block producing signals for operating and controlling the torque motors which is electrically connected with the control board.

The photo of the MAP-120 demonstrator is shown in Fig. 6.1. Its electronic block photo is shown in Fig. 6.2. Its control board for regulating the FAA position is shown in Fig. 6.3. On its front panel there are two limbs with the minimal scale division of 0.5°, in accordance with which two angles are adjusted manually, i.e. the vessel relative heading and the satellite azimuth in the geographical co-ordinates system. The satellite search is realised according to the principle of the "electric spring" mode, where a signal proportional to difference between the vessel relative heading and the satellite azimuth has to be transmitted from the control board to the electronic block and then to the stabilising motor in the azimuth channel. The electro-kinematic scheme of the FAA stabilisation and control system provides three basic operational modes: search, acquisition and tracking in the direction of the maximum satellite TV-signal as well as three service modes necessary to accomplish the basic ones, i.e. stabilisation, rough, and accurate levelling. The extreme system works in the azimutal channel and it provides a correction of the FAA azimutal angle, the criterion being the maximum value of the TV-signal received from a satellite. This signal is transmitted from the TV-receiver into the azimutal channel controlling the FAA position through the feedback. To make it possible to perform the extreme system functions the harmonic oscillations produced with the help of the generator are used in the azimutal channel control system.
Fig. 6.1. Demonstrator of the MAP-120
Fig. 6.2. Electronic block of the MAP-120 demonstrator

Fig. 6.3. Control board of the MAP-120 demonstrator
The succession of modes changes to insure reliable satellite TV-signal acquisition and its tracking corresponds to the cyclogram described above. The techniques and the results of both the laboratory and field tests of this demonstrator are described further on. The basic specification of the MAP demonstrator with the three-axes gyrostabilisation and control system is given in Table 6.3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Range of gimbal mount swaying angles, arc:</td>
<td>±13</td>
</tr>
<tr>
<td>- along horizontal external axis (Y_a),</td>
<td></td>
</tr>
<tr>
<td>- along horizontal intermediate axis (Z_a),</td>
<td>±14</td>
</tr>
<tr>
<td>- along vertical internal axis (X_a).</td>
<td>±145</td>
</tr>
<tr>
<td>2. Range of FAA elevation angle adjustment over the plane of instrumental horizon, arc</td>
<td>+11...+34</td>
</tr>
<tr>
<td>3. Maximum torque value along stabilisation axes gained by collector motor, g (\times) cm</td>
<td>10000</td>
</tr>
<tr>
<td>4. Inertia moments of the gyrostabilised platform relative to corresponding gimbal mount axes, g (\times) cm (\times) s</td>
<td></td>
</tr>
<tr>
<td>- external axis, (I_{Y_a}) ,</td>
<td>145000</td>
</tr>
<tr>
<td>- intermediate axis, (I_{Z_a}) ,</td>
<td>144000</td>
</tr>
<tr>
<td>- internal axis, (I_{X_a}) .</td>
<td>30000</td>
</tr>
<tr>
<td>5. Resistance moments in gimbal mount axes, g (\times) cm, not more than:</td>
<td></td>
</tr>
<tr>
<td>- external axis, (M_{Y_a}) ,</td>
<td>1200</td>
</tr>
<tr>
<td>- intermediate axis, (M_{Z_a}) ,</td>
<td>900</td>
</tr>
<tr>
<td>- internal axis, (M_{X_a}) .</td>
<td>1050</td>
</tr>
<tr>
<td>6. Radom inner radius, mm</td>
<td>1100</td>
</tr>
<tr>
<td>7. Voltage, V</td>
<td>27</td>
</tr>
<tr>
<td>8. Wattage, W</td>
<td></td>
</tr>
<tr>
<td>- peak value</td>
<td>100</td>
</tr>
<tr>
<td>- rated power value</td>
<td>40</td>
</tr>
</tbody>
</table>

*Table 6.3. Specification of the MAP-120 gyrostabilisation system*
6.1.2 Laboratory Investigations

Laboratory investigations consisted of measuring basic static and dynamic characteristics of the three-axes gyrostabiliser demonstrator supplied with a contour of horizontal correction as well as an extreme system in the modes of search, acquisition and retaining the FAA direction in the azimuth in accordance with the maximum level of the satellite TV-signal received. Some effects identical to the exploitational ones, which also influence these characteristics, were estimated. Investigations were accomplished at +20°C indoors with normal relative humidity.

The following static characteristics of the gyrostabiliser were measured as a consequence of these investigations:

- regulator gain factor in each channel,
- static error of the platform stabilisation in the horizon plane,
- error of the distance adjustment of the pre-set FAA angle of elevation.

The regulator gain factor in each channel was measured when the systems of the three-axes stabilisation and horizontal correction were operating. Astatic moment as a system of calibrated loads was applied on a prefixed lever along each mount axis. The initial position of the reference point on each the mount frame was registered with the help of collimator. Following the moment action upon the collimator digital information representing new angular positioning of this point picture in respect to its initial positioning was taken visually. To make the final measurement result more precise measurements were taken up to a dozen times for each axis and then, on the basis of the sample obtained, the maximum (the worst) value was selected.

The static error of the platform stabilisation in the instrumental horizon plane was measured after the mode of rough adjustment in the horizon plane had been completed, as 60 seconds passed after supplying power into the system. Accelerometers zero signals were calibrated in advance with the help of the liquid level during a single system trigger action.
The position of each horizontal gimbal mount frame resulting from such a calibration was regarded as the initial one, and then it was refere to the zero mark on the collimator angular scale. After that the levelling system was re-triggered, and during each triggering new external and intermediate gimbal mount frames positioning in the horizon plane was compared with the initial one with the help of the same collimator after 60 seconds had passed. Measurements were taken up to a dozen times in each horizontal channels, and the maximum (the worst) value of the static error of the platform stabilisation in the instrumental horizon plane was regarded as the final one.

The error of the distance adjustment of the pre-set FAA elevation angle (azimuth) was determined while all the gyrostabiliser systems were functioning. To measure it a special imitator of the satellite signal was used.

A radiation with the pattern identical to a designed one was formed with the help of the LED installed on a stationary arm. A photodiode was attached to the internal gimbal mount frame so that its optical axis was located in the FAA vertical plane and it coincided with the LED optical axis when the antenna passed through its directional radiation pattern. The overlapping of optical axes was fulfilled in accordance with the criterion of the maximum signal on the photodiode outlet and its value was registered with the help of the pointer indicator on the key-board. The reading point on the collimator horizontal scale was set in accordance with the reference mark position on the antenna dish surface and it, in its turn, corresponded to the maximum signal on the photodiode. The relative bearing of an conjectured mobile object and the angle of the FAA azimuthal directioning to the satellite were adjusted arbitrarily on the key-board limb. The initial FAA positioning in the azimuth prior power supply differed from the real directioning to the imitator by ±180°. On supplying power to the gyrostabiliser and after completing the mode of “rough” adjustment into the instrumental horizon plane the mode of “electrical spring” was switched on when a signal from the key-board was transmitted into the channel of the FAA controlling in the azimuth, the latter being proportional to the difference between the pre-set angles. On accomplishing the mode of the “electrical spring” the system of the extreme search began operating. When the indicator pointer reached its
maximum value the position of the reference mark picture was determined in respect to the reading point on the imitator horizontal scale, and it corresponded to the error of the pre-set FAA angle of elevation (azimuth). Such measurements were taken up to a dozen times while the antenna was rotating clockwise and counter clockwise. The maximum error value was regarded as the measurements result.

The following dynamic characteristics of the gyrostabiliser were measured during the investigation:

- time required to set the platform from the maximum initial angles of the gimbal mount frames displacement into the horizon plane with the error not exceeding ±10°,

- time required for the FAA pre-set directioning in azimuth with the error of ±40°, the initial deflection from this direction corresponding to ±180°,

- error of the platform stabilisation during a regular three-component oscillation motion of a mobile basement with the heading amplitude of ±90° and trim angles amplitudes of ±8°, the frequency being 0,06 Hz.

Measuring the time period necessary for setting the platform into the horizon plane was accomplished simultaneously with measuring the static error of the platform stabilisation; in both cases the methods applied were identical. Initial deflection angles along the three gimbal mount axes were set maximum permissible for this mount construction. During each system triggering the timing device registered the time when the picture of the reference mark in the collimator field of vision crossed the range boundary of ±10° in respect to the zero point on the collimator vertical scale. Measurements were taken up to a dozen times in each channel and the maximum time (i.e. the worst) was regarded as the resulting value.

Measuring the time internal necessary for the FAA pre-set directionng in azimuth was accomplished simultaneously with defining the errors of this
directioning, according to the methods which have already been described. A reference sign was marked on the internal gimbal mount frame in the FAA vertical plane, and the position of the co-ordinate grid centre in the collimator vision field was adjusted in accordance with the maximum signal from the imitator photodiode outlet. The FAA vertical plane was determined with the help of the plumb line. During each system triggering the timing device registered the time when the picture of the reference mark crossed the range boundary of $\pm 40^\circ$ in respect to the horizontal zero point in the collimator vision field. Measurements were taken up to 10 times during the antenna rotation in azimuth clockwise and counter clockwise. The maximum time interval was taken as a result. The measurement of the platform stabilisation error was accomplished on a special stand with the payload up to 100 kg and with two degrees of freedom, i.e. in the azimuth and according to the elevation angle. This stand provided complete revolution in the azimuth with the angular velocity of $\Omega_o \approx 150/\text{min}$, the rough scale factor being 1 least division $\approx 1/\text{min}$, and the scale of rough angle indication ranging from $0^\circ$ up to $360^\circ$ with the scale factor of 1 least division $\approx 1^\circ$; it also enabled to change the elevation angle up to $\pm 45^\circ$. The stand properties made it possible to imitate a three-axes component oscillation motion identical to the oscillation of a mobile basement with the heading amplitude of $\pm 90^\circ$, and that of $\pm 8^\circ$ for roll and trim angles, the frequency in each channel being 0.06 Hz. In Fig. 6.4 one could see the photo of this stand. The stabiliser was fixed on the stand table.

On supplying power the stabiliser performed all the operational modes in series. To take measurements an imitator of the satellite signal and a reference mark on the gimbal mount internal frame in the FAA vertical plane were used. The initial position of the reference mark picture was fixed in the three-component oscillation motion. After switching the oscillation motion on, the oscillations of the reference mark picture in respect to the initial point were registered on the collimator vertical and horizontal scales. This experiment was repeated 10 times. The maximum value of the stabilisation error on each scale taken as the measurements result. These results are given in Table 6.4.
For indirect estimation of the horizontal correction system error resulting from linear accelerations occurring in the point of the antenna suspension under angular oscillations of the object the corresponding amplitude and frequency characteristics were measured; for this purpose reference marks drawn on the external and intermediate gimbal mount frames were used. The initial position of each horizontal frame was corrected with the indication point on the collimator scale, this method being similar to that used for measuring the levelling static error. After completing the mode of the antenna adjustment in the instrumental horizon plane harmonic signals with frequencies, being essential for the levelling system, were sequentially transmitted to each levelling channel from the electric signals generator on the accelerometer outlet. This signal was "mixed" with that of the accelerometer and then transmitted to the corresponding torque motor along the gimbal mount horizontal axes. The amplitude of the position change of
each reference mark in relation to initial position was registered if it was in collimator observation area. Mean values given in Table 6.5 were considered to be the resulting ones.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Regulator gain factor</td>
<td></td>
</tr>
<tr>
<td>• of the external axis</td>
<td>$10 \cdot 10^6$</td>
</tr>
<tr>
<td>• of the intermediate axis</td>
<td>$10 \cdot 10^6$</td>
</tr>
<tr>
<td>• of the internal axis</td>
<td>$5,6 \cdot 10^6$</td>
</tr>
<tr>
<td>2. Static error of platform adjustment into instrumental horizon plane</td>
<td>$\pm 7'$</td>
</tr>
<tr>
<td>3. Error of distance adjustment of FAA pre-set elevation angle (azimuth)</td>
<td>$18'$</td>
</tr>
<tr>
<td>4. Time for setting the platform into the instrumental horizon plane from</td>
<td>$50$ s</td>
</tr>
<tr>
<td>maximum initial angles of gimbal mount frames deflection, the error not</td>
<td></td>
</tr>
<tr>
<td>exceeding $\pm 10'$</td>
<td></td>
</tr>
<tr>
<td>5. Time for FAA setting in the pre-set azimuthal direction if the initial</td>
<td>$13$ s</td>
</tr>
<tr>
<td>angle of displacement from this direction is $\pm 180^\circ$; the error being</td>
<td></td>
</tr>
<tr>
<td>$\pm 40'$</td>
<td></td>
</tr>
<tr>
<td>6. Platform stabilisation error during regular three-component oscillation</td>
<td>$2'$</td>
</tr>
<tr>
<td>motion of the mobile basement with heading amplitude of $\pm 90^\circ$, and</td>
<td>$1'$</td>
</tr>
<tr>
<td>trim and roll angle amplitude of $\pm 8^\circ$ and frequency of 0.06 Hz:</td>
<td></td>
</tr>
<tr>
<td>• in azimuth</td>
<td></td>
</tr>
<tr>
<td>• according to elevation angle</td>
<td></td>
</tr>
</tbody>
</table>

