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WESTPAC Satellite.

The Scientific-Technical note for user

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CONTENTS

The Scientific-technical note for user, based on the project's explanation note, contains final information on WESTPAC satellite structure necessary for the personnel of the ground laser stations for laser ranging. Energy and accuracy satellite parameters given in the present note are defined with the use of adjusted mathematics model, and the satellite design is described taking into account adjustments based on production results, experimental bench testing and final adjustment of satellite optical-mechanical design at the final stage of development.

1. Purpose of WESTPAC satellite

WESTPAC satellite is designed for reflection of incoming ground laser rangers' radiation with the purpose to measure distance to the satellite's center of mass. In addition, the satellite is designed for continuation of study of Fizeau effect with reflection of laser light from prism retroreflectors moving with space velocity. In working position WESTPAC satellite must be in condition of free non-oriented flight on altitude of about 835 km above the Earth surface.

2. General information about WESTPAC satellite

WESTPAC satellite is a system of 60 prism corner cube retroreflectors (RR) fixed in holders in the monolith spherical body. The main feature of the satellite is minimum error of link of range measurements to its center of mass - 0.5 mm. This is achieved by such satellite's design that laser light of SLR station incoming from any direction, is reflected only by one reflector with the field of view limited by the lens shading. The general view of WESTPAC satellite is given in the fig. 2.1.

To reduce orbital disturbances and to increase satellite's lifetime during design there was a goal to obtain with pre-defined mass maximum ratio of the satellite's mass to its cross-section area called ballistic factor. Body's material - brass - was chosen to get big enough value of ballistic factor equal to 504.2 kg/m^2 with satellite's mass given in the technical conditions and diameter of 245 mm.

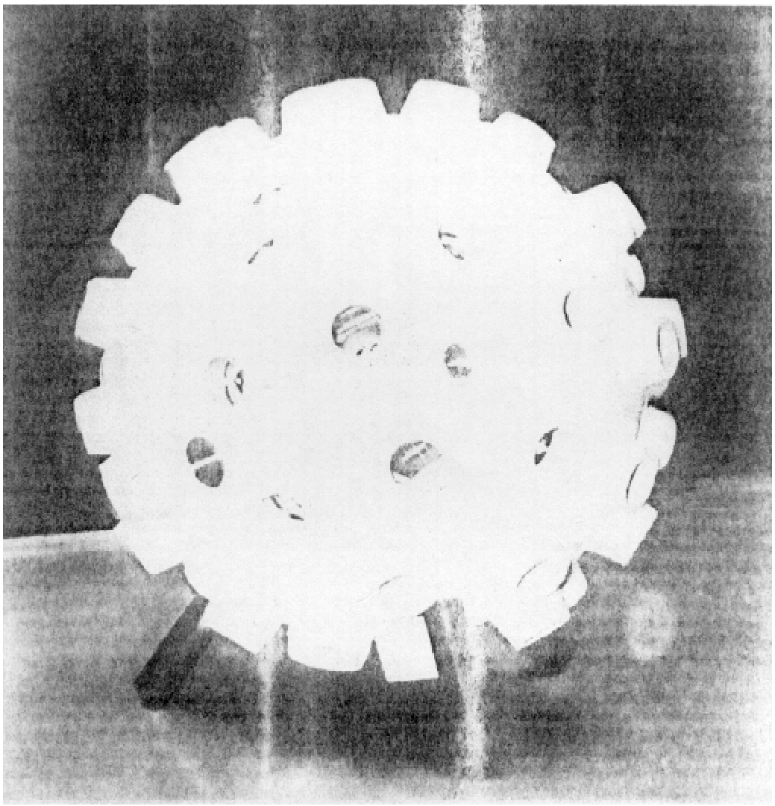


Figure 2.1. WESTPAC satellite

The satellite flight mass consists of the satellite's own weight equal 23.42 kg and small weight (336.8 g) of separation device elements remaining in the satellite body after its separation in the orbit. The separation device elements in the satellite body are placed symmetrically relatively to the center of mass and do not cause the displacement of the satellite center of mass for more than 0.1 mm (Rout mean square error).

RR are distributed regularly, 3 pieces on spherical surface of ball's segments limited by the sides of imaginary perfect shape with 20 sides (icosahedron). To reduce errors introduced in range measurements by RRs system (target errors), prisms are located as compact as their holders' dimensions allow. Diameter of a sphere circumscribed through centers of entrance apertures is 182 mm with dense location of RRs. It is important to note that normal going through centers of entrance apertures of all reflectors are passing strictly through the center of spherical body. Realization of principle "one direction - one reflector" is achieved by limitation of RR's field of view by means of round diaphragms with entrance apertures of 20.5 mm installed in a distance of 31.5 mm from the frontal side of each RR.

RRs have hexagonal entrance aperture with the area equivalent to a circle with diameter 28.2 mm. A distance between the entrance side and RR's vertex is 18.93 mm. Previously used value 19.1 mm was corrected by the results of adjustment and check measurements of real prism RR dimensions as the size tolerance appeared to be non-symmetrical: from +0 to –0.34 mm.

The assumed influence of Fizeau effect on light reflection from prism corner reflectors moving with space velocity was taken into account at the selection of reflection patterns at the wavelength 0.532 µm. It is known that in classical approach the satellite velocity aberration, is defined by the formula:

$$\Theta = \frac{2 * V}{c} \qquad (1)$$

where V - tangential component of satellite's velocity; c - speed of light.

In case when Fizeau effect influence is present, light deviation angle is defined by the formula (See article in the magazine "Letters to the magazine of theoretical and experimental physics", 1992., vol.55, issue 6, p. 317-320):

$$\Theta = \frac{2 * V}{c}(n + 1 - n^2) \qquad (2)$$

where n is refraction factor of the material of prism corner reflector.

It is seen from this formula that with n = 1.618 there is a complete compensation of deviation angle and light deviates strictly in backward direction. As RRs used on the satellite are made from fused silica with n = 1.4607 (at the wave length 0.532 μm), there is a partial compensation of deviation angle. Remain angle is 3.34 arc seconds. As for obtaining of maximum reflected signal, width of reflection pattern (with Gauss-like form) must be equal to 1.7*Θ, width of reflection patterns of RRs aboard the satellite is selected equal to the values about 5.5 …5.6 arc seconds.

The full flight mass of WESTPAC satellite is 23.757 kg.

The overall diameter of WESTPAC is 245±0.2 mm.

Delivered WESTPAC set has passed necessary acceptance tests for correspondence to the requirements of technical specifications with the positive result .

Quality of design of reflectors for WESTPAC satellite and sufficiency of acceptance tests were confirmed by positive results of orbital injection and many-year operation of RRs with similar design in conditions of real space flights on satellite types GLONASS and ETALON, GEOIK, METEOR-3, GPS-35, - 36, SALUT, RADUGA and other. Selection of reflection pattern taking into account partial compensation of velocity aberration by Fizeau effect is proved by space experiments on spacecraft RESURS R-01 # 2, METEOR-2, RESURS R-01 # 3 and ZEYA.

3. The main design parameters of detachable satellite WESTPAC and temperature influence evaluation results on it's design in the conditions of orbital flight

3.1 WESTPAC satellite design

The satellite WESTPAC consists of 60 prism RRs installed in special holders fixed in housings in a monolith spherical body made from brass. The body was done by means of precise machining from hammered half-finished product. It was many times put on stabilizing thermal processing.

As it was mentioned above, RRs are grouped by 3 on spherical surfaces of ball segments limited by each side of imaginary icosahedron. In icosahedron's corners there are 10 deaf holes with directing cones and threading M12. These holes are intended for fixation of half-made product during body machining. They are also used as fixation holes to fix the device during alignment and parameters control.

For mating satellite with separation device there are two contact holes with threading M22x1 located in two opposite corners of icosahedron.

Each RR is placed in a separate holder. A holder is fixed in the body's housing by means of specially shaped screw-nut which works as a lens shading limiting field of view at the same time. A spring ring aimed for compensation of mechanical loads appearing due to changes of body's temperature is installed between the threading ring and the holder. To prevent turning of a holder during fixation, a slot is foreseen in the body and the sprig fixed in the spring ring enters it. After completion of alignment of the device, threading ring is fixed by stopping mastic preventing self-unscrewing.

To provide total root mean square error of link of measurements to the satellite center of mass of not more than 0.5 mm, mechanical errors of satellite fabrication and assembling were minimized at the stage of final assembling and adjustment of optical-mechanical design. To ensure exact location of entrance apertures of RRs on a sphere with diameter 182 mm, there are foreseen special alignment washers (pads) with the thickness 1.0, 0.5, 0.1 and 0.05 mm necessary number of which is installed under RR's holders during installation.

To stabilize thermal regime of WESTPAC satellite in conditions of open space, external (not optical) surface of the satellite is covered by special thermal stabilizing white coating.

Holder's design includes mechanism which controls mechanical load of a RR. This allows to avoid sufficient thermal distortions of RR's pattern appearing due to the difference in thermal expansion factor of a RR and a holder material. Drawings of a RR and of holder's design are given in figures 3.1.1 and 3.1.2.

