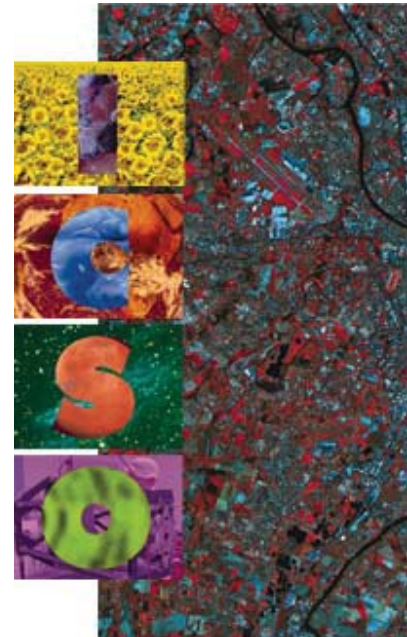


International Conference on Space Optics—ICSO 2000

Toulouse Labège, France

5–7 December 2000

Edited by George Otrio



Small star trackers for modern space vehicles

Vladimir Kouzmin, Vladimir Jushkov, Vladimir Zaikin



SMALL STAR TRACKERS FOR MODERN SPACE VEHICLES

Vladimir KOUZMIN, Vladimir JUSHKOV, Vladimir ZAIKIN

Scientific & Production Enterprise NPP "Geofizika-Cosmos", Moscow, Russia

ABSTRACT – *Based on experience of many years creation of spacecrafts' star trackers with diversified detectors (from the first star trackers of 60's to tens versions of star trackers in the following years), using technological achievements in the field of optics and electronics the NPP "Geofizika-Cosmos" has provided celestial orientation for all the space vehicles created in Russia and now has developed a series of new star trackers with CCD matrix and special processors, which are able to meet needs in celestial orientation of the modern spacecrafts for the nearest 10-15 years.*

In the given article the main characteristics and description of some star trackers' versions are presented. The star trackers have various levels of technical characteristics and use both combined (Russian and foreign) procurement parts, and only national (Russian) procurement parts for the main units.

1 - INTRODUCTION

Increase of quantity of space vehicles (SV), which use star trackers (ST), is noted during last years. It is connected with common increase of efficiency of such devices in the SV control systems and also with appearance of new tasks whose optimal solution could be obtained by means of the ST usage.

Some ST, being in practice autonomous and small devices, are able to output information about the SV attitude for a few seconds relative to directions towards the navigation stars. They provide high accuracy of the SV three axes attitude or angular orientation of the special equipment (telescopes, photo-cameras, radio-antennas etc.), mounted on the SV.

Increase of the ST tasks and operations complexity demands to develop and realise new design and technological solutions on micro-miniaturisation of the equipment, on providing permissible thermal ranges, providing irradiation stability, mechanical strength, reliability and resource. Direct measuring methods for the ST main characteristics should be realised simultaneously with reduction of the ST cost.

2 - CHARACTERISTICS OF THE STAR TRACKERS MAIN REQUIREMENTS

Scientific and production association (Russian abbreviation – NPP) "Geofizika-Cosmos" possesses the experience of many years development and exploitation of the ST intended for various specialised SV. The accumulated experience allows formulating and systematising the main (base) technical requirements for the ST of modern SV. The requirements for modern ST of SV don't come only to realising the required accuracy and sensitivity. The requirements of high economic efficiency are rather essential. The efficiency is determined mainly by the ST small overall dimensions and mass, high operational reliability, detailed tests of the technical characteristics, providing necessary level of metrological equipment, relative small cost as well as by ability of

stable serial reproduction. Realising the ST with the characteristics of high economic efficiency is possible based on modern technologies, usage of national and foreign procurement parts and computer equipment. The last is essential because it is required to process in possible minimum time large amount of video-information solving the problems of the SV orientation by means of navigation stars.

Taking into account the mentioned above, optimal choice of the ST technical characteristics' combination is necessary to provide reliable SV attitude control at minimum expenses.

Analysis of variety of different combinations for the ST main requirements, related to the SV of different types and to various ST technical tasks, shows that the field of view about 6 degrees X 6 degrees is sufficient (under limit sensitivity on a level of (6.0 – 6.5) star magnitude) to provide attitude control on criterion of presence of 4 – 5 navigation stars. Simultaneously, dispersion of errors of the SV orientation angles could be minimised, if the instrumental error of determining the direction towards every navigation star is about 30 arc.min.

