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DETERMINATION OF THE MINIMAL REFLECTING SURFACE POINTS NUMBER REQUIRED FOR ASSESSMENT OF LARGE-SIZE TRANSFORMABLE ANTENNA PATTERN DEVIATION

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Construction of communication spacecraft with large-size transformable antennas developed tendencies to increase the operational band frequencies, to reduce specific mass and to increase the overall dimensions of the structures. The improvement of technical performance of communication spacecraft with large-size antennas cannot be achieved without ensuring the required accuracy of antenna pattern and of the antenna gain coefficient at its maximum.

Factors affecting the final quality of large-size structures for space application (of antennas in particular), keep influencing the products through all their service life – from design and production to tests and actual operation. The "direct" elimination of the negative factors affecting the final output is often unprofitable considering the present development of technological support in hi-tech industries. In this respect, control of the ultimate operational characteristics of large-size spacecraft antennas in conditions of real performance, and compensation, if necessary, of deviations from the required values, is optimal with respect to the output/cost ratio. This approach is practical in determining the onboard antenna pattern and compensating its operational distortions in the process of specified spacecraft performance.

There are two methods of measuring the antenna pattern at the orbit. The first method is based on measurements of radio engineering characteristics obtained from ground space vehicles' service stations. This method is sufficiently accurate, but it has several drawbacks. For example, this method increases the number of requirements to ground stations – their number, location and characteristics of the equipment in use. The second method bases on obtaining radio engineering characteristics from the configuration and orientation of antenna reflector. The reflector is imaged as a cloud of checkpoints reflecting the deviations of the construction's configuration and orientation from the specified values.

To obtain the antenna pattern measurements using the second method, an antenna configuration control system (ACCS) must be worked out for measuring the coordinates of the reflector surface points. To perform its specific function, the system should have the following configuration: measuring equipment mounted on the spacecraft casing, and control elements fixed on the construction components. This configuration allows to present the antenna construction components in the form of checkpoint cloud.

In the process of the system development the constructional analysis of the possibility of using the antenna configuration measurements for the its pattern calculation and for further assessment of its deviation from the specified values was made. This article presents the assessment of the required number of monitored checkpoints on the reflector surface. For this purpose, Ku-band of frequencies was chosen as one of the most common frequency bands used by telecommunication spacecraft. Several sets of points were considered, among them the sets belonging both to the deformed reflector profile and to the one without deformation. For each set the antenna pattern calculation was made. Visual representations of the focal beam and the directive antenna gain were compared. The analysis of the obtained data allowed to determine the necessary minimum of checkpoints for antenna pattern calculation with the required accuracy. The obtained data were taken into account in formulating the requirements for the system of orbital control of antenna configuration.

Keywords: large-size transformable antenna, deployable reflector, antenna pattern, orbital adjustment, antenna configuration control system.

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ПОИСК МИНИМАЛЬНОГО КОЛИЧЕСТВА ТОЧЕК ОТРАЖАЮЩЕЙ ПОВЕРХНОСТИ РЕФЛЕКТОРА, НЕОБХОДИМОГО ДЛЯ ОЦЕНКИ ОТКЛОНЕНИЯ ДИАГРАММЫ НАПРАВЛЕННОСТИ КРУПНОГАБАРИТНЫХ ТРАНСФОРМИРУЕМЫХ АНТЕНН

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В создании связных космических аппаратов с крупногабаритными трансформируемыми антеннами имеются тенденции к увеличению частот рабочего диапазона, снижению удельной массы и возрастанию общих габаритов конструкций. Улучшение технических характеристик связных космических аппаратов с крупногабаритными антеннами невозможно без обеспечения требуемой точности наведения диаграммы направленности, коэффициента усиления в её максимуме.