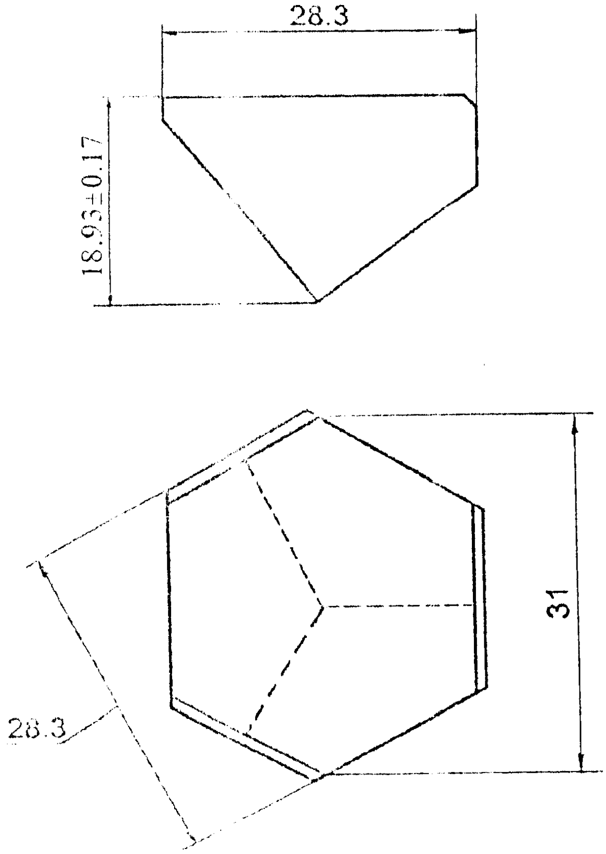


Figure 3.1.1. Corner cube retroreflector. Fused silica KY-1

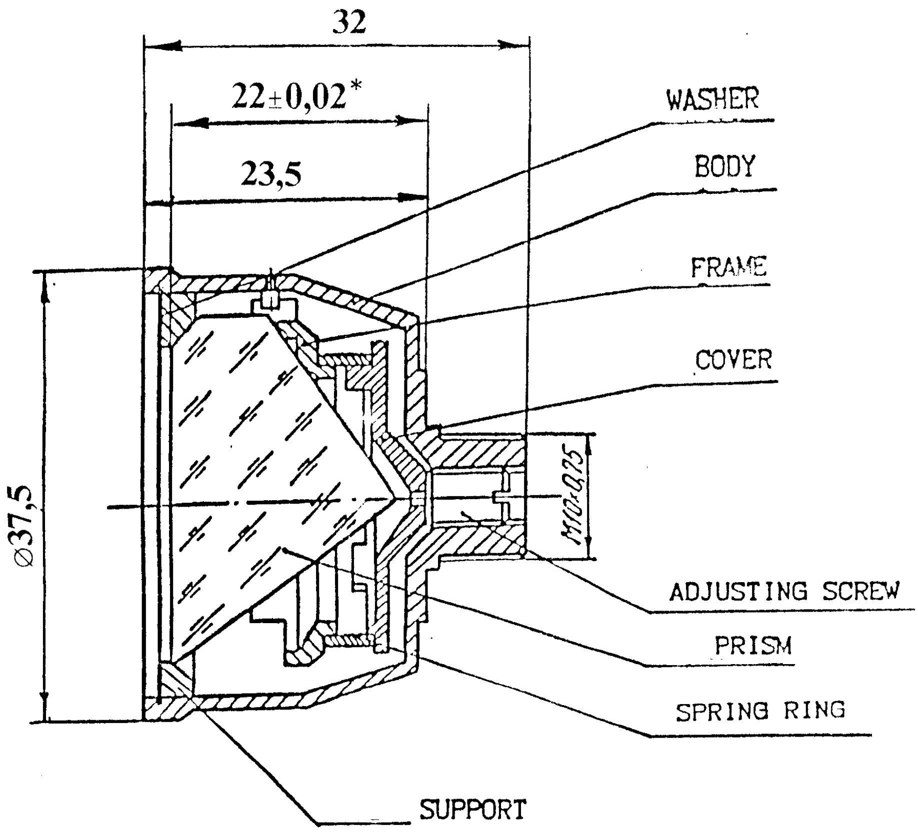


Figure 3.1.2. Prism corner cube reflector in its holder

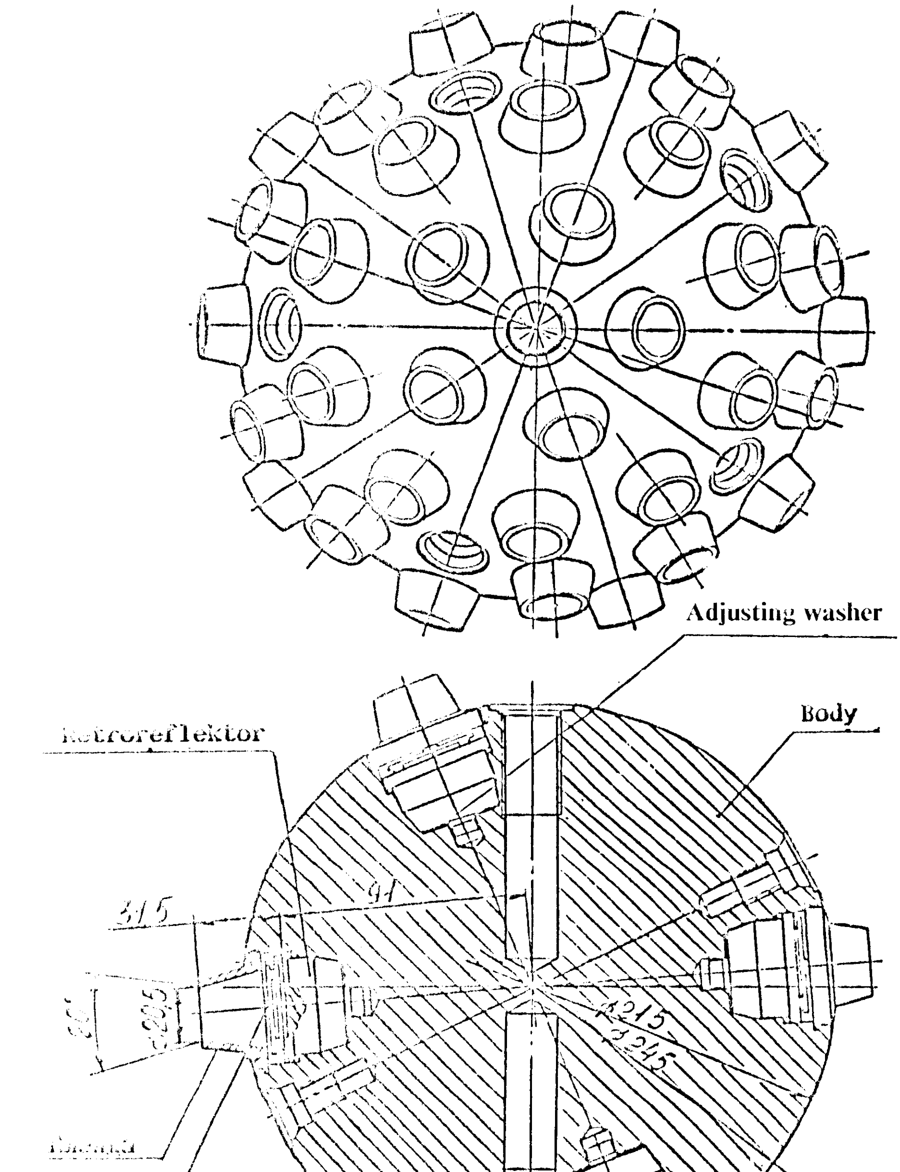


Figure 3.1.3. The precise passive laser satellite WESTPAC

For protection of frontal surfaces of RRs from damage during transportation and preparation of the device for orbital injection, WESTPAC satellite is placed in a special protective bag which must be removed right before its mating with separation device.

Fig. 3.1.3. shows assembling drawing of WESTPAC satellite.

3.2 The design and the principle of action of WESTPAC satellite separation system

Separation System (SS) is designed for separation from the main spacecraft of so-called small satellites to which category WESTPAC belongs to.

SS of WESTPAC small satellite consists of the following main assemblies and components shown in fig. 3.2.1. An explosive bolt (EB) and a group of legs with 4 spring pushers fixed on a dish-like bracket are located on the bottom of the SS.

On sending voltage from a ground command, the EB explodes (explosion line is defined by a special groove on the bolt surface) and pushers give the satellite necessary linear velocity for separation from the main spacecraft.

Action line of one of pushers is declined by the calculated angle from the radial direction towards the center of WESTPAC sphere. Rotational moment and therefore necessary angular velocity of 1 … 2 rad/s are created thanks to this decline. Pushers springs can be adjusted to achieve necessary parameters during testing and adjustment of the SS. Damping of EB triggering shock energy is done by a special mechanism consisting of moving conical rod, a spring and a bushing which warps when pusher's cone enters it.

After triggering of the SS, a part of the EB broken along the explosion line as well as the aforementioned mechanism for shock energy damping remain in the body of the satellite. To avoid displacement of the center of mass due to mass imbalance caused by these parts, WESTPAC satellite's design foresees special mass dummy installed on the satellite side opposite to the SS side. The dummy is similar to the components of the SS remaining in the body of WESTPAC satellite after its separation from the main spacecraft.

Registration of the fact of separation is done using telemetry signal by end micro switch.

3.3. Evaluation of WESTPAC thermal model

3.3.1. Conditions of WESTPAC external thermal exchange are defined by the following parameters of its orbital motion.

WESTPAC small satellite will be operated on the circular solar – synchronized orbit with the height of 835 km. The range of change of angle between orbital plane and Sun direction is 20 … 60 degrees. The angular velocity of satellite revolution relative to its own center of mass created by the system for separation from the main satellite is 1 … 2 rad/s.

Thermal mode calculation is done for extreme – "hot" and "cold" variants of external thermal exchange.

The "hot" option includes WESTPAC satellite operational conditions where the angle between orbital plane and Sun direction is 60 degrees, duration of shaded part of the orbit is 704.5 s (11.8 minutes) and optical coefficients of coatings reach their maximum values (after degradation).

In the "cold" option, the angle between orbital plane and Sun direction is assumed to be 20 degrees, duration of shaded part of the orbit is 2036.3 s (33.9 minutes) and optical coefficients of coatings have their initial values.