Relative simple architecture of such star trackers includes CCD-matrix photodetectors (CCPD) and built-in control and processing unit (CPU) based on microprocessors implementing standard interface with the SV on-board host computer (OHC). It provides minimum dimensions and mass characteristics (DMC) of the star trackers and allows using them as the base ST.

In certain cases it is advisable to use the ST with the field of view about 30×30 degrees and limit sensitivity of 4.0 magnitude. In the base ST it may be provided, for example, using other types of lens and stray-light baffle.

Changing the lens diameter also provides operation of the ST for different ranges of the required sensitivity.

For some SV it is required to reduce further the DMC making the ST architecture simpler: the lens with baffle, the CCPD and the pre-processing unit, which is completed with an analog-to-digit converter (ADC). It is easy to accomplish excluding a series of standard units from the base ST.

Application of a few base ST on the SV allows rather easy realise, if needed, obtaining information for the SV three-axes attitude control with necessary level of the ST redundancy.

During 90's the NPP "Geofizika-Cosmos" has developed a series of standard units and base ST with different types of the CCPD and the CPU using microprocessors and signal processors, as well as technological and metrological facilities for their production and working-out tests. [Kouz 94, Kouz 96, Petr 96]. The mentioned ST are able to meet requirements of stellar orientation for the modern SV during the nearest 10-15 years.

Two types of developed structures are used as the base ST devices:

- the ST in the form of a single unit;
- the ST consisting of two units: imaging unit (IU) and electronic unit (EU).

In the given paper description of the ST operational diagram and base structure, its main technical characteristics and test results are presented for the single unit device (340K type), as well as for a version of applied modification of the base ST consisting of two units (345K type).

3 - THE MAIN CIRCUITRY-AND-DESIGN DISTINCTIVE FEATURES OF THE 340K DEVICE

The operational diagram shown in the Fig. 1 illustrates design of the 340K device intended for determination in the device frame the directions towards a few navigation stars, which are present in the lens field of view.