*Table 6.4. Results of the demonstrator laboratory investigations*
<table>
<thead>
<tr>
<th>Frequency supplied from generator, Hz</th>
<th>Amplitude and frequency characteristic, $20 \log_{10} \frac{A_i}{A_1}$, dB</th>
<th>Amplitude of reference mark positional change in respect to the initial one, minutes of arc</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,050</td>
<td>0</td>
<td>$A_1 = 30,5$</td>
</tr>
<tr>
<td>0,060</td>
<td>-08,5</td>
<td>$A_2 = 11,5$</td>
</tr>
<tr>
<td>0,070</td>
<td>-12,8</td>
<td>$A_3 = 7,0$</td>
</tr>
<tr>
<td>0,083</td>
<td>-17,6</td>
<td>$A_4 = 4,0$</td>
</tr>
<tr>
<td>0,100</td>
<td>-21,7</td>
<td>$A_5 = 2,5$</td>
</tr>
<tr>
<td>0,143</td>
<td>-29,7</td>
<td>$A_6 = 1,0$</td>
</tr>
<tr>
<td>0,200</td>
<td>-35,7</td>
<td>$A_7 = 0,5$</td>
</tr>
</tbody>
</table>

*Table 6.5. Amplitude and frequency characteristics of the levelling system*

The analysis of the laboratory investigations results, conclusions and recommendations for improving the MAP gyrostabiliser properties are given in the following section.

### 6.1.3 Analysis of Laboratory Investigation Results

Laboratory studies of the demonstrator showed that the methods of synthesis as well as those of technical and design solutions made it possible to realise the required metrological and exploitational characteristics of the mobile antenna post gyrostabiliser in general. The value of the regulator gain factor on the external and intermediate gimbal mount frames (the order of $10 \times 10^6$ gcm) tolerates the effect of disturbing moments up to $10^5$ [g×cm] when the required stabilisation error of horizontal channels is less than $\pm 40'$. Disturbing moment in laboratory tests was defined in the way similar to
defining the break-away moment, the latter including three basic components: friction break-away moment, tow moment and disbalance static moment along the corresponding gimbal mount axes. The break-away moment was measured with dynamometer with the help of which force of a certain value was applied to the frame on a fixed lever from the frame centre and this force disturbed the frame from rest. The break-away moment value accounted for 250 gcm for each horizontal frame and this fact made it possible to provide the stabilisation error component of the order of ±6'. The regulator gain factor for the stabilisation system in the azimuthal channel accounted for $5.6 \times 10^6 \ [g\times cm]$. Disturbing moment in this case should not exceed $6.2 \times 10^4 \ [g\times cm]$. The break-away moment along this axis was defined in the similar way and accounted for 450 [g×cm], thus allowing to provide the error component under consideration at the level of ±20'.

The use of pendulous accelerometers of the AK-5 type the technical characteristics of which are given in Table 6.2, made it possible to obtain the static error of the platform adjustment into the instrumental horizon place of the order of ±7'. This error constitutes approximately $\frac{1}{6}$ of all the required error value of the FAA stabilisation in the inertial space. It may be 2 times decreased at the expense of a more accurate preliminary calibration of the accelerometer zero signal.

The error of the FAA elevation angle distance adjustment accounted for 18'; such an error is considered to be the prevailing component of the total error and it is only half as great. This fact confirms the recommendations given before which consisted in replacing the "electric spring" mode with that of the satellite signal circular search in azimuth with the FAA elevation angle towards the satellite having been adjusted before.

Data on the time required for adjusting the platform in the instrumental horizon plane as well as in the predetermined direction in azimuth permit to formulate correctly the requirement to exchange protocol and the cyclogram of the gyrostabiliser operation if the operational modes of the gyrostabilised
antenna post are controlled by PC through standard interface. These data also give a general concept about the time period of the gyrostabiliser functional readiness, and this parameter appears to be very important for this system user.

Experimental tests of the stabilisation error in disturbances effecting sea and river vessels showed that it was possible to provide the error value not exceeding 2' in real exploitative conditions, and this requirement meets those ones imposed on the stabilisation antennas with the dish diameter of 120 cm.

Data, resulting from measuring the amplitude and frequency characteristics of the horizontal correction system influenced by linear accelerations when the object is subjected to angular oscillations, make it possible to conclude that with frequency higher than 0,05 Hz the levelling contour exhibits filtration properties, and the error of retaining the platform in the instrumental horizon plane decreases with the rate of the order of -40 dB/dec, while the frequency of disturbance increases. This error is, for instance, 61 times less at frequency of 0,2 Hz than at frequency of 0,05 Hz. In case the rejection factor happens to be insufficient during adjustment to a concrete object, filtration properties of the horizontal correction should be improved.

When conducting laboratory tests of the three-axes gyrostabiliser demonstrator provided with the horizontal correction contour as well as with the extreme system for the modes of search, acquisition and retaining FAA direction to the satellite in azimuth, some drawbacks in the demonstrator construction became obvious. First of all, it is an insufficient rigidity of the construction which attaches the antenna dish to the internal gimbal mount frame. To obtain the required FAA angles of oscillation in respect to the external and intermediate axes, the place where the antenna dish was attached was displaced 12 cm upwards over the plane within which these axes are situated. The attachment was performed as a cross-piece in which oscillations with the frequency up to 4 Hz occurred under the influence of external disturbances. And the frequency of the gyroscope azimuth channel
proper achieved 50 Hz. To obtain the required root-mean-square value of the stabilisation error it was suggested that the stabilisation system band width should be dozens of Hz and the pole of the gyroscope transfer function should be equalised (compensated), correspondingly. To realise this requirement an attempt was made to displace the frequency of the azimuth axis elastic oscillations beyond the azimuth channel stabilisation system band-width through maximum permissible cross-piece rigidity increase by means of special arm. The frequency of the azimuth axis oscillations was displaced into the region of higher frequencies and it approximated 16 Hz thus allowing to increase the regulator gain factor and to widen the azimuth channel stabilisation system band-width up to 10 Hz. The tendency of elastic oscillations occurrence, if the similar way of attaching the antenna to the internal axis is employed, is to be taken into consideration when designing similar systems.

One of the peculiarities of the demonstrator was limitation of the gimbal mount swaying angles. Limitation along the vertical axis can disrupt the operation of the systems of satellite signal search, acquisition and tracking. Because of this circumstance there was made an attempt to realise complete control over the gimbal mount azimuth axis, and in so doing either special device for cable lying or rotating collectors of two types were employed.

The first collector is intended for supplying voltage to those electromechanical devices which are installed on the mount internal frame as well as for taking the device readings represented in the form of electric signals. However, the number of such electromechanical devices on the mount internal frame should be minimised, that is why it makes sense to employ the electro-kinematic scheme mentioned. In so doing there is no need to employ a sine-cosine transformer as a co-ordinates converter, and two accelerometers should be displaced from the internal frame to the intermediate one.

The second rotating collector transfers the supply voltage to the antenna converter; it also transmits the satellite RF signal received to the TV-receiver and to the feedback contour of the extreme search system. The use
of both collectors will cause some increase of the friction moment and the
tow moment along the azimuth axis, correspondingly, and at the same time
it would allow to control the gimbal mount vertical axis in azimuth
irrespective of the changes of the relative bearing and the yaw angle of a
mobile object.

The employment of a special mechanical device for lying cables of limited
length would, first of all, require constant re-aiming at the satellite thus
interrupting the process of the satellite signal reception. At the same time the
tow moments along the gimbal mount vertical axis will be increased thus
enlarging the gimbal mount construction. These are the reasons for
alternative utilisation of two collectors to organise complete control over the
gimbal mount vertical axis in azimuth.

A more realistic estimation of the gyrostabiliser operation in real conditions
could be considered as result of natural tests, the methods and the analysis
of which are given further on.

6.1.4 Methods and Results of Demonstrator Field Tests

Natural tests of the gyrostabilised antenna post model were being conducted
from August till September, 1993, on the Russian fish vessel "Tosno" in the
North Atlantic. The antenna post was installed in a special place on the
upper deck, where the shadow effect from the mast situated on the same
deck was the least. The distance from the centre of the vessel swaying to the
place where MAP had been mounted was about 30 m. The MAP model
comprised a gyrostabiliser described in Section 6.1., a TV-receiver, a TV-
set, a radom, a complex of cables and equipment necessary for taking
measurements. Power supply to the antenna post was accomplished from the
on-board source with the voltage 220V. Tests were being conducted both in
the day-time and at night in different weather. Tests condition and the most
important results are given in Table 6.6.

In each test the time taken to get the system ready was measured; this period
was registered from the moment the power supply was transferred into the
system up to the moment when a picture appeared on the TV-set screen. In all cases it did not exceed 5 minutes.