Факторы, влияющие на конечное качество крупногабаритных конструкций космического назначения, и антенн в частности, присутствуют на всем жизненном цикле данной продукции: от проектирования и изготовления до испытаний и эксплуатации в натурных условиях. При этом прямое устранение причин, негативно влияющих на конечный результат, зачастую является экономически невыгодным при нынешнем развитии технологического обеспечения данных наукоемких производств. В связи с этим контроль конечных эксплуатационных характеристик крупногабаритных антенн космических аппаратов в натурных условиях и, в случае необходимости, парирование их отступлений от требуемых значений являются наиболее оптимальными с точки зрения отношения результат/затраты. Данный подход реализуется при определении диаграммы направленности бортовой антенны и компенсации её искажения в процессе эксплуатации космического аппарата по целевому назначению.

Существуют два способа измерения диаграммы направленности на орбите. Первый способ основан на измерениях радиотехнических характеристик, производимых по наземным станциям обслуживания космических аппаратов. Данный способ, несмотря на приемлемую точность, имеет ряд недостатков. Например, использование данной методики увеличивает количество требований к наземным станциям – их количеству, размещению и характеристикам применяемой аппаратуры. Второй способ основан на определении радиотехнических характеристик, исходя из формы и положения рефлектора антенны. Рефлектор представляют в виде облака измеренных точек, которые отражают отклонения формы и положения конструкции от проектных значений.

Для реализации измерений диаграммы направленности по второму способу необходимо разработать систему контроля геометрии антенны, предназначенную для измерения координат точек поверхности рефлектора. Для выполнения целевых задач системы имеет место следующая схема: измерительная аппаратура, размещенная на корпусе космического аппарата, и контрольные элементы, размещенные на элементах конструкции. Такая конфигурация системы позволяет представлять элементы конструкции антенны в виде облака контрольных точек.

В рамках работ по разработке этой системы проведен проектный анализ возможности применения измерений геометрии антенны для расчета диаграммы направленности и дальнейшей оценки её отклонения от проектных значений. Проведена оценка необходимого количества измеряемых контрольных точек поверхности рефлектора. Для этих целей был выбран Ku-диапазон частот как один из наиболее популярных диапазонов частот, используемых в телекоммуникационных космических аппаратах. Были рассмотрены несколько вариантов наборов точек. Среди них были наборы точек, принадлежащих как недеформированному, так и деформированному профилю рефлектора. По каждому набору был произведен расчет диаграммы направленности антенны. Проведено сравнение визуальных представлений фокального луча и коэффициента направленного действия. В ходе анализа полученных данных было определено минимально необходимое количество контрольных точек для расчета диаграммы направленности с требуемой точностью. Полученные данные были учтены при формировании требований к системе орбитального контроля геометрии антенны.

Ключевые слова: крупногабаритные трансформируемые антенны, развертываемый рефлектор, диаграмма направленности, орбитальная юстировка, система контроля геометрии антенны.

Introduction. Today one of the priority trends in the world satellite construction is producing communication spacecraft (SC) with large-size transformable antennas (LTA) [1; 2]. LTA is a complex technical system on the deployment and on the required configuration of which depend both the quality of the signal provided for subscribers in the required coverage zone, and general accuracy of SC specified performance.

The quality of the signal is determined by the orientation accuracy of antenna pattern (AP) of LTA [3] for the target coverage zone, and by the level of LTA gain in this zone. The necessary radio engineering characteristics (REC) of LTA are determined by its practically applied construction configuration designed with the required accuracy. One of the LTA configuration characteristics that influence its REC is the accuracy of the feed and reflector interposition, greatly dependent on the reflector load-carrying structure – the rod. The next important LTA component (from the point of view of the AP formation) is the reflector [4–6]. The reflector is a rigid framework consisting of a base and spring-type spokes, a form-building structure fastened to the framework, and a net sheet sewn to the form-building structure (fig. 1). To maintain the quality of the signal the form of the net sheet surface of the reflector must be close to the paraboloid of revolution.

Because of the large size of LTA for its rather small weight, the structure rigidity is not sufficient. As a result, during the operation at the orbit the structure is subject to temperature and elastic deformations [7; 8] which, in turn, cause deterioration of the antenna REC and make the signal in the coverage zone weaker.