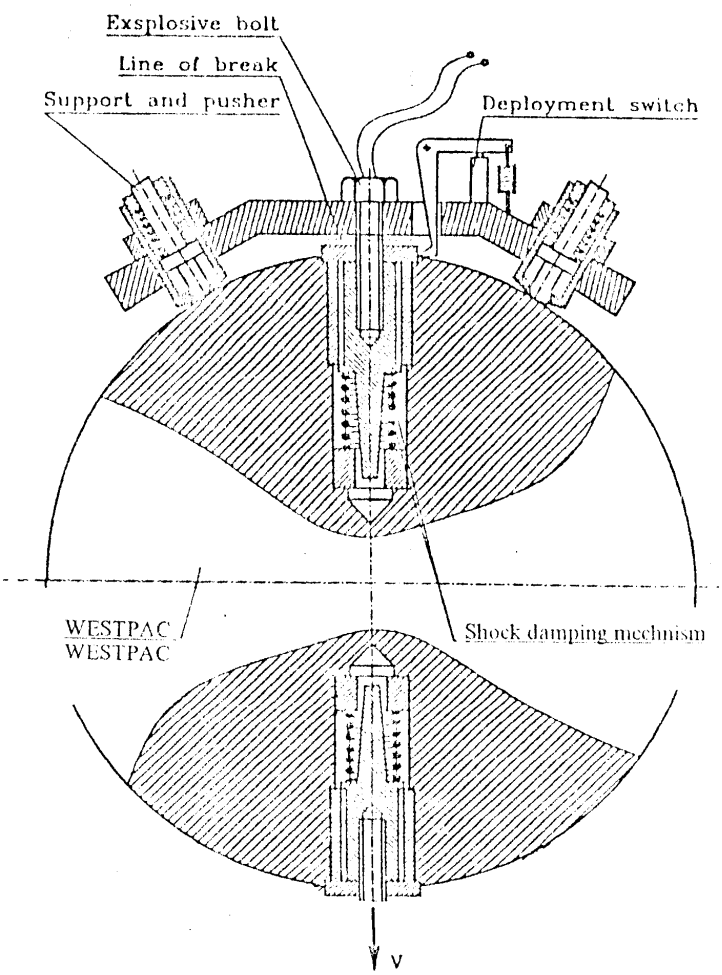


Figure 3.2.1. System for separation of WESTPAC satellite from the main satellite

3.3.2. Thermal calculation was done using TERM-2 software package designed for calculation of spacecraft thermal mode in orbital flight. The calculation includes the following subsequent steps:

- Building of the satellite geometry model;
- Calculation of external incident fluxes;
- Averaging of the external incident fluxes for the time of own rotation of the satellite;
- Calculation of the angular coefficients of the system "RR prism sides – internal surface of lens shading";
- Development of the satellite's thermal model;
- Calculation of thermal fields;
- Graphical processing of calculation results.

3.3.3. Geometry model of WESTPAC satellite is shown in fig. 3.3.1. Spherical surface of the satellite is conventionally shown as polyhedron.

Figure 3.3.2. shows geometry model of the "prism - lens shading" system.

The retroreflector is shown as hexagonal prism inscribed in a cone with bottom diameter 31 mm and height 18.93 mm. For definition of temperature gradient, the prism is divided in 4 parts in height. The correspondence of areas of the accepted geometry model to a real RR is done and adjusted in the thermal model by correction of optical coefficients.

3.3.4. The following procedure was used for calculation of external incident fluxes.

The period of own rotation of the satellite around its center of mass is more less than the period of satellite's rotation around the Earth by 3 orders of magnitude. The step for calculation of external incident fluxes during satellite's orbital motion should be less than 1 s what could lead to an enormous amount of computer calculations. Because of this, the method of averaging of external incident fluxes for the period of own satellite rotation was used. Orbital orientation was conventionally assigned to the satellite: X axis was directed along the orbital velocity vector, Z axis was directed in the zenith and Y axis completed right-hand vector system.

12 calculated positions were selected for analysis of thermal processes during rotation of RR around the satellite’s center of mass. External thermal fluxes of the satellite’s orbital motion were calculated for each of these positions. Then there were calculated average values that were used for further calculations.

Non-oriented rotation of the satellite around its center of mass was conventionally replaced with rotation of the satellite around some own axis. Position of this axis was defined by the following factors:

- RR should absorb maximum amount of external fluxes;
- RR shall pass satellite’s footprint on ground.

As a result, rotation of the satellite around X axis was taken for the “hot” option of thermal exchange, and rotation of the satellite around Y axis – for “cold” one.

To increase accuracy of calculation of external thermal fluxes and prism temperature fields, calculations were performed for an assembly "lens shading – prism" with introduction of relation of prism temperature with calculated temperature of WESTPAC satellite's body averaged for one orbit. Numerical commensurability of thermal capacities of parts of RR optical-mechanical structure participating in the consequent calculation was assured by means of this procedure. For instance, thermal capacity of the body is 7700 J/°C and thermal capacity of the prism near its vertex is 0.3 J/°C. Therefore, if thermal calculation was performed directly for the couple "body – prism vertex" (their thermal conductivities differ by more than 4 orders of magnitude), prism vertex temperature would be defined incorrectly due to loss of accuracy.

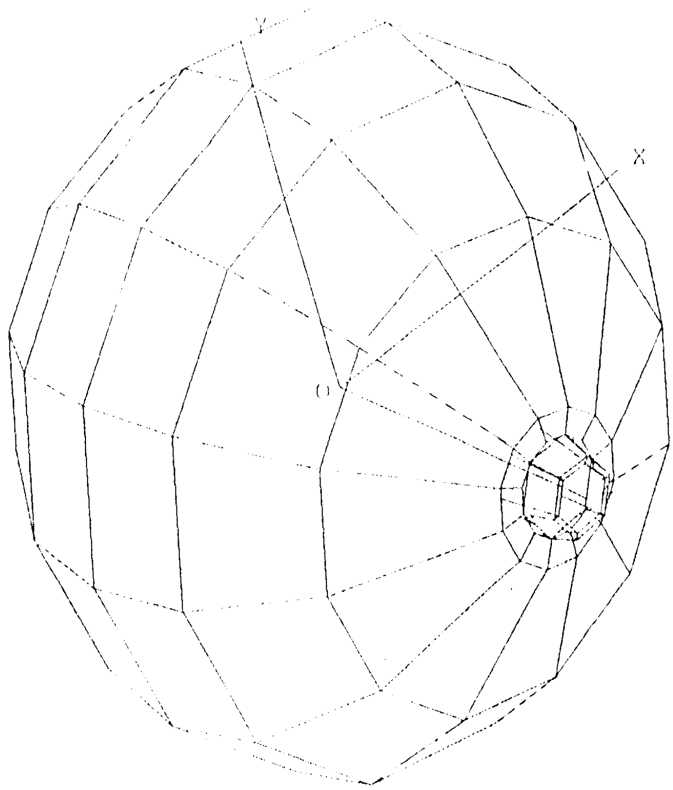


Figure 3.3.1. WESTPAC satellite geometry model

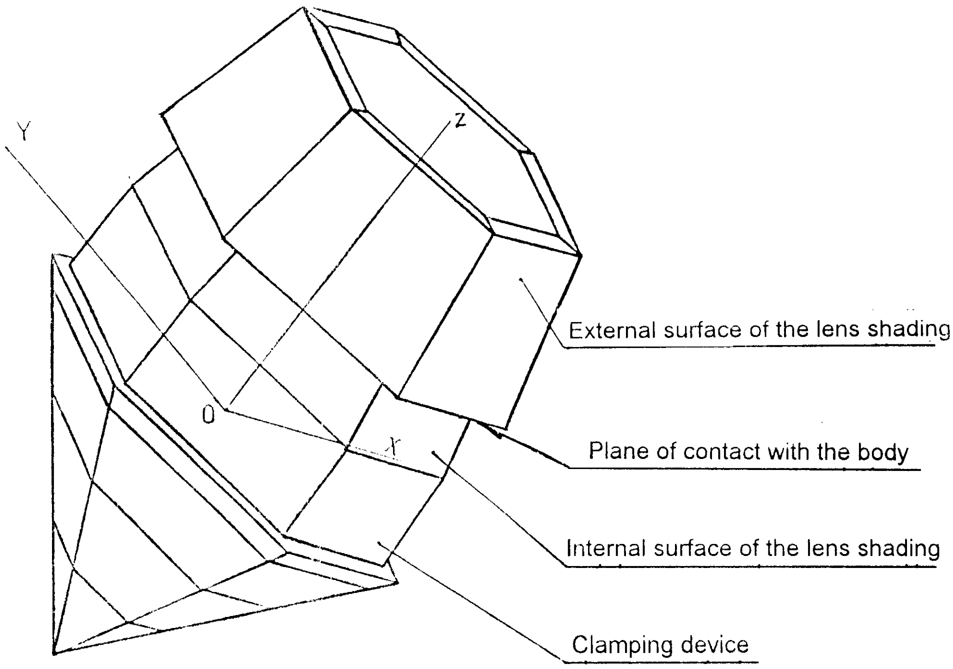


Figure 3.3.2. Reteroreflector and lens shading geometry model

3.3.5. Calculation of angular coefficients is performed for the system "RR prism sides – internal surface of lens shading". Angular coefficients define reflection and reradiation between prism sides and lens shading as well as effective area prism input aperture radiating in outer space.

3.3.6. Thermal model of WESTPAC satellite included 6 following elements;

1- satellite's body;

2- prism input aperture;

3- part of prism adjoining the input aperture;

4- internal part of the prism;

5- part of the prism adjoining prism vertex (prism vertex);

6- lens shading.

The calculation took into account thermal conductivities between parts of prism, lens shading and satellite body; the conductivity between the prism and the satellite body is introduced only for the input aperture of the prism in accordance with RR housing structure. Thermal conductivity in the prism is defined consequently by conductivities between four parts of the prism (between geometry centers of figures).

In the thermal model, radiant heat exchange was taken into account between back sides of the prism and satellite body, between lens shading and satellite body.

Reflections between prism sides were taken into account only in the wavelength range corresponding to solar radiation.

Outer surface of the satellite and RR lens shading is painted with white enamel AK-512. Enamel's optical coefficients are A_S=0.2 and A_S=0.55 for "cold" and "hot" options of thermal exchange respectively. Blackness degree in both calculation options was E_{PS}=0.85.

Type of coating of prism is 1I72P with A_S=0.395, prism emissivity in the IR range is E_{PS}=0.93.