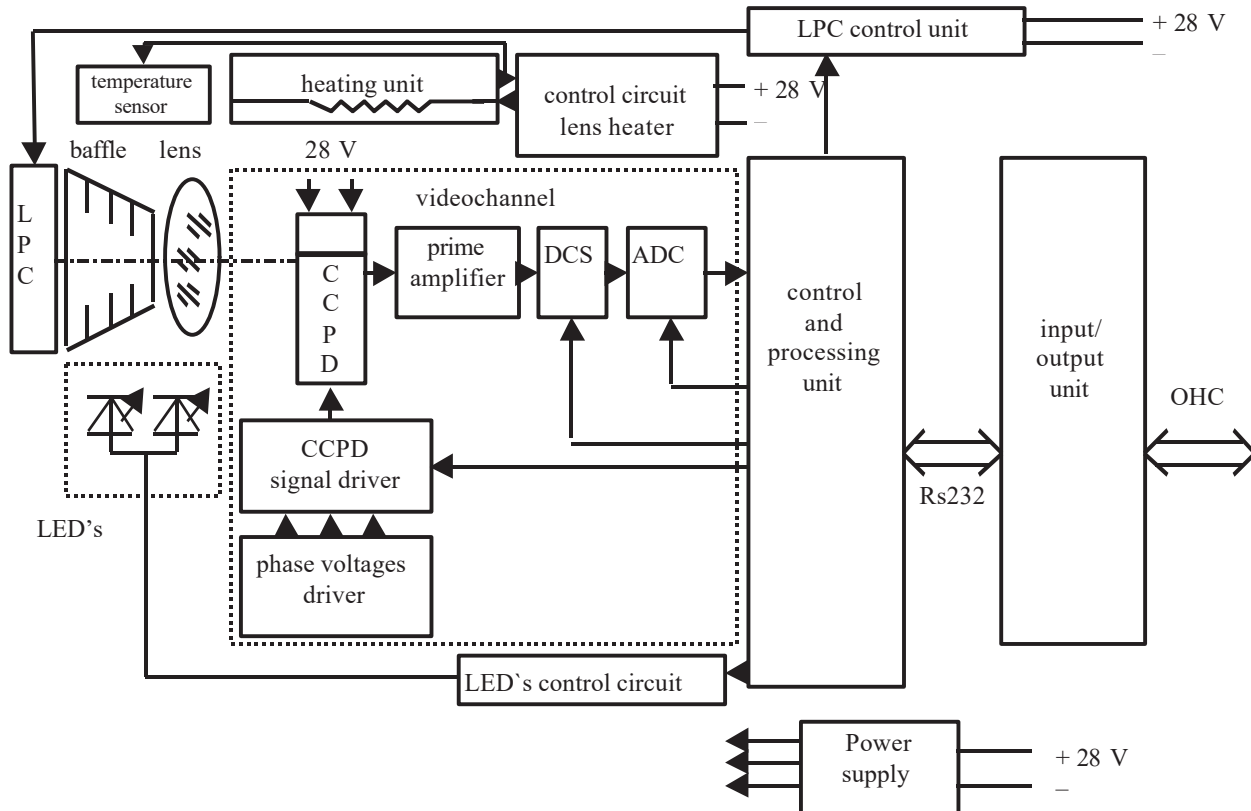


Fig. 1.

The device lens forms the navigation stars images in the focal plane, where the CCD matrix of the CCPD is mounted. The CCPD outputs the electric signals corresponding to the stars' images in the lens field of view. The device electronic units provide:

- control of the CCPD operation by means of signal driver and phase voltages driver;
- signal amplification and processing by means of preamplifier and amplifier with the double correlated selection (DCS);
- transformation of analog signals from the CCPD pixels into parallel binary code by means of the ADC;
- switching the LED's to check on the device operation;
- control of the light protective cover (LPC) actuator according to the code commands from the OHC or by means of direct supply voltage (28 V) to the actuator solenoids.

Adjustment of the preamplifier gain provides correspondence of the CCPD maximum signal (saturation voltage) to the maximum value of the ADC output code signal.

The DCS amplifier provides suppression of the clock jamming and reconstruction of the CCPD signal shape.

12-bit ADC transforms analog signals from the CCPD pixels into the parallel binary code. The ADC outputs information to the CPU. Phase voltages driver generates control pulses with the required amplitude levels for the CCPD. The CCPD control signals driver forms corresponding control pulses for the CCPD phase circuits. The device also includes closed loop autonomous thermal-heating system for the lens.

The CPU is the main unit, which provides interface with the OHC and realises processing information, writing it in required format and storing in a buffer memory. The CPU also performs the following main operations:

- forming the averaged signal value (background component) according to signal level analysis results for a group of the CCPD pixels;
- calculation of the difference between the current pixel signal and the averaged value;
- comparing the difference with the threshold code;
- forming the output signal of exceeding and a code of the difference, if the threshold is exceeded;
- forming the pulses to control the electronic units operation;
- forming the working window, the working window driver being RAM, arranged in the certain form, and is intended to store information about the working window position and the signal codes of the CCPD pixels within the working window co-ordinates.
- forming in accordance with the command "Mode" the pulse of initial setting, which switches the electronic units into the initial state. Further the CPU outputs the signal "Cleaning", which causes cleaning the CCD matrix from the accumulated charges, and the signal "Accumulation", corresponding in its duration to the code of the star magnitude mV received from the OHC;
- final processing the CCPD information according to the stated algorithms (selection on dimension, signal level star image velocity, etc.) and determination the star co-ordinates in the device frame;
- providing the information exchange with the OHC by means of diversified I/O information units.

The power supply units generate the required levels of secondary power supply for all the electronic units, using the SV standard primary on-board supply (28 V).

The electronic units are designed in such a way, that Russian and foreign procurement parts could be used without essential modification of the base operating units structure and structure of the device as whole.

The following criteria were taken into account in development of the electronic units:

- minimisation of the DMC;
- minimisation of power consumption;
- high reliability;
- possibility of program adjustment (including in the SV flight);
- low cost of development and production.

To provide the mentioned aims the foreign procurement parts along with the Russian ones are used in implementation of the electronic unit's circuitry. The CPU is two-processor computer system consisting of the following units:

- digital signal processor ADPS-2181 ("Analog Devices" company, USA);
- microcontroller AT89 LV 51 ("Amtel" company, USA);
- flash-ROM AT 29 C01UA ("Amtel" company, USA).

The signal processor controls the CCPD and processes its information, and the microcontroller provides functions of the central processor, interface, processing the time intervals, etc.