It is possible to compensate REC deterioration, also with the help of the stated current AP [9].

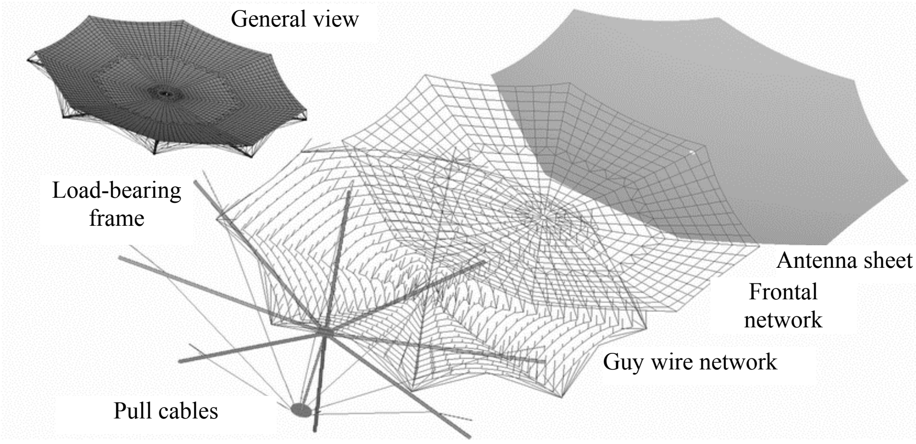

Fig. 1. Reflector design

Рис. 1. Конструкция рефлектора

So the following task can be formulated: to measure the AP and determine the deviations of its axis from the specified values. To assess these AP deviations of SC working at the orbit, two different methods can be used.

The first method is based on the REC measurements made by ground SC service stations. This method is sufficiently accurate, but it has some drawbacks. For example, it can’t be applied when the spacecraft is being used for its specified purpose. The requirements for ground stations – their number, location and equipment – also increase when this method is applied.

The second method is based on deriving REC measurements from the configuration and orientation of the antenna reflector. The reflector is imaged as a cloud of monitored checkpoints able to reflect the deviations of the construction’s configuration and orientation from the specified values.

To obtain AP measurements using the second method, an antenna configuration control system (ACCS) must be worked out [10–13] for measuring the coordinates of the reflector surface points. The system should have the following components: measuring equipment mounted on the spacecraft casing, and control elements (light reflectors), on the construction elements. This configuration allows to present the LTA construction in the form of a checkpoint cloud.

The initial data required for AP calculation are:

– coordinates of the radio-reflecting surface points or general orientation of the given surface (when radio-reflecting surface deformations are negligible);

– feed directional pattern;

– operation frequency.

Thus ACCS measurements complementing AFS characteristics specified at the stage of its design and production form the initial data sufficient for AP setting.

There is also a problem of the required number of checkpoints. To control the configuration of “rigid” reflectors (reflectors having negligible radio-reflecting surface deformations), it is enough to monitor several checkpoints, the number and location of which is chosen to meet the precision requirements when determining the orientation of such reflectors. However, to control the configuration of elastic large-size reflectors functioning as parts of antennas with UHF operation frequencies, it is necessary to assess the reflecting surface deformations, since the deformation data contribute a lot to REC of the antenna. In these cases the required number of monitored checkpoints can reach several thousand. Besides the factors mentioned, the number of checkpoints determined by ACCS depends on:

– weight and dimensions of control elements;

– structural features of the antenna;

– characteristics of calculation algorithms and on-board computer;

– characteristics of measuring instruments.

This paper shows how the number of checkpoints may influence the precision of REC determination for an antenna with a large-size deformed reflector. A calculation was made to find the AP representing the LTA focal beam electrical axis orientation for different numbers of checkpoints. AP calculations were made both for the theoretically determined reflector profile (without deformation) and for the deformed reflector profile. The lower KU-band frequency was taken for the antenna operational frequency.