<table>
<thead>
<tr>
<th>Geo-ographical co-ordinates (L and B), vessel heading ($\varphi_k$), data and time of test</th>
<th>FAA elevation angle</th>
<th>Satellite azimuth (S), channel name</th>
<th>Noise level $U_1$ and total TV-signal level $U_2$ on the receiver inlet</th>
<th>Weather conditions. Vessel swaying parameters: $\psi$ -trim, $\nu$ - roll, $\Delta \varphi_k$ - yaw, $P$ - swaying period</th>
</tr>
</thead>
<tbody>
<tr>
<td>B=57°30' L=19°20' $\varphi_k$=205° 08.08.93 21.07-21.30</td>
<td>$\beta$=24,5°</td>
<td>EUTELSAT IIF2 S=10°East, RAIUNO 971 MHz, Star 1 1617 MHz</td>
<td>$U_1$=1,64V $U_2$=1,91V $U_1$=1,81V $U_2$=2,17V</td>
<td>Gusty wind, 5m/s. Roughness 2 points. Cloudlessness. Air temperature +19° C. $\psi = \pm 4^\circ$ P=6s, $\nu = \pm 2^\circ$ P=8s, $\Delta \varphi_k = \pm 2,5^\circ$, $P=25s$</td>
</tr>
<tr>
<td>B=57°42' L=6°12' $\varphi_k$=270° 11.08.93 21.07-21.30</td>
<td>$\beta$=24,5°</td>
<td>ASTRA 1A S=19,2°East, EUROSPORT 1259 MHz</td>
<td>$U_1$=1,81V $U_2$=3,12V $U_1$=1,74V $U_2$=1,99V</td>
<td>Gusty wind, 10m/s. Roughness 5 points. Variable cloud. Air temperature +16°C. $\psi = \pm 0,5^\circ$, P=4s, $\nu = \pm 0,5^\circ$, P=3s, $\Delta \varphi_k = \pm 1,5^\circ$, P=20s</td>
</tr>
<tr>
<td>B=57°27' L=1°41'</td>
<td>β=23,0°</td>
<td>ASTRA 1A S=19,2° East, EUROSPORT 1259 MHz, CNN 1629 MHz</td>
<td>U₁=1,84V U₂=3,02V U₁=1,73V U₂=1,90V U₁=1,72V U₂=1,95V</td>
<td>Gusty wind, 15m/s. Roughness 1,5 points. Cloudlessness. Air temperature ±10° C. ψ = ±1,5°, P=6s, ν = ±1,5°, P=6s, Δφₖ - anchorage.</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>θₖ =2°</td>
<td>13.08.93</td>
<td>19.55-20.10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B=57°42' L=1°59'</th>
<th>β=23,0°</th>
<th>ASTRA 1A S=19,2° East, EUROSPORT 1259 MHz, CNN 1629 MHz</th>
<th>U₁=1,73V U₂=2,00V U₁=1,84V U₂=3,04V</th>
<th>Gusty wind, 7 m/s. Roughness 2 points. Low cloudiness, rain. Air temperature ±10° C. ψ = ±0,5°, P=6s, ν = ±0,5°, P=6s, Δφₖ - anchorage.</th>
</tr>
</thead>
<tbody>
<tr>
<td>θₖ =233°</td>
<td>14.08.93</td>
<td>23.25-23.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B=57°30'</td>
<td>( \beta = 23,5^\circ )</td>
<td>ASTRA 1A S=19,2° East, EUROSPORT 1259 MHz, SAT1 1288 MHz, RTL P 1229 MHz, PRO7 1406 MHz, 3SAT 1347 MHz, SKY (ONE)-1317 MHz, SKY N 1376 MHz</td>
<td>( U_1 = 1,74V )</td>
<td>( U_2 = 2,02V )</td>
</tr>
<tr>
<td>L=1°57'</td>
<td></td>
<td></td>
<td>( U_2 = 2,04V )</td>
<td>( U_2 = 2,07V )</td>
</tr>
<tr>
<td>( \varphi_k = 90^\circ )</td>
<td></td>
<td></td>
<td>( U_2 = 2,08V )</td>
<td>( U_2 = 2,19V )</td>
</tr>
<tr>
<td>22.08.93</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16.40-16.52</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| B=57°29' | \( \beta = 23,5^\circ \) | ASTRA 1A S=19,2° East, EUROSPORT 1259 MHz, 3SAT 1347 MHz | \( U_1 = 1,74V \) | \( U_2 = 2,03V \) | Gusty wind, 8 m/s. Roughness 3 points. Low cloudiness, no precipitation. Air temperature ±8°C. \( \nu = \pm 1,0^\circ, P=4s, \) \( \psi = \pm 0,5^\circ, P=6s, \) \( \Delta \varphi_k - anchorage. \) |
| L=1°45' | | | \( U_2 = 2,08V \) | | |
| \( \varphi_k = 10^\circ \) | | | | | |
| 03.09.93 | | | | | |
| 17.30-17.50 | | | | | |
| B=55°55'  | \( \beta=25,0^\circ \) | ASTRA 1A S=19,2°East, SKY (ONE) 1317 MHz | \( U_1=1,77\) \( V \)  | Gusty wind, 20 m/s. Roughness 7 points. Low cloudiness, rain. Air temperature \( \pm 11^\circ C \). \( \psi = \pm 1,0^\circ, P=4s, \) \( \nu = \pm 3,0^\circ, P=5s, \) \( \Delta \phi_k = \pm 1,5^\circ, P=33s \) |
| L=10°57'  |  |  | \( U_2=1,94\) \( V \)  | |
| \( \phi_k=225^\circ \) |  |  |  | |
| 25.09.93  | \( 11.10-11.20 \) |  |  | |

| B=56°08'  | \( \beta=25,0^\circ \) | ASTRA 1A S=19,2°East, EUROSPORT 1259 MHz | \( U_1=1,80V \) \( U_2=2,18V \) | Gusty wind, 5 m/s. Roughness 7 points. Low cloudiness, no precipitation. Air temperature \( \pm 10^\circ C \). \( \psi = \pm 3,0^\circ, P=5s, \) \( \nu = \pm 0,5^\circ, P=3s, \) \( \Delta \phi_k = \pm 0,5^\circ, P=26s \) |
| L=16°57'  |  |  |  | |
| \( \phi_k=57^\circ \) |  |  |  | |
| 26.09.93  | \( 15.05-15.24 \) |  |  | |

Table 6.6. Conditions and results of tests

When the vessel screw changed its operational mode the gimbal mount construction exercised vibrations, and their frequency accounted for about 5Hz judging by measurements results. However, the quality of the TV-picture did not change.

The operation of the on-board radio transmitter with the wattage of 1,6 kW during the test affected the TV-picture, although the FAA positioning in the satellite direction was kept constant as the readings of the voltmeter measuring the level of satellite signal received proved. Having analysed the reasons causing this effect it was found out that this interference achieved the gyrostabiliser through the power supply circuit and the TV-receiver as well, because its body had not been specially screened and more than that it was located together with the radio transmitter on the same deck. Thus it
was impossible to perform the satellite television program video recording. When the radio transmitter stopped operating the quality of the TV-picture was restored during 10 s. To get rid of this effect it was necessary to screen all electric connections on the antenna post, to filtrate the supply voltage and to install the receiver in one of the cabins situated lower than the upper deck.

When switching the satellite television channels the change in the level of the signal received which was defined by the radiation power of the corresponding satellite transponders was observed; thus it was necessary to readjust the gain factor in the extreme system contour manually to avoid the effect of the FAA "flying by" true direction to the satellite which might be caused by a reference signal of a significant value on the extreme system outlet in the feedback circuit. The gain factor was regulated within a definite range and its values did not draw the extreme system beyond the range of its stability. One of the possible variants of solving this problem is to be building a special device for automatic regulation of the reference signal amplification in the extreme system contour.

Taking into account the data given in Table 6.6 and all the proceeding commentaries it is possible to conclude that during the tests the reception of the satellite TV-programs intended for the region in which these tests were being conducted was accurate and steady for all vessel states in different weather conditions. The disadvantages revealed during laboratory and natural tests and the way of their elimination were taken into account when developing and producing the experimental sample of the gyrostabilised antenna post, the description of the latter given in the following section.

6.2 Pilot Model Tests

6.2.1 Pilot Model Description

Three pilot models of MAP with the antenna dish diameter of 60 cm were developed and produced on the basis of theoretical and experimental investigations and their results as well as on the gyrostabilisers extreme system mathematical modelling and its natural tests. The pilot model of the MAP gyrostabiliser is based on the principle of a three-axes stabilisation
indicator system which could be realised as a combination of a two- and a single-axis gyrostabiliser with the vertical frame positioning in the latter; this vertically oriented frame is at the same time the internal frame of the three-axes gimbal mount. The exterior view of the pilot model of the MAP gyrostabiliser is shown in Fig. 6.5.

Stabilisation axes in a two-axes gyrostabiliser are positioned in the horizon plane. From the constructional point of view the gyrostabiliser consists of two gimbal mount frames, i.e. the external and the intermediate ones, and the mount axes are realised with the help of ball-bearing supports. The rotors of the brushless DC torque motors operating in the mode of valve motors together with the rotating transformers are connected with the platform axes. Basic technical characteristics of the torque motor and rotary transformer are given in Tables 6.7 and 6.8, accordingly.

The following devices are installed on the platform:

- a rotor vibrational gyroscope with a feedback device and a power supply electronic unit. The gyroscope axes of sensitivity are collinear with the platform axes. Basic technical characteristics are given in Table 6.9.

- two accelerometers, the sensitivity axes of which are collinear with the corresponding platform axes. Basic technical characteristics are given in Table 6.10.

A single-axis gyrostabiliser frame forms the third stabilisation axis (the azimuthal one) as it is vertically attached to the axis with the ball-bearing unit and is perpendicular to the gimbal mount horizontal axes. The following devices are also installed on this frame:
Fig. 6.5. Pilot model of MAP gyrostabiliser with the antenna dish diameter of 60 cm
<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Nominal moment</td>
<td>0,4 N×m</td>
</tr>
<tr>
<td>2. Static synchronising torque</td>
<td>0,84 N×m</td>
</tr>
<tr>
<td>3. Residual moment of resistance relative to nominal moment</td>
<td>5%</td>
</tr>
<tr>
<td>4. Torque fluctuation at nominal moment</td>
<td>10%</td>
</tr>
<tr>
<td>5. Non-linearity of static synchronising torque</td>
<td>7,5%</td>
</tr>
<tr>
<td>dependence on current</td>
<td></td>
</tr>
<tr>
<td>6. Starting phase current</td>
<td>2,45 A</td>
</tr>
<tr>
<td>7. Rotor inertia moment</td>
<td>$2,7 \times 10^{-4}$ kg×m²</td>
</tr>
<tr>
<td>8. Mass</td>
<td>0,6 kg</td>
</tr>
<tr>
<td>9. Dimensions</td>
<td>Ø100 mm</td>
</tr>
<tr>
<td></td>
<td>L=33 mm</td>
</tr>
</tbody>
</table>

*Table 6.7 Basic technical characteristics of the torque motor*

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Nominal exciting frequency</td>
<td>2 kHz</td>
</tr>
<tr>
<td>2. Transformation ratio</td>
<td>0,16</td>
</tr>
<tr>
<td>3. Maximum frequency of rotation</td>
<td>5000 rev/min</td>
</tr>
<tr>
<td>4. Class of accuracy</td>
<td>5'</td>
</tr>
<tr>
<td>5. Rotor inertia moment</td>
<td>$1 \times 10^{-5}$ kg×m²</td>
</tr>
<tr>
<td>6. Mass</td>
<td>0,16 kg</td>
</tr>
<tr>
<td>7. Dimensions</td>
<td>Ø60 mm</td>
</tr>
<tr>
<td></td>
<td>L=20 mm</td>
</tr>
</tbody>
</table>

*Table 6.8. Basic technical characteristics of the rotary transformer*
Pilot Model Tests

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Range of angular velocities measured, °/s</td>
<td>150</td>
</tr>
<tr>
<td>2. Random component of zero signal independent on linear acceleration during triggering, °/h, not more than</td>
<td>5.0</td>
</tr>
<tr>
<td>3. Stability of scale factor, %, not worse than</td>
<td>0.2</td>
</tr>
<tr>
<td>4. Dimensions, mm</td>
<td>Ø25x30</td>
</tr>
<tr>
<td>5. Wattage, W, not exceeding</td>
<td>1.0</td>
</tr>
<tr>
<td>6. Mass, g</td>
<td>50</td>
</tr>
<tr>
<td>7. Life time, h</td>
<td>5000</td>
</tr>
</tbody>
</table>