The power supply unit is designed using the standard modules and filter assemblies ("Interpoint" company, USA).

The ADC of ADC333A type ("Analog Devices" company, USA) is used in the circuit of the CCPD information processing.

In its structure the 340K device is a single unit (ref. Fig. 2), which is mounted to the SV on the base plane, implemented by three hard steel bushings of the base bracket, which is normal to the lens optical axis.

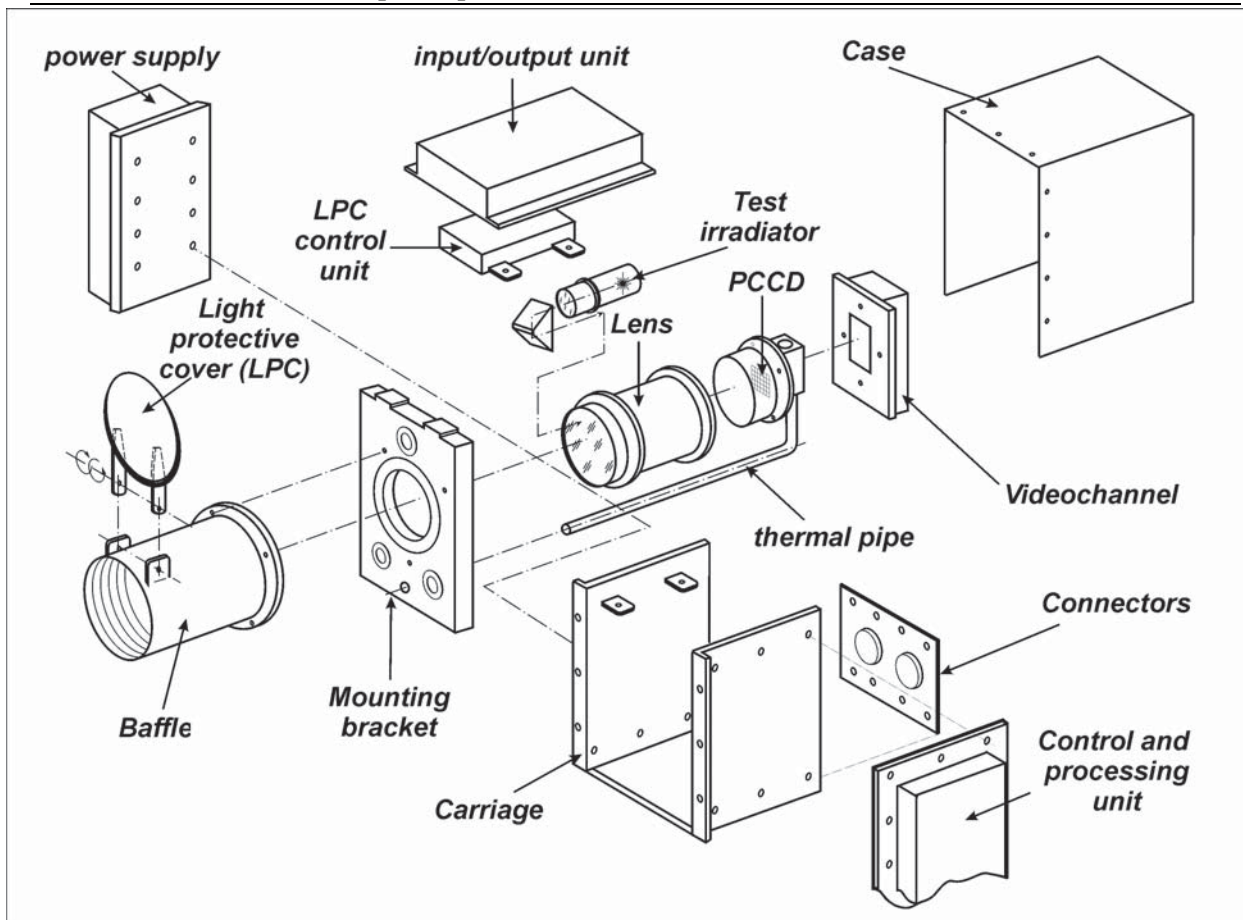


Fig. 2.

The device includes the lens with photodetector (the CCPD), the baffle with multi-operating protective cover, which are mounted to the base bracket.

All the main electronic units (video-channel, the CPU, the LPC control unit, power supply) and also the commutation connectors are mounted to the case.