Initial data for evaluating the electrical characteristics of antennas. To find the necessary number of points of the reflector surface sufficient for calculating the antenna electrical characteristics with proper accuracy, AP and orientation of the focal beam electrical axis were calculated for the antenna reflector with a 12-meter aperture. The calculations were made for different sets of points: 1488, 1250, 1000, 750, 500, 250, 25.

In the documentation for software sets used to calculate AP, it is advisable to choose the number and orientation of control surfaces that make the distance between two neighboring points not more than $\lambda/(5–6)$ mm, where λ is wave length.

However, it must be taken into account that the reflector surface is a set of flat trapezoidal facets formed by the frontal network checkpoints. It means that the location of points inside the facets can be determined by the points forming each facet. Thus, the influence of points within each facet on the AP can be expressed through the 4 nodal points of the frontal network.

Consequently, the basic data on reflector surface deformations can be derived from coordinates of the frontal network nodal points, and to obtain a reliable AP it is enough to use for calculation the data on points, the distance between which (for the current implementation of the frontal network) does not meet the above-mentioned requirement.

So, for the checkpoints, at their maximum number, the frontal network points with coordinates derived from the reflector finite-element model (FEM) can be taken, in case the model is framed according to the method described in [14].

The deformations were obtained in modelling how the reflector KEM is affected by a model device of reflector configuration finishing adjustment (RCFA). RCFA is a device that allows to adjust the position of the spoke in the plane of the reflector symmetry axis. The main controls are the tie-rod devices which tighten the cords attached to the spokes.

A more detailed description of RCFA model and implementation logic is presented in [15].

The cartogram of distribution of the frontal network checkpoints deviations from the theoretical profile made for the reflector initial design is shown in fig. 2. Deviations are calculated as the shortest distance from frontal network checkpoints to theoretical profile. The SCD of the frontal network checkpoints from the reflector theoretical profile is 0.2 mm.

The deformed configuration was framed artificially by changing the RCFA tie-rods position in FEM. Tie-rod movements are presented in tab. 1.

The cartogram of distribution of the frontal network checkpoints deviations from the theoretical profile for the reflector with deformations is presented in fig. 3. The SCD of the frontal network checkpoints from the reflector theoretical profile is 18.1 mm.

The theoretical paraboloid coordinate system (TPCS) is a coordinate system associated with the SC casing, in which the theoretical location of the reflecting surface points (theoretical profile) of the reflector is described by the canonical equation of paraboloid of revolution.

The reflector coordinate system (RCS) is the coordinate system determined in [9].

The coordinates of different numbers of reflecting surface points were formed by performing the following sequence of actions:

1. The coordinates of a large number (1001000) of the reflecting surface points were formed. The coordinates y and z of these points were calculated from the following parametric equations:

$$\begin{aligned} y &= 3\upsilon\cos(\nu) + 8.3, \\ z &= 3\upsilon\sin(\nu), \end{aligned} \qquad (1)$$

where υ – parameter changing from 0.002 to 2 with step of 0.002; ν – parameter changing from 0 to 2π with step of 0.002.