**(Table 6.9. Basic technical characteristics of the unirotor vibrational gyroscope)**

- a rotor vibrational gyroscope with a feedback device and a power supply electronic unit. One of the sensitivity axes of the gyroscope is collinear with the axis of the frame suspension.
- an unit attaching the antenna dish and a device for regulating the FAA elevation angle. The latter is realised by means of the suspension axis which is perpendicular to the azimuthal axis; a step-to-step motor with a reduction gear is attached to the azimuthal axis and it provides the antenna elevation angle adjustment and rigid fixing, and there is also an increment angle-data transmitter providing the FAA elevation angle measuring. The basic operational principle of this transmitter is the photoelectric scanning of line drawing rasters and the conversion of angular transference into a sequence of electric signals which contain information about the value and the direction of this transference, these signals being used for further processing in the digital controlling device. Basic technical characteristics are given in Table 6.11.
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Measurement range</td>
<td>±(1...10) g</td>
</tr>
<tr>
<td>2. Maximum zero signal (constant component)</td>
<td>±20 × 10⁻³ g</td>
</tr>
<tr>
<td>3. Zero signal drift during triggering:</td>
<td></td>
</tr>
<tr>
<td>• short time (during 60 s after switching on), not more than</td>
<td>±10⁻⁴ g</td>
</tr>
<tr>
<td>• long time (from 60 s and more), not more than</td>
<td>±2 × 10⁻⁵ g</td>
</tr>
<tr>
<td>4. Zero signal drift during the life time, not more than</td>
<td>±5 × 10⁻⁴ g</td>
</tr>
<tr>
<td>5. Instability of outlet characteristic slope, not more than</td>
<td>0,05 %</td>
</tr>
<tr>
<td>6. Non linearity, not more than</td>
<td>0,05 %</td>
</tr>
<tr>
<td>7. Temperature coefficient of the outlet characteristic slope (TCS), not more</td>
<td>5 × 10⁻⁴ 1/°C</td>
</tr>
<tr>
<td>8. Instability of TCS, no more than</td>
<td>1 × 10⁻⁵ 1/°C</td>
</tr>
<tr>
<td>9. Temperature coefficient of zero signal displacement (TCD), not more than</td>
<td>8 × 10⁻⁵ g/°C</td>
</tr>
<tr>
<td>10. Instability of TCD, not more than</td>
<td>8 × 10⁻⁶ g/°C</td>
</tr>
<tr>
<td>11. Sensitivity threshold, not more than</td>
<td>1 × 10⁻⁶ g</td>
</tr>
<tr>
<td>12. Frequency characteristic:</td>
<td></td>
</tr>
<tr>
<td>• bandwidth with 3dB level, not more than</td>
<td>0...350 Hz</td>
</tr>
<tr>
<td>• damping factor</td>
<td>0,5...0,7</td>
</tr>
<tr>
<td>13. Operational temperature range</td>
<td>-50°C...+85°C</td>
</tr>
<tr>
<td>14. Mass</td>
<td>45 g</td>
</tr>
<tr>
<td>15. Dimensions</td>
<td>Ø28,5 mm</td>
</tr>
<tr>
<td></td>
<td>L=25,5 mm</td>
</tr>
</tbody>
</table>

Table 6.10. Basic technical characteristics of the pendulous accelerometer
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Number of strobes on circular scale</td>
<td>$Z=5000$</td>
</tr>
<tr>
<td>2. Limit of permissible value of transference error</td>
<td>$60''$</td>
</tr>
<tr>
<td>3. Maximum frequency of outlet signal, not less than</td>
<td>$160$ kHz</td>
</tr>
<tr>
<td>4. Maximum number of revolutions</td>
<td>$\frac{9.6 \times 10^6}{Z}$</td>
</tr>
<tr>
<td>5. Wattage</td>
<td>$15$ V $\pm 5%$</td>
</tr>
<tr>
<td>6. Current consumed</td>
<td>$200$ mA</td>
</tr>
</tbody>
</table>

Table 6.11. Basic technical characteristics of the increment data-angle transmitter

Two collectors are constructionally connected with the vertical stabilisation axis; one is used for transmitting electric signal in digital form, while the other is used for transmitting RF-signal with the wave impedance of 75 Ohms. There is also a rotor of a brushless DC torque motor. The gimbal mount is installed on a round-shape basement. On this basement there is also an electromagnetic arresting device and electronic units. The arresting device accomplishes the gimbal mount horizontal axes automatic clamping in an unspecified position after voltage removal. The exterior view of the electromagnetic arresting device and a three-axes gimbal mount are shown in Fig. 6.6.

There are also some holes on the basement used for MAP mounting on a mobile object as well as a relief construction in the form of a ring of a definite diameter and thickness supplied with a special attachment which provides hermetic combination with the radom. The exterior view of the latter being shown in Fig. 6.7.
Fig. 6.6. Electromagnetic arresting device (left) and the three-axes gyrostabiliser proper (right)

Fig. 6.7. Radom for MAP-60
The gyrostabiliser electrokinematic scheme is identical to that one which is shown in Fig. 2.13 and which is completely described in Section 2.2.4. In accordance with this scheme a three-axes system of gyroscopic stabilisation and FAA control comprises the systems of stabilisation, levelling and FAA pre-set elevation angle adjustment as well as the systems of the satellite signal search, acquisition and tracking; all these systems provide automatic sequential fulfilment of the following functions:

- gyromotors speed-up during 10 seconds, the time being counted by the system internal timer;

- FAA elevation angle adjustment;

- de-arresting the gimbal mount axes, switching off the system of stabilisation and the horizontal correction system.;

- satellite search in the mode of panoramic sight (FAA circular turning round the azimuthal axis with scanning),

- switching on the system of the satellite signal automatic acquisition, its acquisition proper and tracking in the direction of its maximum.

Basic designed technical characteristics of a gyrostabiliser pilot model are given in Table 6.12.

The stabiliser operational modes controlling is accomplished through a monocrystal microprocessor. The microprocessor provides interaction with a PC through a standard interface RS-232 in accordance with the established exchange protocol. Besides, the microprocessor provides forming a number of inner discrete commands controlling the operation of the control and stabilisation unit of stabiliser. A generalised scheme of the MAP-60 junctions is shown in Fig. 6.8.
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Relative angles of gimbal mount swaying:</td>
<td></td>
</tr>
<tr>
<td>• along the internal axis</td>
<td>±360°</td>
</tr>
<tr>
<td>• along the intermediate axis</td>
<td>±30°</td>
</tr>
<tr>
<td>• along the external axis</td>
<td>±45°</td>
</tr>
<tr>
<td>2. Maximum error of orienting the FAA position in the azimuthal direction to</td>
<td>±20'</td>
</tr>
<tr>
<td>the satellite</td>
<td></td>
</tr>
<tr>
<td>3. Maximum error of retaining the FAA elevation angle to the satellite</td>
<td>±20'</td>
</tr>
<tr>
<td>4. Error of the remote FAA elevation angle adjustment</td>
<td>5'</td>
</tr>
<tr>
<td>5. Time period for preparing gyrostabiliser for operation</td>
<td>5 min</td>
</tr>
<tr>
<td>6. Consumed two-phase AC with frequency 50Hz±3Hz</td>
<td>1.5 A</td>
</tr>
<tr>
<td>7. Voltage</td>
<td>220 V±10%</td>
</tr>
<tr>
<td>8. Consumed wattage, in nominal power supply and at normal temperature</td>
<td>300 W</td>
</tr>
<tr>
<td>9. Mass</td>
<td>100 kg</td>
</tr>
<tr>
<td>10. Dimensions</td>
<td>H=1400 mm</td>
</tr>
<tr>
<td></td>
<td>Ø1500 mm</td>
</tr>
<tr>
<td>11. Fixed life time</td>
<td>5000 h</td>
</tr>
</tbody>
</table>

*Table 6.12. Basic technical characteristics of MAP-60 pilot model*
Fig. 6.8. Generalised scheme of the MAP-60 junction

The principal scheme explaining the process of the satellite TV-signal reception and transmission is presented in Fig. 6.9. The MAP-60 switching on, satellite selection, the input of actual co-ordinates of a pre-supposed reception place, the calculation of the FAA elevation angle and azimuth the formation of the signal switching on the system of the satellite signal autoacquisition are accomplished with the help of a special software elaborated by RST GmbH for IBM PC. The main menu is represented in Fig. 6.10. Actual co-ordinates of the place where the satellite signal is received are displayed in corresponding windows in the right hand top corner; they are “Act. Pos. Longitude” and “Act. Pos. Latitude”. The key “Satellite DB” accomplishes the selection of the satellite required, and the co-ordinates of its aiming point on the geostationary orbit and telecasting
frequency range are introduced into the data base. This data base could be enlarged or changed as the necessity arises. In the left-hand top display corner there is a button with the help of which power voltage is supplied. There are two lines in the display lower part, the first indicating serviceability of basic system elements and power sources by means of red and green colours and the second informing about the actual system state, the time and the date of the operational run. Besides, in the middle of the screen there are two windows with the pictures of the FAA elevation angle and azimuth which can change during operation but still correspond to the actual system state. Thus the user is able to envision the system operation in whole.

Basic characteristics which are given in Table 6.12, after the MAP-60 pilot models assembly and adjustment, were tested in the laboratory on a specially designed stand. Methods for these characteristics checking and the stand description are given in the following section.

Fig. 6.9. Principal scheme showing the process of the satellite TV-signal reception and transmission
Fig. 6.10. Main menu of the software controlling the MAP-60 operation from IBM PC
6.2.2 Methods of Pilot Model Tests

Map-60 pilot model was tested in normal climatic conditions. Controlling and checking devices made it possible to measure values with 5% error which does not differ much from their maximum or minimum values. To take measurements a technological software for IBM PC was worked out and a satellite imitator and a controlling and checking tester were produced. The technological routine is based on the instructions exchange protocol, instruction communications being executed between the gyrostabiliser microprocessor and its PC controlled software. Command exchange is asynchronous, the information being encoded in the ASCII format, in the binary code. The exchange rate is 9600 bits per second. The data buffer capacity is 16 bytes. Exchange protocol ensures the gyrostabiliser operational cyclogram shown in Fig. 6.11. The satellite signal imitator construction and its operational principles are identical to those used for laboratory tests of the gyrostabiliser model with the antenna dish diameter of 120 cm, the radiation pattern characteristics formed by it excluded. The radiation pattern was formed in accordance with that of the offset antenna with the dish diameter of 60 cm. The exterior view of the satellite signal imitator attached to the gyrostabiliser when conducting MAP-60 pilot model tests is shown in Fig. 6.12.

The special controlling and checking unit consists of an assemblage of switching and measuring electric circuits and devices; its exterior view is given in Fig. 6.13.

To measure the MAP-60 pilot model basic technical characteristics which have been given in Table 6.12, the gyrostabiliser electronic unit, IBM PC, the controlling and checking units and the satellite signal imitator were connected in accordance with the scheme represented in Fig. 6.14.
<table>
<thead>
<tr>
<th>Fig. 6.11. Operational cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stabiliser stands itself in initial position</td>
</tr>
</tbody>
</table>

| Stabilisation of the azimuth axis is in a working order | Panoramic satellite search | Acquisition and tracking |

| T1=10 s | T2=40 s | T3=20 s | T4=(180...200) s |

A B C D

(. ) A-power switch-on to start gyrostabiliser operation
(. ) B-command from external subsystem to start gyrostabiliser operation
(. ) D-command from external subsystem to start acquisition
Fig. 6.12. Satellite signal imitator

Fig. 6.13. Controlling-checking unit
Fig. 6.14. Connection scheme between stabiliser and checking equipment
Methods checking root-mean square error for instrumental horizon plane retaining

The instrumental horizon plane retaining error on each gyrostabiliser horizontal axes Y and Z was deduced as a root-mean square of two error components, the static and the dynamic ones. The root-mean square error of retaining the instrumental horizon plane relative to Y axis was calculated with the formula:

$$\sigma_Y = \sqrt{A_{Y_1}^2 + A_{Y_2}^2},$$  \hspace{1cm} (6.1)

where $A_{Y_1}$ is the static error root-mean square value of retaining the instrumental horizon plane relative to Y axis (the root-mean square error of the instrumental plane adjustment) and $A_{Y_2}$ is the dynamic error root-mean square value of retaining the instrumental horizon plane relative to Y axis (the root-mean square error of the instrumental horizon plane stabilisation).

The root-mean square error of retaining the instrumental horizon plane relative to Z axis is described with a similar expression:

$$\sigma_Z = \sqrt{A_{Z_1}^2 + A_{Z_2}^2},$$  \hspace{1cm} (6.2)

where $A_{Z_1}$ is the root-mean square error of the instrumental horizon plane adjustment relative to Z axis and $A_{Z_2}$ is the root-mean square error of the instrumental horizon plane stabilisation relative to Z axis.

The error static component along Y and Z axes was measured in the following way:

- the stabiliser was attached to a fixed base;
- the technical accelerometer the zero signal of which had been calibrated was adjusted to the stabiliser internal frame base surface;
• the accelerometer sensitivity axis was turned along each gimbal mount horizontal axes sequentially;

• the technological software was triggered and, in 30 s after power supply, the levelling mode was established in the main menu with the help of a special command;

• a signal at the technological accelerometer outlet was measured with the help of the DC voltmeter in 10 minutes lapse after establishing the levelling mode. The instrumental horizon plane adjustment error in Z and Y channels was calculated with the formula:

$$A_{Z_i, Y_i} = K^{-1} \cdot (U_1 - U_0),$$  

(6.3)

where $K$ is the curvature of the technological accelerometer outlet characteristic and $U_1$ and $U_0$ are the outlet and the zero accelerometer signals, correspondingly. Measurements were taken up to 15 times and on the basis of measurements sample the root-mean square error of the instrumental horizon plane adjustment was determined.