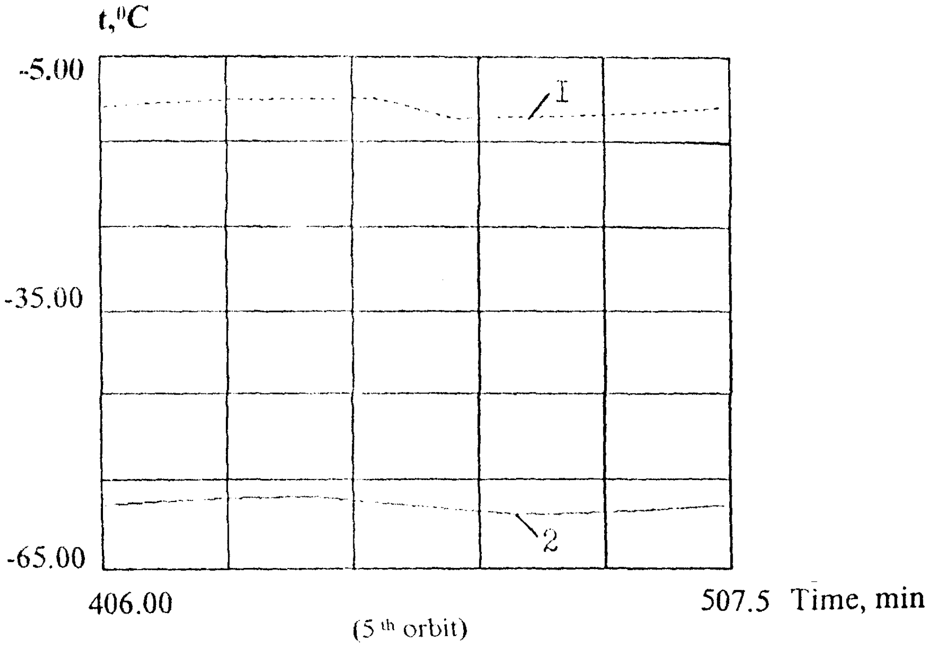
3.3.7. Thermal model working together with databases of external incident fluxes and thermal coefficients was used for calculation of temperature fields. Calculation results are presented in fig. 3.3.3, 3.3.4, 3.3.5.

Figure 3.3.3 shows change of WESTPAC satellite body temperature during one orbit for "hot" and "cold" options of thermal exchange. Axis of abscissa shows time of the fifth orbit, where, as it is accepted in the calculation, the periodically changing thermal mode of the satellite begins.

Figure 3.3.4 shows change of prism temperature during two orbits (from orbit 5 to orbit 6) for the "hot" option of thermal exchange. Maximal change of temperature in prism height is 0.52°C what corresponds to 0.27 °C/cm.

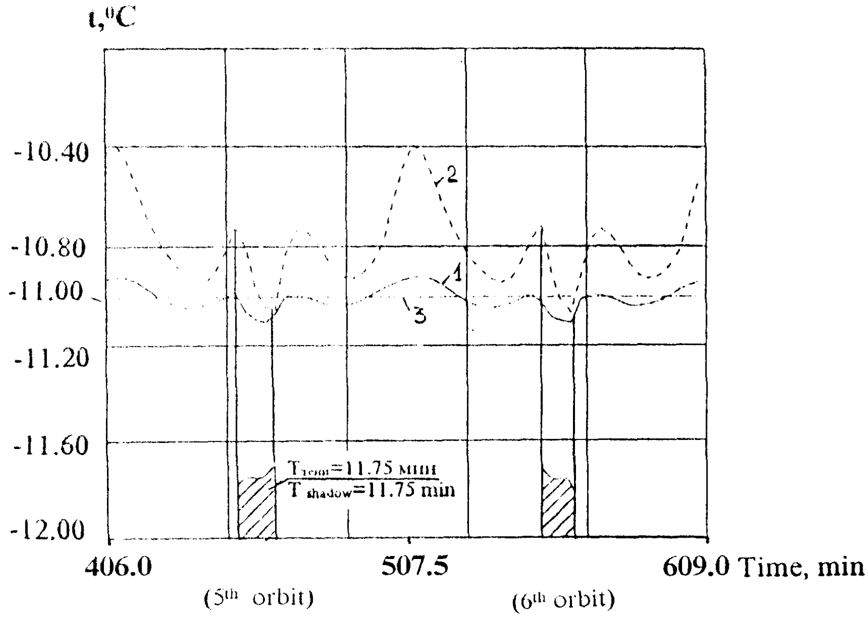
The least change of temperature in prism height corresponds to being of the satellite in Earth shadow what is caused by absence of solar fluxes.

Figure 3.3.5 shows change of prism temperature also during 2 orbits (from orbit 5 to orbit 6) for "cold" option maximum change of temperature in prism height is 0.33°C what corresponds to the gradient of 0.17 °C/cm.



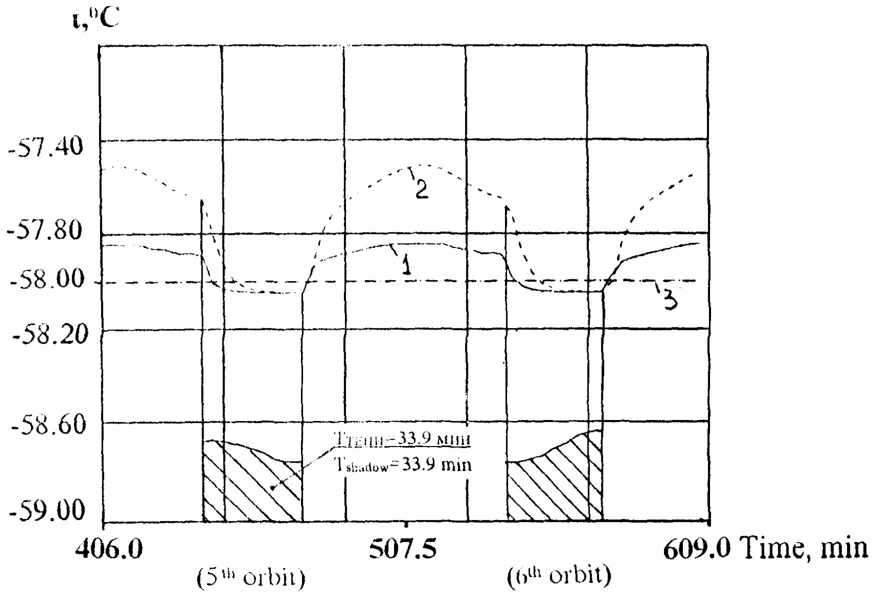
1 – A “hot option of the external heat exchange
2 – A “cold option of the external heat exchange

Figure 3.3.3. Change of the satellite body temperature during one orbit



1 – Input aperture of the prism
2 – Apex of the prism
3 – Mean temperature of the satellite body

Figure 3.3.4. Hot option of thermal exchange
(variation of the retroreflector temperature during 2 orbits)



1 – Input of the prism
2 – Apex of the prism
3 – Mean temperature of the satellite body

Figure 3.3.5. Cold option of thermal exchange
(variation of the retroreflector temperature during 2 orbits)

3.3.8. The following conclusions can be made by results of the performed thermal calculation.

Lens shading limiting RR filed of view, applied in WESTPAC satellite design, dramatically reduces all external thermal fluxes (including solar ones) absorbed by active reflecting sides of the prism what leads to dramatic reduction of temperature gradient in prism height which is not more than 0.27 °C/cm. This minor gradient does not practically effect the change of reflection pattern shape and efficiency of RR because corresponding changes of refraction coefficient and RR prism shape are insignificantly small even in thermal influence of outer space.

Thus, given optical-mechanical design of RR holder and its fixation in the satellite body ensure high thermal reliability of WESTPAC satellite operation in the conditions of passive spaceflight.

4. Description of satellite optical-mechanical mathematical model. Calculation of energy and accuracy parameters of WESTPAC satellite

4.1. Optical configuration of WESTPC satellite

Optical configuration of WESTPAC satellite is a sphere with regularly distributed on it RRs with lens shading, total number of 60. Constructive angle between neighboring RRs is not more than 26 arc degrees.

Radius of this optical sphere R_{sp}, where centers of entrance sides are located, is 91 mm. Equivalent diameter of light aperture of RR is 28.2 mm. RR's height is 18.93 mm. Designed height of lens shading is 31.5 mm, lens shading aperture is 20.5 mm.

Combination of given dimensional and optical parameters ensures realization of basic principle of satellite's design - ranging signal is reflected only by single reflector without overlapping of fields of view of neighboring RRs. Operation using principle "one direction - one RR" allows to reduce root means square (RMS) error of link of measurements to satellite's center of mass down to value of order 0.5 mm.

4.2. Grounds for selection of type of prism RRs for WESTPAC satellite

The selection of RR's designed lens shading diameter – 20,5 mm, defining operative RR light aperture with the lens shading height 31.5 mm, was stipulated by sufficiently strict initial requirements for maximal acceptable WESTPAC small satellite dimensions in combination with its high accuracy.

The combination of RR prism height 18.93 mm with lens shading height and diameters define the angle of RR field of view - 26 arc. degrees in which root mean square error (RMSE) introduced by arbitrary oriented RR is not more than 0.5 mm.

The fulfillment of these requirements leads to some energy decrease due to RR aperture screening from 28.2 mm to 20.5 mm. This is most noticeable in the case of classical velocity aberration when ground SLR station registers low level peripheral parts of RR reflection pattern.

As calculations performed for arbitrary oriented RR model showed, the increase of aluminum-coated RR aperture to the full one of 28.2 mm increases the energy reflection potential almost 2 times, but ranging RMS error increases with this to 0.9 mm what is not acceptable according to WESTPAC satellite requirements.

The other opportunity of WESTPAC satellite energy potential increase could be the replacement of aluminum-coated RR (RR_{Al}) to RR using the complete internal reflection (RR_{CIR}).

Reflection pattern of RR with aluminum-coated reflecting sides (RR_{Al}) is well described by classical Erie distribution which is formed by radiating equivalent diameter of RR aperture.