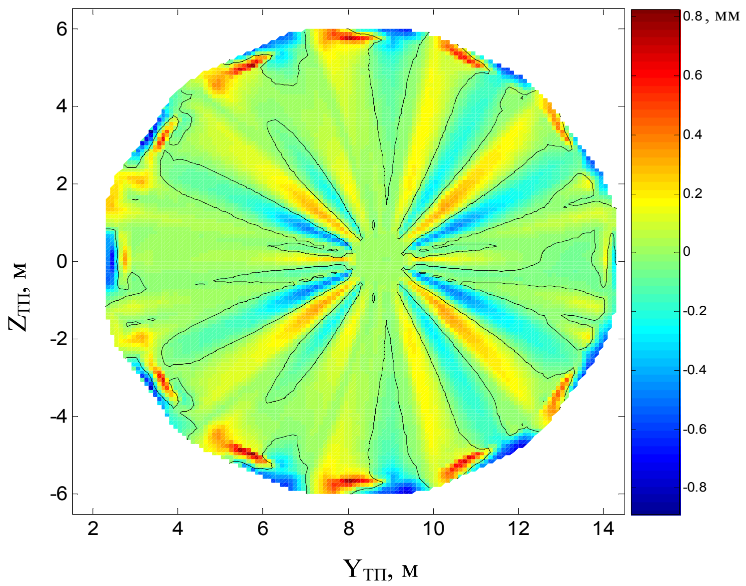

Fig. 2. Distribution of deviations from TP in the initial design

Рис. 2. Распределение отклонений от ТП в проектном состоянии

Table 1

Rod movements, mm

Rod 7	Rod 8	Rod 9	Rod 10	Rod 11	Rod 12	Rod 1	Rod 2	Rod 3	Rod 4	Rod 5	Rod 6
20	0	20	0	20	0	20	0	20	0	20	0

Note: “+” – is the movement in direction of the reflector folding.

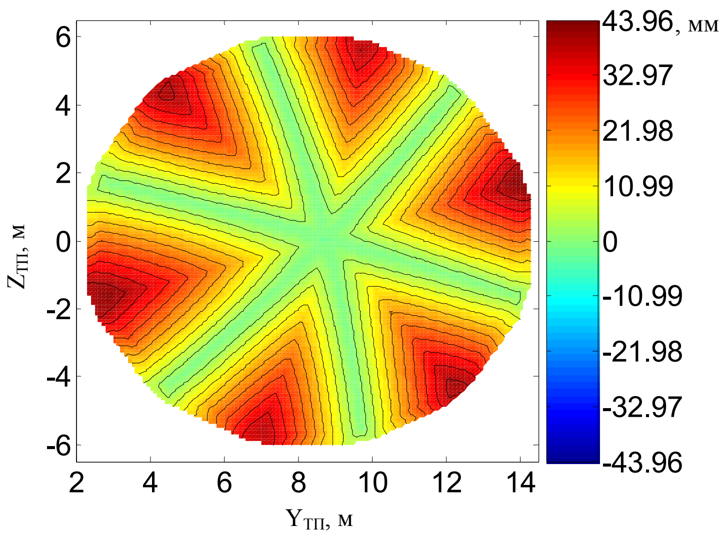

Fig. 3. Distribution of deviations from TP in the deformed state

Рис. 3. Распределение отклонений от ТП в деформированном состоянии

The *x* coordinates of the deformed and undeformed profile were calculated by interpolating the frontal network checkpoints (1488) of the deformed reflector at the points with *y* and *z* coordinates, calculated from the expression (1).

2. The coordinates of the reflecting surface points formed in 1 were recalculated in RCS:

$$\begin{vmatrix} X_{\text{Р}} \\ Y_{\text{Р}} \\ Z_{\text{Р}} \end{vmatrix} = M_{\text{ТП\_Р}} \cdot \left(\begin{vmatrix} X_{\text{ТП}} \\ Y_{\text{ТП}} \\ Z_{\text{ТП}} \end{vmatrix} - \begin{vmatrix} X_{\text{Р\_ТП}} \\ Y_{\text{Р\_ТП}} \\ Z_{\text{Р\_ТП}} \end{vmatrix} \right), \quad (2)$$

where $M_{\text{ТП\_Р}} = \begin{vmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{vmatrix}$ – transition matrix from TPCS to RCS; θ – rotation angle of RCS about the axis of OZ TPCS equal to 26.5651 degr; $X_{\text{ТП}}$, $Y_{\text{ТП}}$, $Z_{\text{ТП}}$ – coordinates of the point in TPCS; $X_{\text{Р}}$, $Y_{\text{Р}}$, $Z_{\text{Р}}$ – coordinates of the point in RCS; $X_{\text{Р\_ТП}}$, $Y_{\text{Р\_ТП}}$, $Z_{\text{Р\_ТП}}$ – coordinates of RCS center location in TPCS equal to [2296.35 mm, 8731.49, mm 0].