The error dynamic component relative to Y and Z axes was deduced in the following way:

• the stabiliser was set on a fixed base;

• the moment of resistance $M_{Z_i, Y_i}$ was determined along each gimbal mount horizontal axes with the help of the dynamometer in accordance with the procedure described in Section 6.1.2;

• a mirror was attached on the antenna dish with the help of a special arm, and, aside the stabiliser, an optical collimator was installed within its focal distance from the place of the mirror attachment; after that the collimator focal axis pre-positioning was accomplished in accordance with the mark position on the mirror reflecting surface;
• in 30 s after power supply, the levelling mode was established in the technological software main menu with the help of a special command;

• the collimator positioning was repeated again in 10 minutes after establishing the levelling mode;

• a short (lasting 0.5-1 second) disturbing moment $M_{z_2,y_2}$ relative to each gimbal mount horizontal axes was produced on a fixed arm with the help of a calibrated load;

• the angle of the mask deflection from initial positioning $\Delta_{z,y}$, within the collimator observation field, was registered;

• static rigidity for each stabiliser horizontal channel was calculated with the formula:

$$C_{z,y} = \frac{M_{z_2,y_2} - M_{z_1,y_1}}{\Delta_{z,y}},$$  \hspace{1cm} (6.4)

• the instrumental horizon plane stabilisation error relative to each gimbal mount horizontal axes was calculated with the formula:

$$A_{z_2,y_2} = \frac{M_{z_2,y_2}}{C_{z,y}}.$$  \hspace{1cm} (6.5)

The instrumental horizon stabilisation root-mean square error was calculated on the sample resulting from 15 measurements takings.

Methods checking root-mean square error for retaining FAA azimuthal directioning to satellite

To measure the error of retaining the FAA directioning to the satellite in azimuth, satellite signal imitator, an oscillograph, a dynamometer, a mirror attached to the antenna and the collimator in accordance with the scheme of
connections shown in Fig. 6.14 were employed. The sequence of measurements taking was similar to measuring the remote adjustment of the pre-set FAA azimuthal angle and the dynamic component of the instrumental horizon plane retaining error, the former being described in Section 6.1.2, the latter being described in this Section. The stabiliser was controlled through PC by means of a technological software, in which the MAP-60 operational cyclogram is fully realised, in accordance with Fig. 6.11. After completing the imitated satellite signal autoacquisition, a disturbing moment $M_{X_2}$ with a definite value was produced relative to X axis during 0,5-1 s, the dynamometer being used for its production. The platform displacement angle $\Delta x$ from initial positioning was registrated in the collimator field of view. Static rigidity for the stabiliser azimuthal channel was calculated. Measurements were taken up to 15 times. The root-mean square value was assumed to be result and it was calculated on the sample, due to measurement taken.

Methods checking root-mean square error for FAA elevation angle remote adjustment

The FAA elevation angle remote adjustment towards the satellite was estimated with the help of technological software, a mirror attached to the antenna and a collimator. Checking meant the following:

- the FAA elevation angle adjustment by means of the software menu, the angle value being pre-determined;

- the collimator focal axis positioning in accordance with the mask positioning on the mirror reflecting surface, the mirror being fixed on the antenna with the arm in a specific way and the FAA elevation angle being adjusted;

- the procedure of the FAA elevation angle adjustment was repeated, the angle being of the same value, and the mask relative positioning in the collimator field of view was measured, this adjustment being accomplished.
Measurements were taken 15 times. The root-mean square value was assumed to be a resulting one and it was calculated on the sample, due to measurements taken.

**Methods checking gimbal mount relative swaying angles**

The gimbal mount relative swaying angles were measured in relation to the external and the internal axes by means of a technological accelerometer, DC voltmeter and a technological software for IBM PC.

In so doing, the technological accelerometer was installed on the gimbal mount external frame base surface at a maximum distance from Y axis, and the accelerometer sensitivity axis was turned along this Y axis. Having supplied power voltage to the stabiliser, the gimbal mount external frame was deviating in reference to Y axis up to the stop with the help of the technological software menu options, and the signal on the accelerometer outlet was measured with voltmeter. The value of this signal was considered to be equivalent to the frame swaying angle value and it was compared with minimum permissible value up to 1,75 V which corresponds to the angle of ±45°. The same procedure was taken when measuring the gimbal mount intermediate frame swaying angle. In this case, the technological accelerometer was oriented by its own sensitivity axis along the mount axis Z at a maximum distance from it. The gimbal mount intermediate frame was deviating from the horizon plane to the maximum permissible angle, and the value of the signal on the accelerometer outlet was compared with the minimum permissible value up to 0,91 V which corresponds to the angle of ±30°. Results of these measurements and their analysis will be described in the next Section.

**6.2.3 Analysis of Pilot Model Tests Results**

The results of MAP-60 pilot model tests conducted to determine the time required to bring it to readiness, the root-mean square error of the FAA elevation angle remote adjustment and the angles of swaying along the gimbal mount axes correspond to information given in Table 6.12. The readiness time does not exceed 5 min, the initial FAA position being
different. The root-mean square error of the FAA elevation angle remote adjustment $\sigma_{\phi}$ does not exceed 5'. The relative angle of swaying along the intermediate gimbal mount axis Z corresponds to ±30°; the relative angle of swaying along the external gimbal mount axis Y corresponds to ±45°. When checking the operational cyclogram technological software was used, and the tests proved that the cyclogram realised by the pilot model during its operation was completely in line with the designed one which had been set forth in software using the protocol of exchange between the gyrostabiliser microprocessor and PC. These results of measuring the MAP-60 pilot model parameters which are necessary for further estimating the instrumental horizon plane adjustment error and the FAA azimuthal directioning to the satellite are given in Table 6.13.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Curvature of technological accelerometer outlet characteristic, $K$</td>
<td>1 mV/minutes of arc</td>
</tr>
<tr>
<td>2. Accelerometer calibrated zero signal:</td>
<td></td>
</tr>
<tr>
<td>• along Y axis, $U_{o_y}$</td>
<td>-2.78 mV</td>
</tr>
<tr>
<td>• along Z axis, $U_{o_z}$</td>
<td>-4.10 mV</td>
</tr>
<tr>
<td>3. Accelerometer outlet signal:</td>
<td></td>
</tr>
<tr>
<td>• along Y axis, $U_{1_y}$</td>
<td>-2.6 mV</td>
</tr>
<tr>
<td>• along Z axis, $U_{1_z}$</td>
<td>-4.5 mV</td>
</tr>
<tr>
<td>4. Moment of resistance:</td>
<td></td>
</tr>
<tr>
<td>• along Y axis, $M_{Y_1}$</td>
<td>200 g×cm</td>
</tr>
<tr>
<td>• along Z axis, $M_{Z_1}$</td>
<td>240 g×cm</td>
</tr>
<tr>
<td>• along X axis, $M_{X_1}$</td>
<td>300 g×cm</td>
</tr>
<tr>
<td>5. Stabilisation channels static rigidity:</td>
<td></td>
</tr>
<tr>
<td>• along Y axis, $C_Y$</td>
<td>$1,51 \times 10^3$ g×cm/rad</td>
</tr>
<tr>
<td>• along Z axis, $C_Z$</td>
<td>$1,19 \times 10^3$ g×cm/rad</td>
</tr>
<tr>
<td>• along X axis, $C_X$</td>
<td>$0,61 \times 10^3$ g×cm/rad</td>
</tr>
</tbody>
</table>

*Table 5.13. Measurements resulting from test*
Using data given in Table 6.13 and formulas presented in the preceding section corresponding root-mean square errors were calculated and they are shown in Table 6.14.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Root-mean static error in retaining instrumental horizon plane relative to axis Y, $A_{y_1}$</td>
<td>±0,6'</td>
</tr>
<tr>
<td>2. Root-mean static error in retaining instrumental horizon plane relative to axis Z, $A_{z_1}$</td>
<td>±0,17'</td>
</tr>
<tr>
<td>3. Root-mean square error of instrumental horizon plane stabilisation relative to axis Y, $A_{y_3}$</td>
<td>±1,7'</td>
</tr>
<tr>
<td>4. Root-mean square error of instrumental horizon plane stabilisation relative to axis Z, $A_{z_3}$</td>
<td>±2,3'</td>
</tr>
<tr>
<td>5. Root-mean square error in retaining instrumental horizon plane relative to axis Y, $\sigma_y$</td>
<td>±1,7'</td>
</tr>
<tr>
<td>6. Root-mean square error in retaining instrumental horizon plane relative to axis Z, $\sigma_z$</td>
<td>±2'</td>
</tr>
<tr>
<td>7. Root-mean square error of retaining instrumental horizon plane, $\sigma_{zy}'$</td>
<td>±2,6'</td>
</tr>
<tr>
<td>8. Root-mean square error of retaining FAA directioning in azimuth, $\sigma_{x}'$</td>
<td>±6'</td>
</tr>
</tbody>
</table>

Table 5.14. Root-mean square errors of MAP-60 pilot model gyrostabiliser

The maximum error of orientating the FAA position in the azimuthal direction to the satellite is composed of two components: maximum error of retaining the FAA directioning in the azimuth ($3\sigma_{x}' = ±18^\circ$) and an additional component which, by its nature, is the FAA scanning amplitude in azimuth if the extreme system operates in the mode of maximum satellite signal acquisition and tracking. Its value for the pilot model accounts for
±5’. That is why estimate error of retaining the FAA azimuthal direction to the satellite does not exceed ±23’. The maximum error of retaining the FAA elevation angle to the satellite (3σφ) also comprises two components: the maximum error of retaining the instrumental horizon plane (3σzy = 7.8’) and the maximum error of the FAA elevation angle remote adjustment (3σφ = 15’). Thus the estimate error of retaining the FAA elevation angle to the satellite 3σφ does not exceed ±16’. Judging by the data received it is possible to estimate the maximum error of FAA orientating in the satellite direction in the geographical co-ordinates system. The estimate error of FAA orientating to the satellite 3σ does not exceed ±28.5’ and corresponds to 47.5% of the permissible value, which as shown in Table 2.1 does not exceed ±1° for the antenna with the dish diameter of 60 cm. The tests of the other two MAP-60 pilot model and the analysis of their results showed their highest recurrence in each model, they were in order with the technical decisions and technologies employed. Functional possibilities of the MAP-60 pilot model were shown in March, 1996 in the German Space Agency (DARA) GmbH, Satellite Communication and Navigation Department, Bonn, Germany. The pilot model was installed on the car trailer as it is shown in Fig. 6.15 and Fig. 6.16.

![Fig. 6.15. MAP pilot model installed on trailer](image)
Power for the gyrostabiliser, TV-receiver and PC was supplied from an independent power source which was also mounted on the trailer. By means of the main menu for software controlling the stabiliser (it has been described in Section 6.2.1), the geographical co-ordinates of the reception place, the frequency band of the satellite signal reception and the longitude of the chosen satellite aiming point on the geostationary orbit were pre-set. After supplying the gyrostabiliser with power the car began moving with the average speed of 20 km/h across the broken rugged ground with low grass. TV-programme reception through ASTRA and EUTELSAT channels remained stable as could be observed on the TV-set screen. Linear accelerations occurring during the car speeding up and braking did not affect the quality of the TV-picture when their amplitudes corresponded to the transfer accelerations amplitudes which occur on board the vessel, i.e. to those design values which were used for the horizontal correction system synthesis. When the car stopped, the trailer was released and swayed relative to its chassis gimbal mount axis manually. In so doing the disturbing moment imitating a one-component swaying was produced and its
amplitude and frequency were similar to those of the vessel swaying. The TV-picture deterioration or its vanishing were not registered.

Despite the fact that, during the MAP-60 tests on a land vehicle, some outward disturbances approximated those occurring on board the vessel, the results of this experiment demonstrated the possibility to use, in principle, technical decisions and technologies when designing the analogous antenna posts for land vehicles.