The test irradiator provides check on the device operation. The irradiator light flux enters the CCD matrix of the CCPD through the rotating prism and the lens.

Changeable I/O units, which provide diversified interfaces, may be connected to the device main circuitry without dismounting the protective case.

Five-lens lens is calculated to minimise chromatism and distortion. Radiation stability at operation in space environment and long lifetime on the orbit is provided by means of choice of the lens glass sort.

The main characteristics of the lens:

- field of view 6 degrees × 6 degrees;
- light aperture 25 mm;
- focal length 105 mm;
- spectral range (0.4 – 1.1) mkm.

The baffle is used to protect the optics against stray light background from the Sun, the Earth, the Moon, and the SV structure components illuminated by the Sun. The baffle structure is cylindrical using the ring vanes.

The photodetector is the CCPD of “Lider 1” type. It has 512×512 pixels of (23×23) mkm size.

The star tracker operation in the wide range of temperature is provided by means of a thermal pipe, which transfers heat from the hot part of the thermal cooler to the device case.

The 340K device overall view is shown in the Fig. 3.

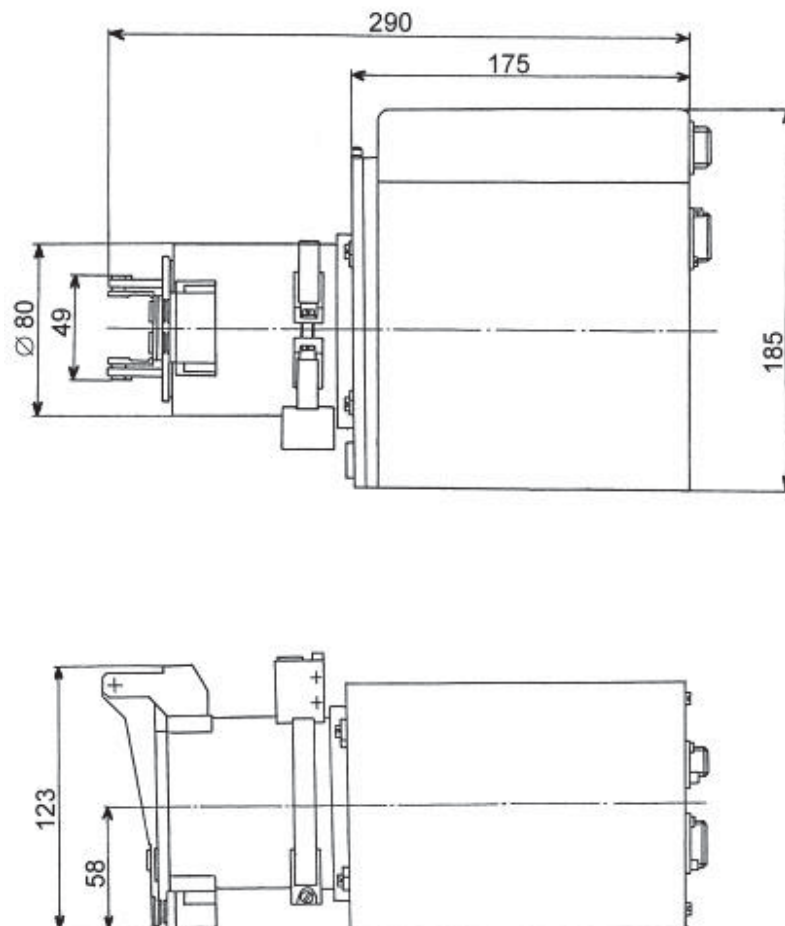


Fig. 3.

4 - THE MAIN TECHNICAL CHARACTERISTICS OF THE 340K DEVICE

The 340K device operating on the SV board has the following technical characteristics:

- limit error of the navigation star position determination (star group up to 5)
in the star magnitude range (-0.5 – 2.6) mV, and in the field of view
6 degrees × 6 degrees doesn't exceed 20 arc.sec.;
- mass 3.0 kg;
- dimensions (290×185×123) mm;
- power consumption 10 W;
- with the thermal cooler (if necessary) 15 W;
- limit angular distance to the Sun disk edge 50 degr.;
- update frequency (0.5 – 2) Hz;
- interface RS 232 or MIL STD 1553 B.