3. Coordinates of the required number of reflecting surface points were formed. For the purpose a formation of a network of points uniformly distributed in the *YOZ* RCS plane was carried out: *y* coordinate of the network points changed from –7 to 7 m; *z* coordinate of the network points changed from –6 до 6 m; interpoint step relative to both coordinates made *h* (tab. 2).

The coordinates *x* of the points of the reflector's deformed and undeformed profiles were determined by interpolation of the points obtained in 2, at the points of the pre-formed network. In the process of interpolation, the network points located outside the radio-reflecting surface were discarded. A network of 250 points of radio-reflecting surface in the *YOZ* plane of RCS after interpolation is shown in fig. 4.

4. The coordinates of the required number of reflecting surface points formed in 3 were recalculated in TPCS

$$\begin{vmatrix} X_{\text{ТП}} \\ Y_{\text{ТП}} \\ Z_{\text{ТП}} \end{vmatrix} = M_{\text{Р\_ТП}} \cdot \begin{vmatrix} X_{\text{Р}} \\ Y_{\text{Р}} \\ Z_{\text{Р}} \end{vmatrix} + \begin{vmatrix} X_{\text{Р\_ТП}} \\ Y_{\text{Р\_ТП}} \\ Z_{\text{Р\_ТП}} \end{vmatrix}, \quad (3)$$

where $M_{\text{Р\_ТП}} = \begin{vmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{vmatrix}$ – transition matrix from RCS to TPCS; θ – rotation angle of RCS about the axis of *OZ* TPCS; $X_{\text{ТП}}$, $Y_{\text{ТП}}$, $Z_{\text{ТП}}$ – coordinates of the point in TPCS; $X_{\text{Р}}$, $Y_{\text{Р}}$, $Z_{\text{Р}}$ – coordinates of the point in RCS; $X_{\text{Р\_ТП}}$, $Y_{\text{Р\_ТП}}$, $Z_{\text{Р\_ТП}}$ – coordinates of RCS center location in TPCS.

A network of 250 points of radio-reflecting surface in *YOZ* plane of TPCS is shown in fig. 5. Dashed lines in fig. 5 show the circle that is the generator of a cylinder, the intersection of which with the paraboloid of revolution forms the radio-reflecting surface.

Antenna REC calculation. That was made for the following numbers of reflector surface points: 1488, 1250, 1000, 750, 500, 250 and 25.

Fig. 6 shows the focal beam pattern at the lower operational band frequency for the antenna reflector theoretical profile at different profile points number.

Fig. 7 shows the focal beam pattern at the lower operational band frequency for the deformed reflector profile of antennas with different profile points number.

Fig. 8 shows the focal beam pattern for the undeformed profile (left) and for the deformed profile (right) at 25 points.

Tab. 3 presents calculations of antenna focal beam DG at the upper KU-band frequency for the deformed reflector profile and for that without deformation.

Analysis of calculation results. Fig. 6 and 8 of the focal beam pattern indicate that with the lower number of reflector's monitored points, the beam pattern is distorted; the effect is present even at 500 checkpoints, and the beam pattern gets completely distorted at 25 checkpoints.

Table 2

Network step *h*, m

Reflecting surface points number	1250	1000	750	500	250
Theoretical profile	0.31775	0.355	0.4098	0.499986	0.7052
Deformed profile	0.317	0.3552	0.40954	0.5	0.7055