To provide MAP functioning on a land vehicle it is necessary to obtain information about its actual position. To maintain the FAA angular orientation and the antenna polarisation plane, the information about the object actual position should possess the error not exceeding ±33 km. One can obtain information of this type, especially if the object is in motion, through the Global Positioning System (GPS) operating with the help of for instance “NAVSTAR” communications satellites. The GPS receiver, when installed on a mobile object, receives signals from several satellites (usually 6 or 8) and measures actual geographical longitude and latitude for this object with precision from several hundred up to dozen meters. Such receivers are equipped with a standard digital interface used for further transmitting the co-ordinates measured. The data enter PC through the corresponding serial port in which they can be used in the software to calculate actual FAA elevation angles and its azimuth. In this case, the necessity to manually enter information about the object geographical position into the software controlling the stabiliser both at the beginning of the communication with a concrete satellite and during re-aiming at another satellite, is lacking.

If the MAP-60 configuration is used on board the high-speed land objects which significantly change their position during a short time period, i.e. without the extreme system in the channel of the FAA elevation angle control, there arises a requirement to correct the FAA elevation angle in the satellite direction frequently. If the MAP is installed on board the vessel moving with the average speed of 18 knots it is necessary to provide frequently renovation of information about the geographical co-ordinates of
this vessel, and it should be done not less than once an hour. For a land vehicle moving with the speed of 60 km/h information should be renovated two times oftener, i.e. two times an hour. The renovation about the actual object position received from the middle class GPS is sufficient to correct the actual FAA elevation angle value automatically without interrupting communication with the satellite.

Thus MAP and GPS integration will increase the degree of the complex independence during its exploitation and it will enlarge the sphere of its application, but the cost will undoubtedly grow.

6.3 Conclusions

The analysis of results obtained in experiments and tests with the MAP demonstrator and its pilot model enabled us to draw the following conclusions:

- The combined scheme of constructing the three-axes gyroscopic stabiliser of the indicator type on rotor vibrational rate gyroscopes with the horizontal correction contour and the extreme system for the satellite signal search in azimuth put forward permits to solve the problem of isolating and controlling FAA relative angular positioning in disturbances characteristic of sea and river vessels.

- Methods of synthesis utilised as well as technical and constructive solutions provide in store the required metrological and exploitative characteristic of the MAP gyrostabiliser for antennas with the dish diameter from 60 cm up to 120 cm.

- A high degree of pilot models characteristic estimates occurrence suggests that technical solution and technologies used might provide further MAP-60 serial production.

- There exists a principal possibility of employing technical solutions and technologies used for designing analogous antenna post, the criterion of
their maximum unification for a wide class of mobile objects and varied purposes taken into consideration.

- Widening the sphere of MAP application and the increase of its autonomy require further elaboration of the problem of MAP and Global Positioning System integration.
Gathering the conclusions, summarising the contents, presenting suggestions for improvements and recommending further research are the topics of this final chapter. The first part presents the summary and the conclusions. Comprehensive conclusions have already been given at the end of each chapter, hence the more global ones are stated here. The second part provides an outlook on future perspective, not only with respect to the research presented in this thesis, but also to the gyrostabilisation systems of the indicator type in general.

7.1 Summary and Conclusions

- The analysis of modern mobile communication systems and the major trends in instrumentation development showed that the mobile antenna post constructed as an autonomous gyroscopic indicator system of stabilisation and control of the focal antenna axis orientation and its polarisation plane in the inertia space appears to be promising with regard to accomplishing reliable and high-quality reception of the satellite TV-picture on board the sea and river vessels. Being realised
in a non-traditional approach for constructing the stabilisation system as a combination of a two-axes gyrostabiliser with a contour of horizontal correction and a single-axis gyrostabiliser with a contour of azimuthal correction installed on the former one, it meets the requirements imposed on mobile antenna posts functional and operational characteristics and provides their autonomy from the onboard navigational equipment.

- To meet the requirements imposed on basic sensitive elements of the scheme suggested, uniorotor vibrational gyroscopes operating in the mode of a two-component sensor of angular velocity and pendulous accelerometers prove worth of being employed at present. These sensors provide required metrological characteristics within a wide range of pre-set functional characteristics under the environments, their cost being minimal.

- The complete mathematical model with the help of which the motion of the mobile antenna post generalised scheme is described appears to be a non-linearly one. A number of assumptions, such as linearisation of some non-linearised elements and disregard of the high order of smallness, justified and approved of in the analysis, allowed to linearise and to simplify the mathematical model of the system as a whole. Linear mathematical models for mobile antenna post subsystems given as differential equations of motions in the operator form permit to perform parameters selection and to accomplish their further transformation in regard to any measuring co-ordinates systems.

- The method of dynamic synthesis of linear continuous automatic control systems appears to be the most effective one for synthesising the mobile antenna post linearised mathematical model. The functional purpose of some subsystems determines basic criteria for their synthesis: transitional process duration stands for a criterion in the rough levelling subsystem synthesis, the error of levelling serves as a criterion for synthesising the subsystem of accurate levelling and
the oscillation index can be meant as the extreme subsystem synthesis criterion. Using correcting elements with a justified structure and parameters in each channel it is possible to obtain the desired quality of the transition process in phase and amplitude.

- The methods employed and the mathematical expressions received allow to determine the structure and the basic parameters for the horizontal correction contour complying with the requirements to the metrological and operational characteristics of mobile antenna posts.

- The linearised mathematical model and the filter hypothesis taken into consideration allowed to find out a simple engineering method for calculating the parameters and for choosing the structure of the azimuthal channel extreme system.

- Simulating mathematically complete equations for the extreme system motion with regard to characteristic non-linearities and real disturbances, assumptions adopted for linearising the system mathematical model were justified. The mathematical model developed makes it possible to carry out selection of some separate elements and to optimise the system parameters in general.

- Major errors in the system are caused by the influence of disturbing moments upon the gimbal mount axes, by linear accelerations in the antenna point of suspension in diverse object motions, by the gyroscope zero signal and the vector of angular velocity of the Earth’s revolution. The instrumental error in the focal antenna axis elevation angle channel at frequencies lower than the basic frequency of the accurate levelling system is proportional to the gyroscope zero signal, the latter being equivalent to angular acceleration, while at higher frequencies it is proportional to the zero signal equivalent to the gyrostabilised platform turn around the corresponding axis. The instrumental error of the azimuthal channel comprises the amplitude of the single-axis gyrostabiliser search motion and has no static components caused by the disturbances mentioned. Limitations imposed on harmonic components of the gyroscope zero signal in the
elevation angle channel with reference to the error model elaborated dominate when choosing the type of gyroscopic sensitive elements.

- Experimental investigations of the mobile antenna post demonstrator and its pilot model showed that methods of analysis and synthesis as well as technical and design decisions provide the over designed metrological and operational characteristics of mobile antenna post for antennas with varied diameters of dish and configurations. High degree of repeatedness of the pilot model characteristic values permits to organise serial production of varied mobile antenna posts modifications.

- The mathematical model elaborated, the methods and the results of structural and parametrical synthesis, the methods of errors distribution and their estimation, and the expressions for their calculation are presented in a generalised form convenient for conducting calculations and for optimising when designing similar systems.

Experimental investigations of MAP-60 pilot models also revealed some disadvantages in the scheme proposed. They are as follows.

1. Increased sensitivity of the scheme offered towards linear accelerations influence.

2. Limitations on location and duration of a continuous TV-communication with one satellite, if there is no additional focal antenna axis elevation angle correction performed by the man.

The first disadvantage mentioned belongs to methodical errors of the levelling system and it can be remedied by using accelerometer signals for maintaining the levelling system which is partly invariant to linear accelerations with frequencies typical for sea vessels swaying. There exists another way of obtaining a levelling system invariant to linear accelerations influence, i.e. through introducing the extreme system into the structure of
the elevation angle channel. To employ this method it is necessary to change correspondingly the generalised structural scheme and the gyrostabiliser operational cycle accounting for the possibility to switch the levelling mode into the mode of the extreme system operation after rough adjustment has been completed. In this case, readings from accelerometric sensors in the mode of the extreme system operation in accordance with the elevation angle could be used for improving its dynamic accuracy.

Limitations on the location and duration of a continuous TV-communication with one satellite as well as turning-up to another satellite on the geostationary orbit could be removed by using information about the object actual location from the maintenance equipment through the interface as well as by varying the software and the exchange protocol between the computer and the gyrostabiliser electronic block microprocessor. Onboard navigation equipment, or GPS with a rather low accuracy, presenting information about the object actual positioning in the geographical coordinates system four times an hour with the accuracy up to dozens of kilometres could be used as maintenance equipment. The use of on-board navigational devices will deprive the system of its autonomy, that is why it is preferable to employ GPS for this purpose.

7.2 Future Perspective

There exists a principal possibility to improve the mobile antenna post functional properties and to enlarge the sphere of its applications as well as to use technical decisions obtained as the basis for developing mobile antenna posts for varied receiving-transmitting antennas and for optico-electronic systems, too. The visual line, the field of view, or both could be objects of spatial stabilisation and control for latter ones. Such systems could be performed as a module, or as a single optical track and they usually comprise such devices as lasers, infra-red, IR imagining and TV-units, as the case requires [27]. The beam, the field of view and the pixel dimensions determine requirements to stabilisation accuracy. These requirements are high enough and they can come to dozens of minutes of arc. Similar requirements are to be met when stabilising and controlling the receiving-
transmitting antennas, the dominating parameter of their accuracy of spatial orientation being the smallest width of the radiation pattern along one of the co-ordinates. That is why further investigations in this area should be aimed at reducing and compensating methodical and instrumental errors in levelling and stabilisation systems.

As to enlarging the mobile antenna post functional possibilities, it is necessary to emphasise that the need for accomplishing bilateral TV-communication on board the mobile objects with the satellites on the elliptic orbits of varied parameters is growing. In connection with this, the principle governing the focal antenna axis angular positioning with a pre-set accuracy during initial adjustment and satellite search would obviously represent a more complex function depending not only on the form and parameters of the object’s motion along the Earth’s surface and the Earth’s velocity of revolution but on the laws governing the satellite motion as well. To design such a system some methods and approaches given in this thesis could be employed. However, it is more likely to be a subject for a profound scientific research than a topic for a mere discussion.
A "Extreme Search" Algorithm