As it is known from literature and experimental data, (See article in the magazine "Optical-Mechanical Industry", 1982, #9, p. 1-3) reflection pattern of reflection of RR employing CIR (RR_{CIR}) is central spot and 6 side spots what corresponds to reflection pattern of diffraction lattice with six radiators (slots) with different polarization which size is defined by 1/6 of RR aperture.

The performed calculations taking into account this fine detailed form of RR_{CIR} reflection pattern, showed that the use of RR_{CIR} would really allow increase WESTPAC satellite energy potential near intensive central RP RR_{CIR} spot zones approximately up to 3 times with the keeping of target RMS error within 0.5 mm. However, the reflected signal level difference for classical velocity aberration and its compensation due to Fizeau effect will be just 1.5 times. Such situation will not allow to conduct sufficiently authentic and reliable experimental research of Fizeau effect influence on the velocity aberration compensation, corresponding to the flight program and WESTPAC satellite purpose. At this the RR_{CIR} RP spotted interrupted structure presence would come to noticeable decrease of total solid angle of WESTPAC satellite RR system field of view and would negatively tell on the stability of satellite reflected signal receipt and reliability of its further energy analysis.

Besides this, as it was noted before, aluminum-coated prism RR (diameter-28.2 mm) placed on WESTPAC satellite, have well developed technology and high reliability proved in big number of space flights.

4.3. Special features of ranging mathematical model of WESTPAC satellite

Not oriented rotating movement of the satellite makes undefined such parameters of spatial position of some de-facto operating RR as light incidence angle ε (not more than 13 arc degrees) and its polar aspect φ (from 0 to 360 arc degrees) relatively the velocity aberration vector.

Sloping light incidence on RR transforms circular radiation output aperture into elliptical one because of vignetting. In connection with this, level of reduction of reflected signal due to velocity aberration also depends of turn angle of velocity aberration direction and widening of reflection pattern which in our case has diffraction form.
This functional representation of reflection process of RR of WESTPAC satellite, in our opinion, is the closest to the real situation during ranging of such objects.

Development of theoretical model based on above mentioned ideas, is the result of consequent and detailed analysis and our knowledge development about the process of reflection from indefinitely located in a field of view single operating RR of WESTPAC satellite.

The present model is a development of preliminary accepted model where most probable and maximal signal from RR with zero light incidence was received, when normal to its entrance side coincides with direction of ranging signal.

According to our knowledge at the final stage of development, the position of equivalent reflection plane and level of reflected signal become some weight functions depending on incidence angle, polar aspect of ranging and direction of velocity aberration.

4.4. Basic mathematical proportions for determination of accuracy and energy parameters of WESTPAC satellite

The effective RR area within it's field of view:

$$S_{eff} = f(\Psi(\varepsilon,\alpha), \overline{\Theta}, \alpha, \varepsilon) \qquad (3)$$

where Θ - aberration velocity vector;

ε - light incidence angle;

α - RR pattern polar aspect angle;

$\Psi(\varepsilon,\alpha)$ – RR reflection pattern.

RR normalized energy efficiency (weight function):

$$P = \frac{S_{eff}(\Psi(\varepsilon,\alpha), \overline{\Theta}, \alpha, \varepsilon)}{\int^{\Omega} S_{eff}(\Psi(\varepsilon,\alpha), \overline{\Theta}, \alpha, \varepsilon)\, d\Omega} \qquad (4)$$

where $\Omega_r = f(\varepsilon,\alpha)$ – RR field of view.

The average weight systematic error (Δ_c):

$$L = \int^{\Omega_r} P(\Psi(\varepsilon,\alpha), \overline{\Theta}, \alpha, \varepsilon) \cdot L(\varepsilon)\, d\Omega \qquad (5)$$

where L (ε) – the dependence of single RR systematic error current value versus light incidence on RR.

Rout Mean Square optical error (RMS) of the satellite:

$$\sigma = \sqrt{\int^{\Omega_r} P(\Psi(\varepsilon,\alpha),\overline{\Theta},\alpha,\varepsilon)(\overline{L} - L(\varepsilon))^2 d\Omega} \qquad (6)$$

The average statistic signal level reflected from the satellite:

$$n_s = \frac{\sum \Omega_r}{4\pi} \frac{1}{\Omega_r} n_o \int^{\Omega} S_{eff}(\Psi(\varepsilon,\alpha),\overline{\Theta},\alpha,\varepsilon) d\Omega \qquad (7)$$

WESTPAC satellite total RMSE taking into account production errors is calculated in the following way:

$$\sigma_{total} = \sqrt{\sigma^2 + \sigma^2{}_{sp} + \sigma^2{}_{hous} + \sigma^2{}_{hol} + (\sigma_h * n)^2 + \sigma_{sep}{}^2} \qquad (8)$$

where $\sigma_{sp} \leq 0.017$ mm – Body sphere manufacture RMSE;

$\sigma_{hous} \leq 0.017$ mm – Body housings depths for RR holders installation RMSE;

$\sigma_{hol} \leq 0.013$ mm – RR holder RMSE is provided by alignment washers (pads), more detailed information see section 7.2;

$\sigma_h \leq 0.057$ – RMSE because of geometrical sizes dispersion of RR prism heights;

n – RR material refraction factor at working wave lengths;

$\sigma_{sep} \leq 0.1$ mm – Satellite center of mass displacement RMSE because of misbalance caused by the Separation System (SS) components remaining in the WESTPAC satellite body after its separation from the main satellite.

The more detailed information related to satellite RMSE budget and used methods of RMSE reduction is given in the section 7.

The main optical satellite parameters and energy parameters of real rangers having decisive value at the accuracy and energy range characteristics analysis are given in the Table 1 and 2.

SLR parameters used for energy calculations.

Table 1

SLR parameters	Sign	Value	
Working wavelength, μm	λ	0.532	1.54
Transmitter energy, J	E_{tr}	0.05	0.05
Transmission coefficient of optical transmitting antenna	K1	0.25	0.25
Transmission coefficient of optical receiving antenna	K2	0.12	0.12
Diameter of receiving aperture, m	D	0.5	0.5
Transmission beam width at level 0.5 arc minute	$2\varphi_{0.5}$	1	1
Atmosphere transmission coefficient in zenith	T	0.7	0.85
Quantum efficiency of photo receiver	η	12%	50%
Photon energy at working wavelength, $J*10^{-19}$	$h\nu$	3.74	1.29

Optical parameters of WESTPAC satellite

Table 2

Parameter	Value
Diameter of a sphere circumscribed through RR input apertures centers	182 mm
Equivalent diameter of input aperture of RR prism	28.2 mm
RR height	18.93 mm
Refraction factor (fused silica) at: λ=0.532 μm λ= 1.54 μm	 1.4607 1.4438
Transmission factor taking into account aluminum coating at: λ=0.532 μm λ= 1.54 μm	 0.57 0.78
Lens shading diameter	20.5 mm
Lens shading height	31.5 mm

Calculation of photoelectrons number n_{S*} was performed according to the following algorithm, corresponding to the equation (7), where:

$$n_o = \frac{E_{tr} * K1 * K2 * D^2 * T^{2\sec(Z)} * \eta}{(2\theta_{0.5})^2 * H_Z^4 * h * \nu} K_{RR} * K3 * \psi, \quad (9)$$

where in addition to above mentioned signs:

H_Z - sloping distance from ranger to the center of mass of WESTPAC satellite orbiting at the altitude 835 km;

K_{RR} - transmission coefficient of fused silica aluminum-coated RRs,

$K_{RR\ 0.532}$ = 0.57

$K_{RR\ 1.54}$ = 0.78;

K3 = 0.7 - possible reduction of reflection pattern levels due to technological deviations of real RRs from ideal ones;

ψ - function of WESTPAC satellite RR reflection pattern [steradian^{-1}].

Form of RR reflection pattern is assumed Gauss-like, beam width is determined in general case of light inclined incidence by the size of operating diffraction aperture of RR and spectral range of ranging. For wavelength 0.532 μm, real diffraction reflection beam width at level 0.5 at normal light incidence to the RR is 5.5 arc seconds, for wavelength 1.54 μm reflection beam width increases up to 15.8 arc seconds.

Size of RR reflection pattern ψ is defined by the formula:

$$\psi = \psi_{max} * \psi,$$

where ψ_{max} is maximal axis value of Gauss-like reflection pattern of RR,

$\psi_{max\ 0.532} = 1.258*10^9$ steradian^{-1};

$\psi_{max\ 1.54} = 0.1502*10^9$ steradian^{-1};

ψ - relative level of Gauss-like reflection pattern of RR for current value of velocity aberration Θ,

$\psi_{0.532} = \exp(-0.092855 * \Theta^2)$,

$\psi_{1.54} = \exp(-0.011089 * \Theta^2)$.

Together with the average probable signal level n_{s*}, maximal from achievable signal level n_{sMAX} can be rather useful for analysis. This value, like the average probable one, depends on current value of velocity aberration but corresponds to the optimal combination of aspect and light incidence angle on the arbitrary oriented RR at which the optimal shape of RR reflection pattern is formed within its field of view.

Analysis of energy and accuracy parameters of the satellite was performed for two variants of physical interpretation of velocity aberration phenomenon - classical and taking into account Fizeau effect.

In classical approach velocity aberration value for altitude 835 km is changing from 10.2 arc seconds (parameter pass) to 5.7 arc seconds (zenith pass at elevation 20 arc degrees).

In case of partial compensation of velocity aberration due to Fizeau effect, its angular value for wavelength 1.53 µm changes from 3.7 to 2.0 arc seconds.

Energy potential of WESTPAC satellite during ranging at wavelength 0.532 µm.

The average probable signal level n_{s*}, maximal signal level n_{sMAX} in photoelectrons.