5 - OPERATION MODES OF THE 340K DEVICE

“Search” and “Measurement” are two main modes of the 340K device required for the SV attitude control. Some additional modes: “Defect Pixels Writing”, “Check on Photo-electric Channel Sensitivity), “Testing” may be used to provide the device technical characteristics (sensitivity, accuracy, jamming stability, large resource) under some specific conditions of the SV exploitation.

The modes: “Defect Pixels Writing” and “Check on Photo-electric Channel Sensitivity should be performed before the modes “Search” and “Measurement”.

“Search” mode

In the “Search” mode scanning the whole field of view is performed with the initial values of selection threshold and exposition time. If the star, which meets the given requirements on the total energy and the image size, is detected the device forms and outputs into the OHC the signal “Star detection”. It means that the device is ready to operate in the mode “Measurement”.

The device program forms round the chosen source the working window along the axes X and Y in the CCD matrix frame. The working window size is chosen taking into account velocity of the movement of the star image in the CCD matrix plane. Gain of the photo-electronic channel is determined, according to the value of the source total energy, and is used in the next mode “Measurement”.

Switching into the mode “Measurement” may be accomplished by the device program or according to the OHC command .

“Measurement” mode

Measurement of the source co-ordinates and total energy is accomplished with the parameters (accumulation time, the first selection threshold, the photo-electronic channel gain, the working window co-ordinates) chosen in the mode “Search”. Due to movement of the source image in the CCD matrix plane the working window co-ordinates are varied for different frames. The working window co-ordinated are calculated in the device for every frame by means of comparing the star image co-ordinates X and Y for two preceding frames. In every frame of the mode “Measurement” the co-ordinates of the point source image are calculated taking into account the defect pixels’ signals and the total signal of the source image.

“Defect pixels writing” mode

The mode “Defect pixels writing” is performed under closed light protecting cover.

Three frames of measurement are accomplished at the maximum accumulation time and the initial value of the first threshold of selection. According to the results of the information comparison within whole the working area in three frames the defect pixels set, which contains their co-ordinates and signals, is generated and stored. Accounting the defect pixels’ signals of the PCCD is realised in the mode “Measurement”.

“Check on the photodetector channel sensitivity” mode

Two frames of measurement are performed in the given mode under closed light protecting cover. The first frame is performed at illumination of the CCD matrix by the light flux from the control irradiator, the second one – then the illumination is absent. Both frames are performed at the same accumulation time and zero value of the first threshold of selection.

“Testing” mode

In the “Testing” mode the internal check on all the device operating units and the device software is performed according to the special programs.

6 - THE 340K DEVICE CONTROL ALGORITHMS

A series of the standard algorithms, worked out and proved at long time exploitation is realised both in the SV OHC and in the 340K device CPU to provide operation of the 340K device in all the listed above modes.

The software which implements the mentioned algorithms both in the 340K device and in the customer's equipment (the SV OHC, the SV testing facilities, etc.) may be offered by the NPP "Geofizika-Cosmos" at working out mutual operation of the 340K device with the SV equipment.

7 - FEATURES OF THE 340K DEVICE PRODUCTION TECHNOLOGY AND EXPERIMENTAL WORKING OUT

Development of the 340K device production technology was aiming to provide ability of the devices serial production based on maximum usage of formerly developed technological facilities for similar products. The main purpose was maximum reduction of the device production cost.

The NPP "Geofizika-Cosmos" possesses sufficient experience to produce the devices of such kind. Available stock of metal-cutting machine tools provides whole scope of mechanical processing of the device components with the required accuracy of size, form deviations, mutual positioning the surfaces and their roughness.

Assembly shop is sufficiently equipped with the universal test & measuring equipment, as well as unified assembling and installation and wiring facilities to provide high quality mounting, wiring, and adjusting the base units and the device as whole.

Special verifying facilities (panel-boards, desks, optical instruments, stands) as well as the facilities checking on the device centre of mass position and overall dimensions are created to measure the electric, optical and other parameters both of the device base units and the device as whole.

The assembling shops and the testing station possess all required equipment to simulate the environmental impact (temperature, pressure, mechanical impact, the Sun stray light, background jamming, electromagnetic interference, etc.).

The special facilities are created for strict measurements of the device parameters directly under the environmental impact.

Necessary metrological equipment is developed for the opto-mechanical stands, which have an error of the angular measurements on a level of 1–2 arc.sec., for the star simulators with light flux simulation error on a level of 16%, for the Sun simulators and the simulators of light background, fixed and movable light particle jamming, etc.