Begin

Input terminal time: tend,
number of value
in table: nbeg,
initial conditions: x0

h1 = tend/nbeg
hz = 1
n = nbeg; sk = 0

①

t = 0
xh1.x = x0
xh2.x = x0
```
\text{\textbf{"Extreme Search" Algorithm}}
```

```
\text{nor1=0}
\text{bool=false}
```

```
\text{\textbf{loop}}
\text{noma=0?}
\text{i=0}
\text{OV=false}
```

```
\text{\textbf{loop}}
\text{i < n ?}
\text{OV=false}
```

```
\text{i = i + 1}
```

```
\text{arg = xh1.x[i] - Vo + Vs}
```

```
\text{f = Vr*2.15}
\text{arg1 = 0 ?}
```

```
f = Vr*2.15*\sin(180*(\text{arg1})/1.55)
(180*\text{arg1}/1.55)
```
\[
\begin{align*}
\text{if } t > U_p \quad \text{or} \quad \text{bool} = \text{true} \\
\text{then} \\
\text{nbrsys} = 0 \\
\text{bool} = \text{true}
\end{align*}
\]

\[
\begin{align*}
t' &= t \\
h &= h_1 \\
x_0' &= x_{h1.x} \\
nbrsys' &= nbrsys
\end{align*}
\]

procedure integr (III)

\[
\begin{align*}
x_{h1.x} &= x
\end{align*}
\]

\[
\begin{align*}
t' &= t \\
h &= h_{1/2} \\
x_0' &= x_{h2.x} \\
nbrsys' &= nbrsys
\end{align*}
\]

procedure integr (IV)

\[
\begin{align*}
x_{h2.x} &= x
\end{align*}
\]

\[
\begin{align*}
t' &= t + h_{1/2} \\
h &= h_{1/2} \\
x_0' &= x_{h2.x} \\
nbrsys' &= nbrsys
\end{align*}
\]

procedure integr (V)
xh2.x = x

j = 1

if xh1.x[j] > |d0|

OV = true

j = j + 1

if j > nu

yes

no

sk = hz - l

if no

yes

Xgr[hz] = (xh1.x[1]-Vo+Vs)*180/pi*60
sk = (sh+1) mod h2

\[ t = t + h1 \]

\[ j = 1 \]

\[ \text{nor}_1 = |xh1 \cdot x[j] - xh2 \cdot x[j]| \]

no \[ \text{norm}[j] < \text{nor}_1 \]

\[ \text{norm}[j] = \text{nor}_1 \]

\[ j = j + 1 \]

no \[ j > nu \]

yes \[ \text{norm} = \text{norm}[1] \]

\[ j = 2 \]
h1 = h1/2
n = n + 2
h2 = h2 * 2
OV = false

norm<0.15
or
n>30000

Output Xgr

End
procedure integr

\[
a[2] = \frac{1}{3}; \quad a[3] = \frac{1}{3}; \quad a[4] = \frac{1}{2}; \quad a[5] = 1
\]

\[
b[2,1] = \frac{1}{3}; \quad b[3,1] = \frac{1}{6}; \quad b[3,2] = \frac{1}{6}; \quad b[4,1] = \frac{1}{8}
\]

\[
b[4,2] = 0; \quad b[4,3] = \frac{3}{8}; \quad b[5,1] = \frac{1}{2}; \quad b[5,2] = 0;
\]

\[
b[5,3] = -\frac{3}{2}; \quad b[5,4] = 2
\]

\[
c[1] = \frac{1}{6}; \quad c[2] = 0; \quad c[3] = 0; \quad c[4] = \frac{2}{3}; \quad c[5] = \frac{1}{6}
\]

\[
t' = t \quad x'' = x^0 \quad \text{nbrsys}^* = \text{nbrsys}'
\]

procedure fun1(I)

\[
f = K[1].x = f
\]

\[
i = 2
\]

\[
tn = t' + a[i]*h
\]

\[
j = 1
\]

\[
Y[j] = x^0[j]
\]
\[ y[j] = y[j] + h*b[i,j]*K[l,j] \]

\[ l = l + 1 \]

\[ l > n \]  
- yes:  
  \[ j = j + 1 \]
- no: 
  \[ \text{ procedure fun1 (II) } \]
  \[ t'' = t' \]
  \[ x'' = x_0' \]
  \[ \text{nbrsys}'' = \text{nbrsys}' \]
  \[ j = i + 1 \]  
  \[ j > nu \]  
- yes:  
  \[ j = j + 1 \]
- no: 
  \[ K[l,j] = f \]

\[ l > s \]  
- yes: 
- no:
procedure fun1

\[ Mb = m_1 \sin(m_2 t') + m_3 \]


\[ \text{OrgMom} = A_A \sin(w^*t') - k_i x[5] \]
\( \text{deltaM=OrgMom+Mb} \)

- If \( |\text{OrgMom}| > 10000 \) then:
  - \( f[2] = \frac{(\text{deltaM}\times p^x_2)}{4p} \)
  - \( f[3] = \frac{(K_g\times x[2] - x[3])}{T_g} \)
  - \( W_{i} = 0 \)

- If \( T_{bsk} < T_{sk} \) then:
  - \( W_{t} = K_0 \)

- Else:
  - \( W_{t} = K_0 \)
```
```

B.1 Description

Only standard functions of the algorithmic language Pascal have been used, such as: "ab1" is a module, "round" is a rounding off and etc., thus making this program easily accessible when designing such systems with required parameters by means of the hardware compatible with IBM PC. The time in the mathematical model is measured by frequency shares. The program is controlled with a help of the Main Menu consisting of the following commands: "Exit", "Help", "Enter", "Results", "Graphics". The choice of the command is executed with the help of the key "Tab", and execution occurs after pushing of the key "Enter".

The Main Menu commands mean the following:

- "Exit" means to leave the program for DOS.

- "Help" means to view the program text brief description. The pages shift is executed with any key push.
• "Enter" means to introduce the control factors. Sub-Menu-1 depends from this command choice. This Sub-Menu-1 consists of the following commands:

1. "Control coefficient" means to put in the equation coefficients and the magnitude of the FAA initial deviation from the meridian plane \( \vartheta_0 = \alpha_0^\circ \). The input format is in the form of "Coefficient = data". Besides, each factor can be chosen from the list of parameters, which occurs at the "P" key push.

2. "T = data" means to put in the \([0, T]\) time interval, within which the equations should be solved.

3. "N = data" means to put in the number of points in the final table.

4. "Exit" means to switch over to the main menu.

• "Result" means to view the tabulated data of the FAA relative position \( \vartheta(t) = \Delta \varphi \). This command choice results in displaying Sub-Menu-2 on the screen, this Sub-Menu-2 consisting of the following commands:

5. "Screen" means to view the results, and any key push shifts the pages.

6. "Print" means to copy the calculated results with the printer or to file them.

7. "Exit" means to switch over to the main menu.

• "Graphic" means to plot a chart \( \vartheta(t) = \Delta \varphi \) with the help of tabulated data. In response to this command Sub-Menu-3 is displayed and it consists of the following commands:
8. "Ibg = data", "Iend = data" mean to put in the table parameters which correspond to the beginning and the end of a chart.

9. "Options" means to view Sub-Menu-4 on the screen which allows to change the colour of the background, grids, axes, charts, numbers and co-ordinate axis names. The chart is constructed with a help of the "Graphic" command.

10."Exit" means to switch over to the main menu.

The coefficients of all equations, the end of the time interval, the initial angle and the tabulated points number are displayed within help line at the bottom of the screen. The help line contents is displayed on the screen with the "Z" key push.

It should be mentioned, that when the gap between tabulated data is too large and \( \frac{T}{N} \) is big enough, the chart could differ from the true process. The greatest amount of tabulated points is 1000, and the smallest step of integration is \( \frac{T}{1000} \). Probably, the larger \( T \), the less is the possibility to obtain the required accuracy of calculations. If so, the message about the utmost possible accuracy of calculation is stipulated on the screen.

B.2 Main Text

program md;

{ $n+ }  
uses dos,crt,graph,printer;
const nu=7;
type vekt_X= array[1..nu] of real;
  sss=string[4];
  zap_rech=record

  x:vekt_X;
end;
mas=array[0..1000] of real;
mas_menu=array[1..5] of string[16];
type_fun=procedure(t:real;x:vekt_X;nbrsys:byte;
var f:vekt_X;
Ekr=array[1..4000] of byte;
var
Ip,mu_p,AA,w,T1,TT,T2,kof,
post,Kr,Kg,Tg,Kof1,Kof2,Ki,Ti,k
sif,Tf,Vr,Ks,fi,Ku,
Up,Vs,Vo,
tend,tbsk,tesk,k0,
m1,m2,m3, c1,c2,c3,c4,
e1,e:real;
color,colst:byte;
n, nbeg,
colornadp,colornbr,colorfon,colorl
ine,colorxy,colorset,
ipr,ipd,ppp,ddd,s,i,j:integer;
x0:vekt_X;
Xgr:mas;
strok:mas_menu;
op: boolean;
istart,iend:integer;
c,cc,ccc,cc1,cc5:char;
ekran:ekr absolute

$B800:$0000;
save3,save2,save1:ekr;
Mbs:string;
function Vk(t:real):real;
begin
Vk:=c1*pi/180*t+c2*pi/180*sin(c3*t)+c4*pi/180;
end;
function dVkdt(t:real):real;
begin
dVkdt:=c1*pi/180+c2*pi/180*c3*
    cos(c3*t);
end;

function Vkl(t:real):real;
begin
Vkl:=0;
end;

function dVkl(t:real):real;
begin
dVkl:=0;
end;

{SF+}
procedure
fun1(t:real;x:vekt_X;nbrrsys:byte;
    var f:vekt_X);
var
argum,deltaM,W_t,dW_tdt,dFdx,
Mb,OgrMom:real;
begin
Mb:=m1*sin(m2*t)+m3;
f[1]:=x[2];
    OgrMom:=AA*sin(w*t)-
Kr*x[5];
    if abs(OgrMom)>10000
then
    OgrMom:=abs(OgrMom)/OgrMom*
    m1*100000;
    deltaM:=OgrMom+Mb;
f[2]:=(deltaM-
mu_p*x[2])/Ip;
f[3]:=(Kg*x[2]-x[3])/Tg;
W_t:=0;
if (t>Tbsk)and(t<Tesk)
then W_t:=K0;
dW_tdt:=0;
if nbrrsys=1 then
    begin

dFdxi:=0;
argum:=x[1]-
Vo+Vs+post;
if argum<>0 then
dFdxi:=-
Vr*2.15*(cos(180*argum/1.55)/argum-sin(180*argum/1.55)
/(180*argum*argum/1.55));
f[7]:=(TT*10*kof*dFdxi*x[2]-
x[7])/TT;
f[4]:=Ki*(Ti*f[3]+x[3])
+Kof2*(T2*(f[7]*sin(w*t+fi)+
x[7]*w*cos(w*t+fi)+dW_tdt)
+x[7]*sin(w*t+fi)+W_t);
end
else
begin
f[7]:=0;
f[4]:=Ki*(Ti*f[3]+x[3])
+Kof1*Kr*(T2*(x[2]+dVkti(t)-
dVk1dt(t))
+x[1]-(Vo-Vkt(t))-(Vkt1(t)-Vs));
end;
f[5]:=x[6];
f[6]:=(Ku*(T1*f[4]+x[4])-2*ksi*Tf*x[6]-x[5])/Tf/Tf;
end;
procedure integr(t,h:real;
x0:vekt_X;
fun:type_fun;nbrsys:byte;
var x:vekt_X);
var k:array[1..5] of zap_rech;
y:vekt_X;
a:array[2..5] of real;
b:array[2..5,1..4] of real;
c:array[1..5] of real;
ln:real;
l,i,j:integer;
begin
a[2]:=1/3;a[3]:=1/3;a[4]:=1/2;a[5]:=
1;
b[2,1]:=1/3;
b[3,1]:=1/6,b[3,2]:=1/6;
b[4,1]:=1/8,b[4,2]:=0,b[4,3]:=3/8;
b[5,1]:=1/2,b[5,2]:=0,b[5,3]:=2;
b[5,4]:=2;
c[1]:=1/6;c[2]:=0;c[3]:=0;c[4]:=2/3;
c[5]:=1/6;
fun(t,x0,nbrsys,k[1].x);
for i:=2 to 5 do
begin
  tn:=t+a[i]*h;
  for j:=1 to nu do
  begin
    y[j]:=x0[j];
    for l:=1 to i-1 do
      y[j]:=y[j]+h*b[i,l]*k[l].x[j];
    end;
    fun(tn,y,nbrsys,k[i].x);
  end;
  for j:=1 to nu do
  begin
    x[j]:=x0[j];
    for l:=1 to 5 do
      x[j]:=x[j]+h*c[l]*k[l].x[j];
    end;
  end;
end;
procedure gr(lstart,iend
:integer;end:real;Xgr:mas);
var
strok: string;
cc: char;
h, max, min: real;
col, Yo1, Yos, i, iplr1: integer;
x, y: array[0..1000] of integer;
grDriver: Integer;
grMode: Integer;
ErrCode: Integer;
begin
  grDriver := Detect;
  InitGraph(grDriver, grMode, "");
  ErrCode := GraphResult;
  if ErrCode <> grOk then
  begin
    exit;
    max := 0; min := 0; h := tend/nbeg;
    setfillstyle(1, colorfon);
    bar(20, 20, 20, 20);
    floodfill(50, 50, colorfon);
    for i := Istart to Iend do
      begin
        if max < Xgr[i] then
          max := Xgr[i];
        if min > Xgr[i] then
          min := Xgr[i];
      end;
      for i := Istart to Iend do
        begin
          y[i] := round((-Xgr[i]-
            min)/(max-min)*440+440)+20;
        end;
      x[i] := round((i-Istart)/(-
          iend+Iend)*500+100);
    end;
    Yos := round(20+440-(0-
        min)/(max-min)*440);
    i := 0;
    Yo1 := Yos-20;
  While Yo1 > 20 do
    begin
      setcolor(colorset);
      line(100, Yo1, 600, Yo1);
      setcolor(colornbr);
      str(-(i*20)/440*(max-
        min)-6:3, strok);
      OutTextXY(35, Yo1+16, strok);
      Yo1 := Yo1-20;
      i := i-1;
    end;
    Yo1 := Yos;
    i := 0;
  While Yo1 < 460 do
    begin
      setcolor(colorset);
      line(100, Yo1, 600, Yo1);
      setcolor(colornbr);
      str(-(i*20)/440*(max-
        min)-6:3, strok);
      if (Yo1+16-20) < 460 then
        begin
          OutTextXY(35, Yo1+16-20, strok);
          Yo1 := Yo1+20;
          i := i+1;
        end;
      setcolor(colorset);
      for i := 6 to 30 do
        line(20*i, 460, 20*i, 20);
      setcolor(colorxy);
      line(100, 460, 100, 20);
      line(100, 10, 103, 20);
      line(103, 20, 97, 20);
      line(97, 20, 100, 10);
line(100,Yos,600,Yos);
line(610,Yos,600,Yos-3);
line(600,Yos-3,600,Yos+3);
line(600,Yos+3,610,Yos);
for i:=0 to 10 do
  begin
    setcolor(colorxy);
    line(50*i+100,Yos-3,50*i+100,Yos+3);
  end;
setcolor(colorline);
setlinestyle(0,0,2);
col:=colorline;
for i:=Istart+1 to Iend do
  begin
    if i>ipr then
      setcolor(colorline-2);
      line(x[i-1],y[i-1],x[i],y[i]);
    end;
setlinestyle(0,0,0);
for i:=0 to 10 do
  begin
    str(istart*h+(i*50)/500*(iend-istart)*h:4:2,strok);
    setcolor(colornbr);
    OutTextXY(50*i+100,Yos+10,strok);
    end;
setcolor(colornadp);
outtextxy(50,0,'... (g . .)');
outtextxy(535,yos-15,'t ( b . )');
cc:=readkey;
CloseGraph;
window(1,1,80,25);
end;
procedure model(var e:real;
              tend:real;
              nbeg:integer;
              x0:vekt_x;
              var Xgr:mas);
var xh1,xh2: zap_rech;
  fun:type_fun;
  sk,hz:integer;
  norma:vekt_X;
  n,i,j,kkk,l:word;
  t,h1,h2,h,
  arg1,f,nor1,norm:real;
  bool2,bool1,bool,ov:boolean;
  nbrys:byte;
begin
  h1:=tend/nbeg;
  h:=h1;
  t:=0;
  n:=nbeg;
  for j:=2 to nu do x0[j]:=0;
  nbeg:=n;
  hz:=1;
  Xgr[0]:=(x0[1]-(V0-Vk(0))-(Vk1(0)-Vs))*180/pi*60;
  fun:=fun1;
  nbrys:=0;
  sk:=0;
  repeat
    t:=0;xh1.x:=x0;xh2.x:=x0;
    nor1:=0;
    bool:=false;
    bool1:=true;
    bool2:=true;
    ipr:=1001;
  