Table 3

Zenith distance, arc degrees	Compensation of velocity aberration				Classical velocity aberration			
	Zenith pass		Parameter pass		Zenith pass		Parameter pass	
	n_{S*}	$n_{S\,max}$	n_{S*}	$n_{S\,max}$	n_{S*}	$n_{S\,max}$	n_{S*}	$n_{S\,max}$
0	13.3	64.8	13.3	64.8	0.91	4.0	0.91	4.0
10	12.7	62.2	12.5	60.7	0.87	3.9	0.85	3.7
20	10.9	54.5	10.2	49.7	0.85	3.5	0.7	3.1
30	8.1	42.8	7.2	35.2	0.7	2.9	0.49	2.2
40	5.2	29.2	4.3	20.9	0.6	2.2	0.29	1.3
50	2.7	16.1	2.1	10.0	0.4	1.4	0.14	0.6
60	1.0	6.5	0.7	3.5	0.2	0.7	0.05	0.2
70	0.22	1.46	0.15	0.7	0.06	1.21	0.01	0.04

Energy potential of WESTPAC satellite during ranging at wavelength 1.54 μm.

The average probable signal level n_{s*}, maximal signal level n_{smax} in photoelectrons.

Table 4

Zenith distance, arc degrees	Compensation of velocity aberration				Classical velocity aberration			
	Zenith pass		Parameter pass		Zenith pass		Parameter pass	
	n_{S*}	$n_{S\,max}$	n_{S*}	$n_{S\,max}$	n_{S*}	$n_{S\,max}$	n_{S*}	$n_{S\,max}$
0	63.3	457.2	63.3	457.2	36.2	166.7	36.2	166.7
10	59.8	432.3	59.5	430.8	34.7	161.4	34.1	157.1
20	50.4	365.6	49.8	359.9	30.5	145.6	28.6	131.2
30	37.2	271.7	36.5	263.7	23.5	120.6	20.9	96.1
40	23.7	174.7	23.0	166.4	16.2	88.2	13.2	60.7
50	12.6	93.8	12.1	87.6	9.2	54.4	6.9	32.0
60	5.3	39.7	5.0	36.4	4.1	26.1	2.9	13.3
70	1.6	11.8	1.5	10.6	1.3	8.6	0.8	3.9

WESTPAC satellite accuracy characteristics at the ranging at the wavelength 0.532μm .

The average optical error σ, systematic error Δc – mm.

Table 5

Zenith distance, arc degrees	**Compensation of velocity aberration**				**Classical velocity aberration**			
	Zenith pass		**Parameter pass**		**Zenith pass**		**Parameter pass**	
	σ	Δc	σ	Δc	σ	Δc	σ	Δc
0	0.429	62.824	0.429	62.824	0.459	62.178	0.459	62.178
10	0.428	62.826	0.429	62.824	0.460	62.187	0.459	62.178
20	0.425	62.833	0.429	62.824	0.467	62.227	0.459	62.178
30	0.422	62.841	0.429	62.824	0.473	62.279	0.459	62.178
40	0.418	62.852	0.429	62.824	0.483	62.363	0.459	62.178
50	0.413	62.863	0.429	62.824	0.488	62.459	0.459	62.178
60	0.409	62.872	0.429	62.824	0.486	62.562	0.459	62.178
70	0.405	62.882	0.429	62.824	0.476	62.653	0.459	62.178

WESTPAC satellite accuracy characteristics at the ranging at the wavelength 1.54μm .

The average optical error σ, systematic error Δc – mm.

Table 6

Zenith distance, arc degrees	**Compensation of velocity aberration**				**Classical velocity aberration**			
	Zenith pass		**Parameter pass**		**Zenith pass**		**Parameter pass**	
	σ	**Δc**	**σ**	**Δc**	**σ**	**Δc**	**σ**	**Δc**
0	0.3966	63.217	0.3966	63.217	0.430	63.136	0.430	63.136
10	0.3965	63.217	0.3966	63.217	0.429	63.138	0.430	63.136
20	0.3962	63.218	0.3966	63.217	0.426	63.147	0.430	63.136
30	0.3956	63.219	0.3966	63.217	0.423	63.155	0.430	63.136
40	0.3938	63.221	0.3966	63.217	0.418	63.167	0.430	63.136
50	0.3942	63.222	0.3966	63.217	0.413	63.180	0.430	63.136
60	0.3936	63.223	0.3966	63.217	0.408	63.191	0.430	63.136
70	0.3930	63.225	0.3966	63.217	0.404	63.201	0.430	63.136

Tables 3, 4 contain calculated values of the average statistic energy potential n_{S^*} and maximal energy potential n_{smax} in photoelectrons of WESTPAC satellite for working wavelengths 0.532 μm and 1.54 μm.

It is worth mentioning that at some satellite aspects none of the RR is illuminated by the sounding laser radiation, therefore there will be observed the absence of reflected pulses, at this the total solid angle in which there is no signal comprises 23.1% of the complete sphere of 4π steradian.

This is equivalent to 23.1 % loss of reflected signals what we consider to be acceptable (taking into account the obtaining of unique small RMSE of the satellite). At this the drop of reflected signals will be statistically regular in time as the satellite rotation will be provided after its separation.

Tables 5, 6 contain calculated data about accuracy characteristics of the satellite: about the optical RMS error σ (without errors of satellite's fabrication) and systematic error Δ_C, mm, at this it is important to note that these parameters depend on satellite observation angles, working wavelength and on presence or absence of Fizeau effect.

Tables 3-6 present two options of satellite's pass - zenith pass, when satellite's orbital plane goes through zenith of ranging station's local coordinate system, but velocity aberration changes from minimal to maximal value with increase of zenith distance, and parameter pass (maximal elevation of the satellite), when satellite's velocity vector is perpendicular to ranging direction but the velocity aberration is maximal. Thus, it gives opportunity to evaluate the range of possible changes of energy and accuracy parameters of the satellite.

4.5. Analysis of results of energy and accuracy calculations

The analysis of obtained calculated results shows that ranging at wavelength 1.54 μm is guaranteed method for realization of high energy potential of the satellite with the least RMS error. Noted advantages do not depend on presence or absence of Fizeau effect influence on angular velocity aberration.

The maximum value of optical RMS error in given spectral range is not more than 0.43 mm and total RMS error taking into account errors of fabrication of mechanical components of the satellite is not more than 0.461 mm. Values of systematic errors change insignificantly.

Ranging at wavelength 0.532 μm which is basic in experimental program of study of Fizeau effect influence on compensation of velocity aberration gives slightly different results.

Energy potential of WESTPAC satellite is totally lower in this spectral range, though for the case of velocity aberration compensation it remains high enough and total RMS error does not exceed 0.5 mm.

In the case of classical mechanism of velocity aberration optical components of RMS error is increasing up to 0.488 mm, but the total RMS error, taking into account errors of fabrication of optical and mechanical components - up to 0.506 mm what exceeds the required one for 1.2%.

This slight exceeding will be observed only at the near-zenith satellite passes at the zenith distances from 40 to 70 arc degrees. Evidently, the part of measured ranges with this error will be sufficiently small in comparison with the total number of measurements at the rest of satellite passes and only in the case of Fizeau effect influence absence.

As it is seen from Table 3, the main criterion at the experimental research of Fizeau effect influence on the velocity aberration compensation, must be analysis of the average for the session reflected signal level n_{s*}. The level of reflected signals in the case of the presence of Fizeau effect influence must correspond to 4 left columns of Table 3, in the case of its absence – to 4 right columns of Table 3, and differ in approximately 5-15 times.

5. Control of reflection pattern of WESTPAC satellite

Special optical-electronic measuring bench was used for the control, study and certification of the form of RP for the reflected from WESTPAC satellite laser radiation. The bench allows to perform measurement of RP of separate reflectors of WESTPAC satellite, and resulting RP of the whole satellite. Determination of the form of RP is done by the measurement of its width at different levels.

The basic modules of optical-electronic bench are:

- long-focus autocollimating optical system;
- laser;
- TV system for visualization and measurement of reflection patterns.

Equipment is placed on the massive platform isolated from room's foundation to protect the bench from external mechanical vibrations.

Autocollimation system is equipped with changeable optical elements what allows to form equivalent focal lengths according to different requirements.

5.1 Basic technical characteristics of measurement system during the registration of reflection pattern

Working wavelength	λ=0.63 μm
Aperture of autocollimating system lens	D1=150 mm
Equivalent focal length	f1 =32 m
Reflection pattern measurement range	from 1 to 47 arc seconds
Error of measuring of reflection pattern width	0.5 arc second

As calculations and performed comparisons with measurements with the use of YAG laser at the wavelength 0.532 μm show, the use of HeNe laser with the wavelength 0.63 μm in the testing facility does not distort results of measurements of RP of RR, during the measurement of diffraction RP one shall take into account the correction for RP reduction with the coefficient K=1/1.184.

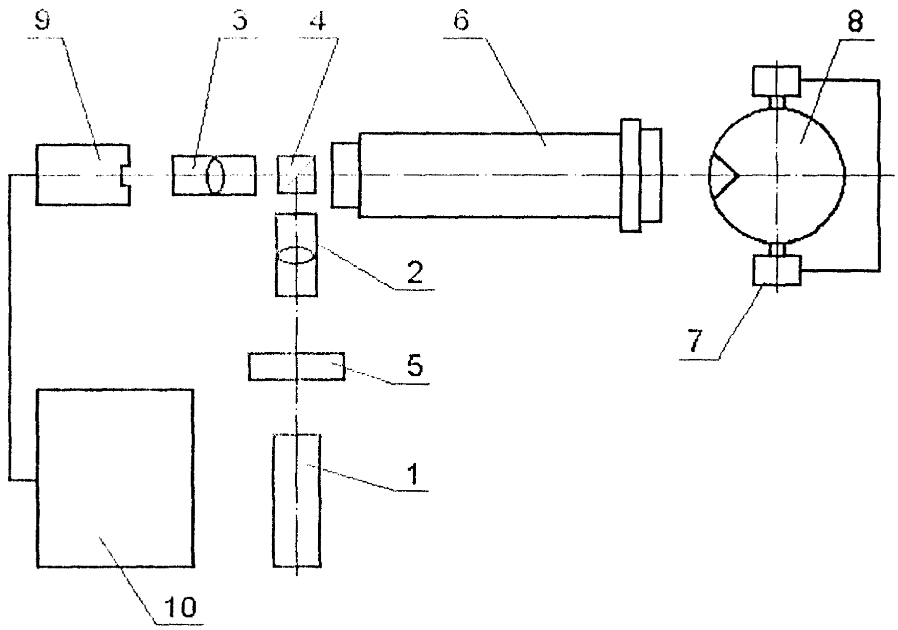
5.2 Short description of the design and functioning control-measuring bench

Block diagram of the measuring bench is given in figure 5.2.1.