The working places equipped with IBM PC are used for testing the electric parameters of the device base units.

Such an approach allows to compensate significantly labour-consuming nature of development of the special technological equipment, to provide automated testing of the 340K device, to make diagnostics more reliable, to reduce manufacture cost of the device.

Experimental confirmation of the 340K device technical characteristics is performed on the testing base of the NPP "Geofizika-Cosmos", which is intended for the device autonomous working out under the conditions of maximum approach to the real ones.

Various criteria of checking on the 340K device quality are developed in connection with complexity and multi-factor nature of the experimental working out scope.

The objective criterion of validity and quality of the technical characteristics confirmation for the devices being manufactured is the positive experience of their implementation at working out a large series of the SV star trackers (ST). This experience is characterised by absence, in practice, of

the ST catastrophic failures and proving the main technical characteristics during flight tests and long time exploitation.

Creation and successive implementation of the system of the ST experimental working out at the NPP "Geofizika-Cosmos" has allowed to transfer the main scope of the ST technical characteristics working out to the stage of autonomous ground testing. Only the tasks of confirmation of the technical characteristics in the real flight conditions are left for the flight testing. It significantly reduces the required expenses for the SV being developed.

The main standard types of the verifying tests are the checks on the 340K device main characteristics on the special stands under the following interference:

- temperature;
- space vacuum;
- mechanical impact in the wide range of vibrations, shocks, linear accelerations;
- electromagnetic fields;
- stray light from the Sun simulator in vacuum;
- stationary and non-stationary light background, influence of sunlit particles, etc.

Specially developed equipment simulating light flux of the navigation stars, background stars, the Sun, sunlit particles, etc. is used at testing.

The characteristics of the device accuracy and sensitivity are verified on the special opto-mechanical stands of hard stone material, which provide stability of the angular attitude between the star simulators at the level of 1–2 arc.sec.

8 - MODERNISATION OF THE STAR TRACKER BASE STRUCTURE (THE 345K DEVICE)

Development of the 345K device for the SV, which is now designing according to the program "Resours – DK", is an example of the star tracker base structure modernisation. The specific requirements from the SV implementation, which cause necessity of the structure modification in the given case are:

- change of limit permissible stray light angle to the Sun and to the SV structure components to the value of 30 degrees;
- additional restrictions of the thermal fluxes which are transferred through the contact surfaces from the ST case to the SV body ;
- usage of the code signals to control the light-protecting cover;
- changes of the interface and the method of the primary power supply commutation, etc.

Usage of the 340K device's main base units has allowed to meet the main requirements to the star tracker by means of recombination of the main units with adding the commutation unit, new spare input/output device and new baffle. Restriction of the permissible thermal flux by the value of 2000 cal/cm² led to the ST structure of two sub-devices. As a result, the main technical characteristics of the 345K device were provided at the level similar to the 340K device with minimum increase of total mass and overall dimensions.

The volume of expenses for the base star tracker (340K device) adoption to the specific SV in the given case doesn't exceed 30% of the total expenses for development and experimental working out the ST base structure.

9 - CONCLUSION

Presented in the paper results of the development, production and experimental working out the base structures of star trackers for modern space vehicles are founded on analysis of the specific

requirements related to the modern space vehicles and on the NPP “Geofizika-Cosmos” experience of many years development, production and exploitation of similar devices.

Developed base structure of the 340K device, which is relative low-cost and available for serial reproduction as well as its modification (star tracker 345K), allow to meet the requirements of the most modern space vehicles for the next 10-15 years.

REFERENCES:

- [Kouz 94] V.S. Kouzmin, B.V. Medvedev, V.P. Jushkov, V.I. Zaikin et al “Small wide-field star tracker based on CCD matrix”, *Journal of gyroscopy and navigation*, St.Petersburg, vol.1, 1994, pp. 23-26.
- [Kouz 96] V.S. Kouzmin, V.I. Fedoseev “Electro-optical devices for attitude control and navigation of space vehicles: experience of development, problems and tendencies”, *Journal of optical technology*, St Petersburg ,vol.9, 1996, pp. 26-31.
- [Petr 96] V.A. Petrovich “Small star tracker”, *Journal of optical technology*, St Petersburg, vol.7, 1996, pp. 48-49.