...
for j:=1 to nu do norma[j]:=0;
i:=0;ov:=false;
while (i<=n) and (ov=false) do
begin
i:=i+1;
arg1:=xh1.x[1]-Vo+Vs;
if abs(arg1)<1.55*pi/180 then
begin
  f:=Vr*2.15;
  if (arg1)<=0 then
    f:=Vr*2.15*
sin(180*(arg1)/1.55)
)/(180*arg1/1.55);
end
else f:=0;
if (f>Up) or bool then
begin
  nbrsys:=1;
  bool:=true;
end
else nbrsys:=0;
integrt(h1,xh1.x,
  fun,nbrsys,
  xh1.x);
integrt(h1/2,xh2.x,
  fun,nbrsys,
  xh2.x);
integrt(h1/2,h1/2,xh2.x,
  fun,nbrsys,
  xh2.x);
for j:=1 to nu do if
abs(xh1.x[j])>1.0e+10 then
ov:=true;
if sk=hz-1 then
begin
  Xgr[round(i/hz)]:==(xh1.x[1]-Vo+Vs)*180/pi*60;
  if bool1 and bool then
    begin
      lpr:=round(i/hz);
      bool1:=false;
    end;
    sk:=(sk+1) mod (hz);
t:=t+h1;
for j:=1 to nu do
begin
  nor1:=abs(xh1.x[j]-xh2.x[j]);
  if norma[j]<nor1 then
    norma[j]:=nor1;
end;
  norm:=norma[1];
  for j:=2 to nu do
    if norma[j]>norm then
      norm:=norma[j];
    if (norm>=e*15) and
    (n<=15000) then ov:=true;
    end;
h1:=h1/2;n:=n*2;hz:=hz*2;ov:=false;
    until (norm<e*15) or
    (n>30000);
e1:=norm/15;
end.
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List of Symbols and Abbreviations

This list contains the most important symbols and abbreviations used in this thesis, and gives some words on notation.

1 Abbreviations

ES: Extreme Search
FA: Phasing Arrays
FAA: Focal Antenna Axis
GPS: Global Positioning System
GSP: GyroStabilised Platform
LFC: Log-log Frequency Characteristic
MAP: Mobile Antenna Post
MSS: Mobile Satellite System
RVG: Rotor Vibrational Gyroscopes
2 Symbols

$\alpha_p$: GSP absolute angle along X axis
$\beta$: FAA elevation angle
$\beta_p$: GSP absolute angle along Y axis
$\beta'$: FAA actual elevation angle
$\Delta$: signal received loss
$\Delta B$: object latitude error
$\Delta L$: object longitude error
$\Delta M$: resulting moment
$\Delta_{\text{max}}$: FAA directioning maximum permissible error
$\Delta S$: satellite longitude error
$\Delta \beta$: elevation total error
$\Delta \phi$: azimuthal total error
$\Delta \phi_1$: search motion amplitude
$\Delta \phi_k$: object relative bearing variable component
$\delta$: polarisation plane disposition error
$\ddot{\varepsilon}_r$: basement angular acceleration
$\gamma$: kinematic error
$\gamma_p$: GSP absolute angle along Z axis
$\varphi$: FAA place angle
$\varphi_k$: object relative bearing angle
$\varphi_{k_o}$: object relative bearing constant component
$\varphi_S$: phase steadiness margin
\( \varphi_y \): yaw angle
\( \varphi' \): FAA actual azimuthal angle
\( \lambda \): wave length
\( \mu_p \): GSP damping factor
\( \nu \): object heeling angle
\( \Theta \): major lobe width
\( \sigma_j \): mean square value
\( \omega_b \): system basic frequency
\( \omega_c \): open system cut-off frequency
\( \omega_f \): angular velocity equivalent value
\( \bar{\omega}_f \): basement angular velocity
\( \omega_g \): generator frequency
\( \omega_k \): object bearing rate
\( \bar{\omega}^o \): object angular velocity vector
\( \xi_A \): accelerometer damping factor
\( \xi_f \): filter attenuation parameter
\( \psi \): object trim angle
\( \zeta \eta \xi_O \): geographical co-ordinate system
\( \Omega_H \): Earth angular velocity horizontal component
\( \Omega_V \): Earth angular velocity vertical component
\( A \): transformation matrix
\( A_S \): amplitude steadiness margin
\( B \): object latitude
\( B_0 \): object ideal latitude  
\( C \): error coefficient  
\( D \): effective antenna diameter  
\( E \): electric field intensity  
\( G \): antenna amplification factor  
\( g \): gravitational force acceleration  
\( I_p \): GSP inertia moment  
\( J_n \): Bessel’s function  
\( j^E \): accelerometer error  
\( j^o \): acceleration projection  
\( K \): open system gain factor  
\( K_A \): accelerometer gain factor  
\( K_{1E} \): open corrected extreme system gain factor  
\( K_{es} \): feedback gain factor  
\( K_{re} \): correction unit gain factor  
\( K_{oE}^r \): corrected extreme system transfer function  
\( K_g \): gyroscope gain factor  
\( K_i \): integrator gain factor  
\( K_j \): accurate adjustment closed system transfer function with respect to linear acceleration  
\( K_M \): torque motor gain factor  
\( K_o \): closed system gain factor  
\( K_{U_g} \): accurate adjustment closed system transfer function with respect to gyroscope equivalent angular velocity
\( K^X \): closed system transfer function with respect to external disturbance

\( K^{\Delta \beta}_{\Delta B}, K^{\Delta \rho}_{\Delta B} \): latitudinal error weight coefficients

\( K^{\Delta \beta}_{\Delta (s+\Delta L)}, K^{\Delta \rho}_{\Delta (s+\Delta L)} \): longitudinal error weight coefficients

\( K_{\rho} \): closed system transfer function with respect to Earth's angular velocity

\( k \): adjustment accuracy in fractions

\( L \): object longitude

\( L_o \): object ideal longitude

\( M \): oscillatory index

\( M^C \): control moment

\( M_G \): generator moment

\( M_i \): disturbance moment

\( O_i Y_i Z_i X_i \): inertial space co-ordinate system

\( O_o Y_o Z_o X_o \): object co-ordinate system

\( O'Y'Z'X' \): external frame co-ordinate system

\( O_a Y_a Z_a X_a \): antenna co-ordinate system

\( O_p Y_p Z_p X_p \): gimbal mount co-ordinate system

\( O''Y''Z''X'' \): intermediate frame co-ordinate system

\( P \): received power

\( R_E \): Earth radius

\( \bar{r} \): basement swaying radius vector

\( S \): satellite longitude
$S_j$: spectrum density
$S_o$: satellite ideal longitude
$\bar{s}$: Laplace standardised operator
$T_A$: accelerometer time constant
$T^E_R$: extreme system time constant
$T_F$: filter time constant
$T_g$: gyroscope time constant
$T_i$: integrator time constant
$T_M$: torque motor electromagnetic constant
$U_A$: accelerometer outlet signal
$U^C_A$: corrected signal
$U_{DM}$: demodulator outlet signal
$U^E_C$: extreme system control signal
$U_{es}$: "electrical spring" control voltage
$U_F$: filter outlet signal
$U_G$: generator outlet signal
$U_M$: torque motor outlet signal
$U_{TV}$: receiver outlet signal
$U'_{TV}$: TV-receiver threshold signal
$\bar{V}$: object linear velocity vector
$W^C_A$: adopting correction transfer function
$W^E_R$: extreme system transfer function
$W_F$: filter transfer function
Symbols

\( W_{OH} \): open levelling system transfer function
\( W_R \): transformation operator
\( x \): FAA relative position
Curriculum Vitae

Irina Popova was born in Belgorod, Russia, on May 1, 1965. After finishing with honours the secondary school on 1982 she entered the Leningrad Institute of Aviation Instrumentation, the Faculty of Gyroscopic Devices (Leningrad, Russian Federation). She graduated from the Institute with the first-class honours in 1988, having presented the diploma project on “Compact Attitude and Heading Reference System Built on Dynamically Tuned Gyroscope” in which the method of optimal regulators analytical constructing was used as one of the basic methods of synthesis. She was given the qualification of Master of Science in Engineering.

In may 1988 she started working in the Leningrad Optico-Mechanical Amalgamation as the 1st category engineer in the Design Office elaborating optico-electronic systems. She participated in the scientific-research and experimental works aimed at designing optico-electronic systems with a gyrostabilised sight line on the basis of uniorotor vibrational gyroscopes. Since 1992 she heads the “GYROOPTICS Co. Ltd. department engaged in designing gyroscopic systems of stabilisation and control of the optico-
electronic systems sighting line and antenna systems focal axes. She is also head research worker at the Department of Aerodynamics and Aircraft Construction, the Faculty of Aviation Instrumentation and Automation, the Academy of Aerospace Instrumentation, Saint Petersburg, Russian Federation.