Working laser consists of:

- permanent single-mode He-Ne laser with the wavelength 0.6328 μm type -207-3, -207 or -13;
- variable optical density filter which allows to reduce intensity of laser radiation smoothly;
- optical matching system which main component is an ocular with focal length 12.5 mm for transfer of laser radiation waist plane to the collimator's focal plane and for transformation of the size of focal spot to 0.015 mm;
- light splitting cube prism which is used to input radiation in the autocollimation system;
- autocollimation system consisting of a collimator from optical bench -2 and projection lens H2.

Autocollimation system is designed to form regular light flux with diameter 150 mm with flat wave front. It also forms an image of RR's reflection aperture in the plane of TV-camera's photo cathode.



1 – laser radiator
2 – optical matching system
3 – projection objective
4 – light splitting cube prism
5 – filters of variable density
6 – main objective of the autocollimation system
7 – technological fixation device
9 – transmitting TV camera
10 – TV system for processing of electrical signal of the TV camera

Figure 5.2.1. Block-diagram of the measuring bench

HeNe laser is used both for adjustment and tuning of the optical-electronic part of the bench and also for control of the aperture.

Forming of the RP of the whole satellite (or its separate parts) in far field is performed in the following way. The radiation of laser source is collimated by the autocollimating system during the forward pass, and as a result, the RP is formed during the backward pass in the point of equivalent focus. Electronic system connected with TV camera shows a section of RP for chosen level and measures angular dimensions of this section on the monitor.

Equipping of WESTPAC with separate RRs is performed by the use of specially elaborated technique which includes:

- selection of suitable RRs from a big party;
- personal analysis of RP of each RR proposed for satellite equipping and their final selection;
- the final control of RP of assembled WESTPAC satellite;
- check of the RP after mechanical tests.

6. Mechanical tests of WESTPAC satellite

To check assembling and mounting quality of WESTPAC satellite, mechanical vibration tests are performed. These tests are performed on vibration test facility VVP-600.
The facility VVP-600 has the following technical characteristics:

Capacity	75 kg
Frequency range	5 - 2500 Hz
Pushing force	3600 kg force
Maximum displacement	10 mm
Maximum acceleration	100 g

Outline of the facility is shown in fig. 6.1.1

Before beginning of tests, measurements of WESTPAC satellite optical parameters and visual check are performed.

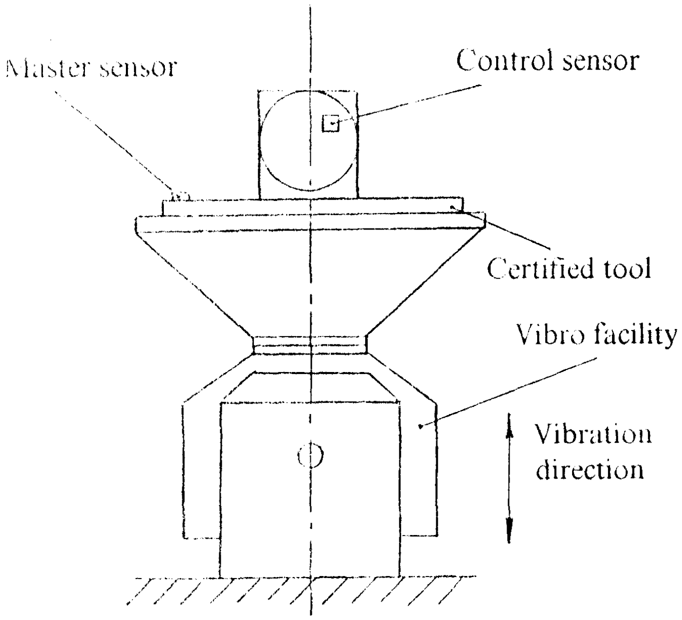


Figure 6.1.1. Mechanical test facility

Then WESTPAC satellite is installed and fixed on the specially certified appliance which is firmly fixes the satellite on the vibration facility's platform. Vibration sensors are fixed on the satellite's spare fixation hole and on the certified appliance. These sensors are used for control of level of vibration overloads.

Then, according to technical conditions, necessary cycles of vibration influences on the satellite are applied. Quality of WESTPAC satellite assembling and mounting is checked by vibration tests with the spectral density of vibration acceleration s=0.02 G/Hz in frequency range 20 Hz - 2000 Hz and time of influence up to 1 minute in three mutually orthogonal directions.

After completion of cycles the satellite is dismounted from the vibration facility and its visual check is performed to confirm absence of mechanical damages. Then measurements of WESTPAC satellite parameters are performed and if these parameters correspond to technical conditions, tests are considered to be successfully completed.

7. The checkout and minimization of WESTPAC satellite fabrication and assembling RMSE

During the development of precise WESTPAC satellite with RMSE not more than 0.5 mm there was made errors minimization of assembling of RR holder optical-mechanical construction with the help of alignment washers (pads). As it was noted before, there were also minimized optical RMSE, technological RMSE of size dispersion of RR prism heights and also RMSE of SS misbalance. The errors related to the satellite body fabrication and body housings for installation of RR holders are defined by the instrumental accuracy of the corresponding technological processes. Below there is given more detailed information about the RMSE components and used methods of minimization.

7.1. RMSE budget of WESTPAC precise satellite

The total RMSE of WESTPAC satellite is defined by (see formula 8, section 4.4) the following main sources.

7.1.1. Non-oriented rotation character of the passive WESTPAC satellite relatively to ground SLR station makes position of each single RR within its field of view indefinite. Therefore, the plane position of equivalent reflection relatively to the satellite center of mass is defined by some probability weight function which has systematic error and RMSE **-** σ. The mathematical equations and values defining the satellite optical RMSE are given in the section 4.4 and Tables 5 and 6. This is the biggest from the expected errors $\sigma \leq 0.488$ mm.

7.1.2. The following component of satellite ranging accuracy reduction are mechanical errors of the fabrication and assembling of the satellite optical-mechanical construction.

The RMSE caused by this, appear due to the geometrical size deviation of mechanical and optical components and parts of WESTPAC satellite from the accepted rated values.

The RMSE of basic sphere fabrication of the satellite heavy brass body σ_{sp} and RMSE of housings depths in the body for the RR holders installation σ_{hous} are related to these errors.

$$\sigma_{sp} \leq 0.017 \text{ mm}$$

$$\sigma_{hous} \leq 0.017 \text{ mm}$$

The RR holders fabrication and assembling errors lead to the RMSE appearance of the input prism sides installation relatively to their mating areas in the body housings. This error was minimized as the result of the use of alignment washers (pads).

$$\sigma_{hol} \leq 0.013 \text{ mm}$$

The RR prism fabrication technological process also gives the prism sizes deviations from the rated values. Due to the prism heights dispersion h, the RMSE σ_h appears that defines the RMSE of the light beam pattern length in the RR with the refraction factor n

$$\sigma_h * n.$$

The RR average prism height was clarified and checked during WESTPAC satellite assembling. Its value appears to be h=18.93 mm, that differs from earlier used size h=19.1 mm , relatively to which the prism dispersion was non-symmetrical (from +0 to –0.34 mm). Therefore, the additional systematic error relatively to the corrected heights h=18.93 mm was introduced into the calculations. At this, the RMSE value σ_h became symmetrical and reduced to the

$\sigma_h \leq 0.057$ mm.

Therefore, the value of RMSE directly summing in the total budget came to (σ_h* n) ≤ 0.083 mm, due to the RR prism height dispersion.

7.1.3. The misbalance caused by slight weight component differences of the Separation System (SS) remaining in WESTPAC satellite body after its separation, leads to the appearance of one more RMSE of the center of mass displacement relatively to its geometrical position in the sphere center σ_{sep}.

The value of the weight misbalance was minimized by the installation (from the opposite to the SS side) the weight compensator-analog of SS components remaining in the satellite body after its separation from the main satellite. The residual value of misbalance σ_{sep} is guaranteed by the ground adjustment SS testing

$$\sigma_{sep} \leq 0.1 \text{ mm.}$$

Finally the maximal total RMSE of WESTPAC satellite σ_{tot} taking into account the budget of comprising errors given above comes according to the equation (8) to the value

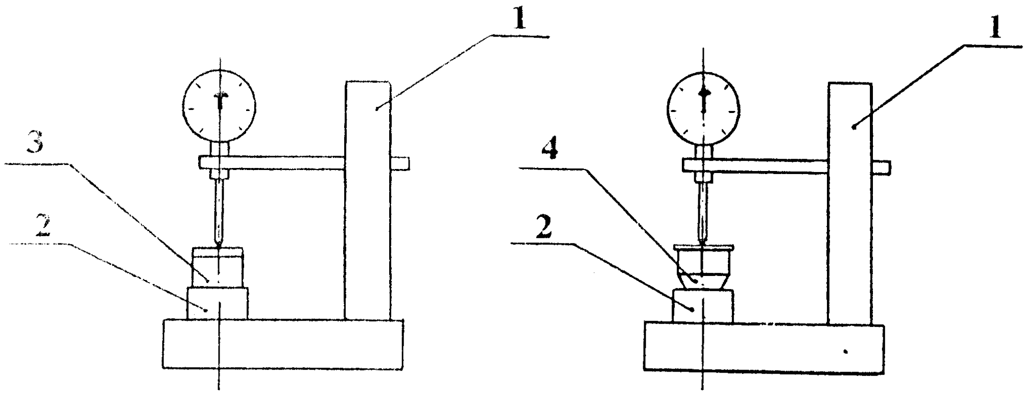
$$\sigma_{tot} \leq 0.506 \text{ mm,}$$

hat exceeds the required for 1.2 %. This slight exceeding, as it was noted before, will be observed at the ranging at the wavelength 0.532 mm in the case of classical mechanism of velocity aberration compensation and only at the near-zenith satellite passes on the zenith distances from 40 to 70 arc. degrees. The part of measured ranges with this error will be rather small in comparison with the total number of measurements at the WESTPAC satellite residual passes.

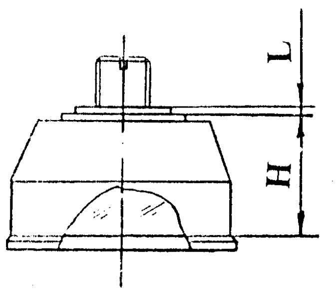
7.2. The RR input side position checkout relatively to the mating area of WESTPAC satellite body

The checkout and final RR input side position adjustment relatively to the body mating areas was conducted for error minimization of RR holders assembling (see protocol N 1003-6). At first, before the holder assemblies installation with RRs, the linear measurements of each RR assembly component were performed.
The checkout and adjustment of the plane position of RR input side were conducted with the help of special device which is indicator rack (scale interval of round pointer indicator – 0.01 mm) with the frame fixed on it for the RR holder mating area.

Prior to the control measurements for the provision of the precise registration of indicator pointer movement, the preliminary technological operation was performed. The set of standard plane plates corresponding to the average preliminary measured distances from RR input side to its mating area in the body housing is installed on the frame of the indicator rack.



1 – Indicator stand with indicator
2 – Frame
3 – Set of precision measures
4 – Frame with CCR (cube corner retroreflector)



Cube corner retroreflector

Figure 7.2. Diagram of the check and adjustment of RR input side position relative to mating plane

Then the set of standard plates was replaced with the holder with the RR, after that the real value of distance from the RR input side to the holder mating area was measured and the thickness of the required set of alignment washers L_{re} for the adjustment to the nominal distance – 22mm was calculated.

The real set of pads L (closest to the required thickness) was selected from the set of alignment washers with the thickness 1.0, 0.5, 0.2, 0.1 and 0.05 mm. The value of the residual dispersion $\Delta = L - L_{re}$ was recorded.

Further RR holders with this selected set of alignment washers L were installed into the housings of the satellite, then they were finally fixed and locked.

The residual RMSE ≤ 0.013 mm of RR input sides installation relatively to the mating areas in the satellite body housings was calculated using the deviation values Δ for all 60 RR.

8. WESTPAC satellite main parameters

Orbit height	835 km.
Orbit inclination	98.68 arc degrees
Orbit period	101.5 min
Angular velocity of rotation around own center of mass	1…2 rad/s.
Total flight mass	23.757 kg.
Overall diameter	245±0.2 mm.

WESTPAC satellite optical parameters

Table 7.

Parameter	Value
The number of RRs	60
Diameter of a sphere circumscribed through RR input apertures centers	182 mm
Equivalent diameter of input aperture of RR prism	28.2 mm
RR height	18.93 mm
Refraction factor (fused silica) at: λ=0.532 µm λ= 1.54 µm	 1.4607 1.4438
Transmission factor taking into account aluminum coating at: λ=0.532 µm λ= 1.54 µm	 0.57 0.78
Lens shading diameter	20.5 mm
Lens shading height	31.5 mm
RR with lens shading field of view	26 arc degrees
The ration of the total solid angle of the field of view of 60 RRs installed on the satellite to 4π steradian.	76.9%

WESTPAC satellite accuracy parameters

The total average error σ_{tot}, systematic error Δc – mm at the ranging at the wavelength 0.532μm.

Table 8.

Zenith distance, arc degrees	Compensation of velocity aberration				Classical velocity aberration			
	Zenith pass		Parameter pass		Zenith pass		Parameter pass	
	σ_{tot}	Δc	σ_{tot}	Δc	σ_{tot}	Δc	σ_{tot}	Δc
0	0.449	62.824	0.449	62.824	0.478	62.178	0.478	62.178
10	0.448	62.826	0.449	62.824	0.479	62.187	0.478	62.178
20	0.445	62.833	0.449	62.824	0.486	62.227	0.478	62.178
30	0.442	62.841	0.449	62.824	0.491	62.279	0.478	62.178
40	0.439	62.852	0.449	62.824	0.501	62.363	0.478	62.178
50	0.434	62.863	0.449	62.824	0.506	62.459	0.478	62.178
60	0.430	62.872	0.449	62.824	0.504	62.562	0.478	62.178
70	0.426	62.882	0.449	62.824	0.494	62.653	0.478	62.178

The total average error σ_{tot}, systematic error Δc – mm at the ranging at the wavelength 1.54μm.

Table 9.

Zenith Distance, Arc degrees	Compensation of velocity aberration				Classical velocity aberration			
	Zenith pass		Parameter pass		Zenith pass		Parameter pass	
	σ_{tot}	Δc	σ_{tot}	Δc	σ_{tot}	Δc	σ_{tot}	Δc
0	0.4181	63.217	0.4181	63.217	0.450	63.136	0.450	63.136
10	0.4180	63.217	0.4181	63.217	0.449	63.138	0.450	63.136
20	0.4176	63.218	0.4181	63.217	0.446	63.147	0.450	63.136
30	0.4172	63.219	0.4181	63.217	0.443	63.155	0.450	63.136
40	0.4154	63.221	0.4181	63.217	0.438	63.167	0.450	63.136
50	0.4158	63.222	0.4181	63.217	0.434	63.180	0.450	63.136
60	0.4153	63.223	0.4181	63.217	0.429	63.191	0.450	63.136
70	0.4147	63.225	0.4181	63.217	0.425	63.201	0.450	63.136

WESTPAC satellite energy parameters

The average probable signal level n_{s*}, maximal signal level n_{sMAX} in photoelectrons for ranging at wavelength 0.532 μm

Table 10.

Zenith distance, arc degrees	Compensation of velocity aberration				Classical velocity aberration			
	Zenith pass		Parameter pass		Zenith pass		Parameter pass	
	n_{S*}	$n_{S\,max}$	n_{S*}	$n_{S\,max}$	n_{S*}	$n_{S\,max}$	n_{S*}	$n_{S\,max}$
0	13.3	64.8	13.3	64.8	0.91	4.0	0.91	4.0
10	12.7	62.2	12.5	60.7	0.87	3.9	0.85	3.7
20	10.9	54.5	10.2	49.7	0.85	3.5	0.7	3.1
30	8.1	42.8	7.2	35.2	0.7	2.9	0.49	2.2
40	5.2	29.2	4.3	20.9	0.6	2.2	0.29	1.3
50	2.7	16.1	2.1	10.0	0.4	1.4	0.14	0.6
60	1.0	6.5	0.7	3.5	0.2	0.7	0.05	0.2
70	0.22	1.46	0.15	0.7	0.06	1.21	0.01	0.04

The average probable signal level n_{s*}, maximal signal level n_{smax} in photoelectrons for ranging at wavelength 1.54 μm

Table 11.

Zenith distance, arc degrees	Compensation of velocity aberration				Classical velocity aberration			
	Zenith pass		Parameter pass		Zenith pass		Parameter pass	
	n_{S*}	$n_{S\,max}$	n_{S*}	$n_{S\,max}$	n_{S*}	$n_{S\,max}$	n_{S*}	$n_{S\,max}$
0	63.3	457.2	63.3	457.2	36.2	166.7	36.2	166.7
10	59.8	432.3	59.5	430.8	34.7	161.4	34.1	157.1
20	50.4	365.6	49.8	359.9	30.5	145.6	28.6	131.2
30	37.2	271.7	36.5	263.7	23.5	120.6	20.9	96.1
40	23.7	174.7	23.0	166.4	16.2	88.2	13.2	60.7
50	12.6	93.8	12.1	87.6	9.2	54.4	6.9	32.0
60	5.3	39.7	5.0	36.4	4.1	26.1	2.9	13.3
70	1.6	11.8	1.5	10.6	1.3	8.6	0.8	3.9

SLR stations parameter used for WESTPAC satellite energy calculation.

Table 12.

SLR parameters	**Sign**	**Value**	
Working wavelength, μm	λ	0.532	1.54
Transmitter energy, J	E_{tr}	0.05	0.05
Transmission coefficient of optical transmitting antenna	K1	0.25	0.25
Transmission coefficient of optical receiving antenna	K2	0.12	0.12
Diameter of receiving aperture, m	D	0.5	0.5
Transmission beam width at level 0.5 arc minute	$2\varphi_{0.5}$	1	1
Atmosphere transmission coefficient in zenith	T	0.7	0.85
Quantum efficiency of photo receiver	η	12%	50%
Photon energy at working wavelength, $J*10^{-19}$	$h\nu$	3.74	1.29

9. Conclusion.

As always, during design of engineering objects, in our case the final result is a compromise of many factors. During development of WESTPAC satellite, together with achievement of record accuracy of link of measurements to the center of mass - 0.5 mm, very important place was given to factor of reliability of reflectors operation. 60 fused silica prism reflectors with equivalent light aperture of 28.2 mm and with mirror coating of reflecting facets, having higher steadiness to one-side heating by Sun radiation were used. Their design was tested in a few dozens of space flights.

In our opinion, satellite's design is good for testing of Fizeau effect influence on light reflection from prism RR from viewpoint of exclusion of distortions of results of space experiment by thermodynamics aberrations of RP. Prisms are located deeply in holes of massive body fabricated from material with good thermal conductivity what shall well protect them from internal temperature gradients. Prisms are protected by deep lens shadings from external sources of heat radiation.

We performed evaluation of energy efficiency and accuracy characteristics of the satellite at wavelength 1.54 μm because diffraction reflection pattern of installed RRs at wavelength 1.54 μm is optimal for classical approach to velocity aberration mechanism. As it is seen from table 4, at this wavelength there will be high reflected signal both in presence of Fizeau effect and in its absence. This increases reliability of expensive space experiment for laser ranging of satellite with RMS error 0.5 mm in case if influence of Fizeau effect will not be confirmed.