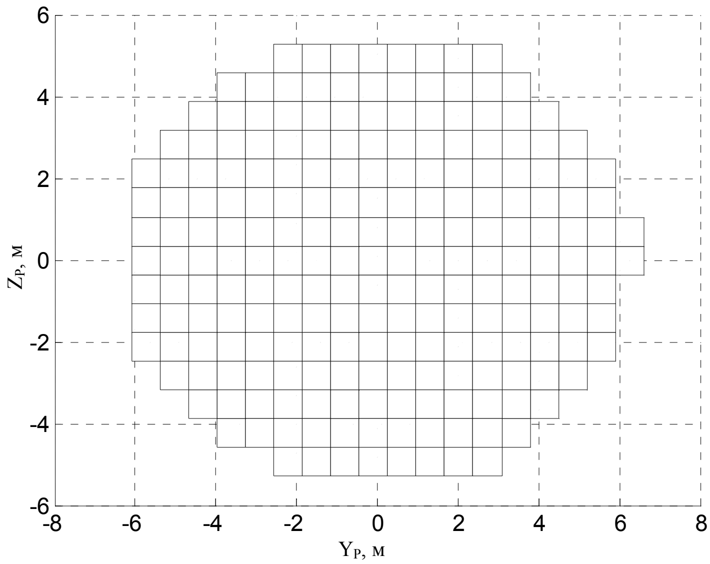

Fig. 4. Network of 250 points in the *YOZ* plane of RCS after interpolation

Рис. 4. Сетка из 250 точек в плоскости *YOZ* СКР после интерполяции

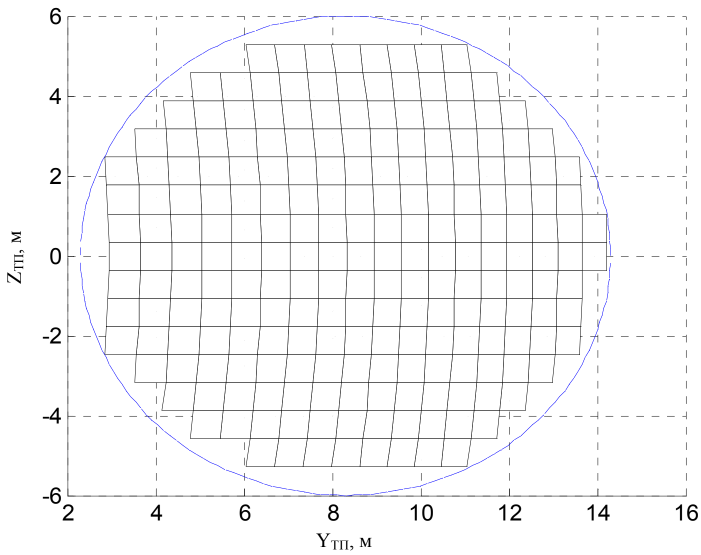

Fig. 5. Network of 250 points in the *YOZ* plane of TPCS

Рис. 5. Сетка из 250 точек в плоскости *YOZ* СКТП

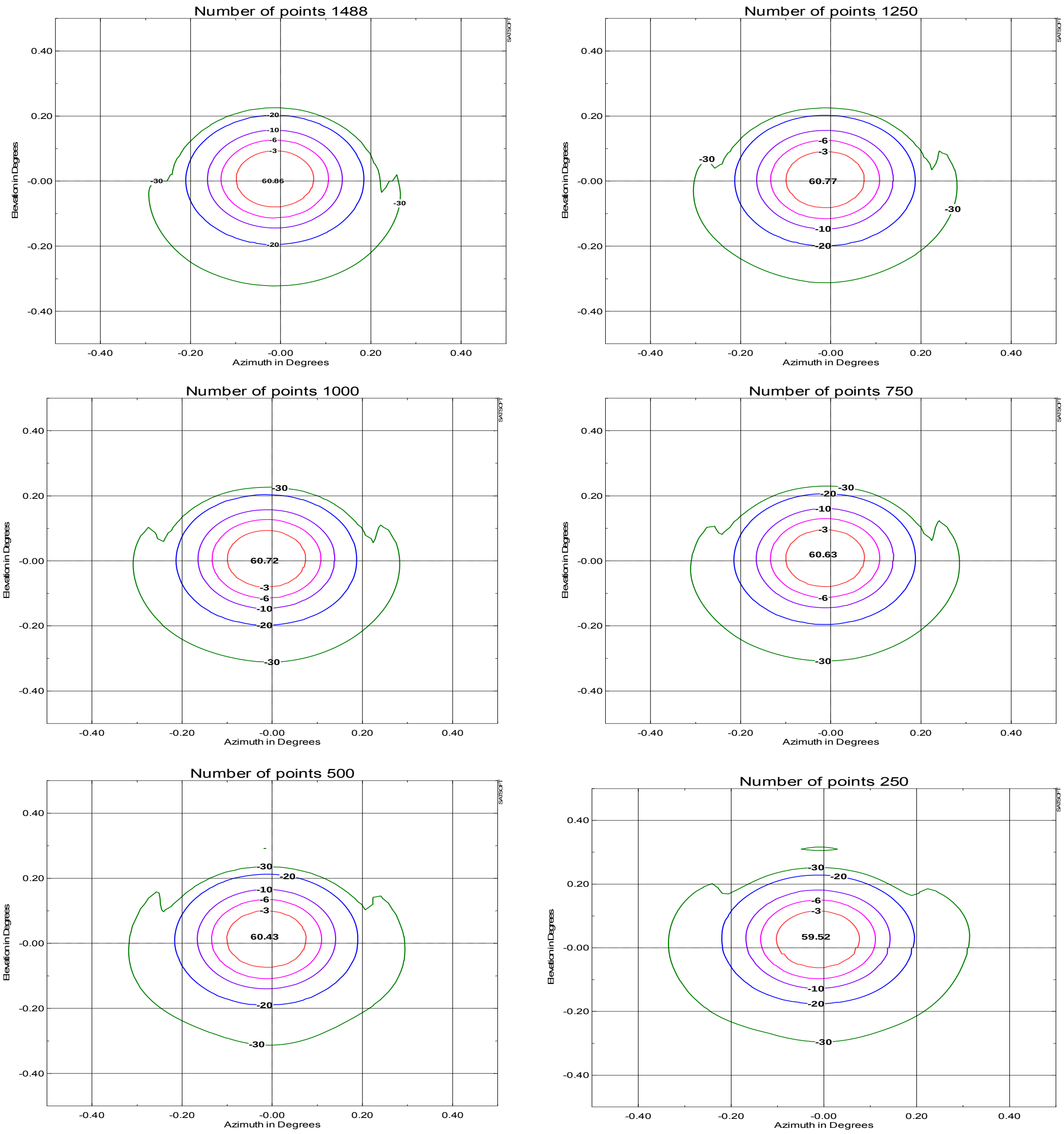

Fig. 6. Focal beam pattern at the lower operational band frequency
with different numbers of the reflector theoretical profile points

Рис. 6. Контур фокального луча на нижней частоте рабочего диапазона
при различном количестве точек теоретического профиля рефлектора

Fig. 7 and 8 showing the focal beam pattern for a deformed reflector indicate that the given reflector deformation causes a deep distortion of the beam. They also confirm that with a decrease in the number of reflector's monitored points the contour of the beam is distorted. For the deformed reflector the beam contour is completely blurred at 25 checkpoints.

The results of directive gain of antenna focal beam calculation presented in tab. 2 confirm the deterioration of focal beam characteristics at the upper operational band frequency with the decrease in the number of reflector's monitored points. The minimum of 250 monitored reflector checkpoints is acceptable; at that the calculated deterioration of the focal beam DG at the upper operational band frequency is 2.21 %. That number of the reflector surface monitored points makes it possible to assess the antenna focal beam electrical characteristics with a permissible error.

Conclusion. The problem of choosing the monitored points number of the reflecting surface considered in this paper is relevant for the problem of design of LTA configuration control system at the orbit. Such system allows to determine the AP when the orientation and form of the LTA components is stated. The proposed approach to determination of the monitored points number, as well as the results of its application for a specific operating antenna are aimed at perspective SC projects and at formulating the technical specification requirements for making SC antenna-feeder systems.

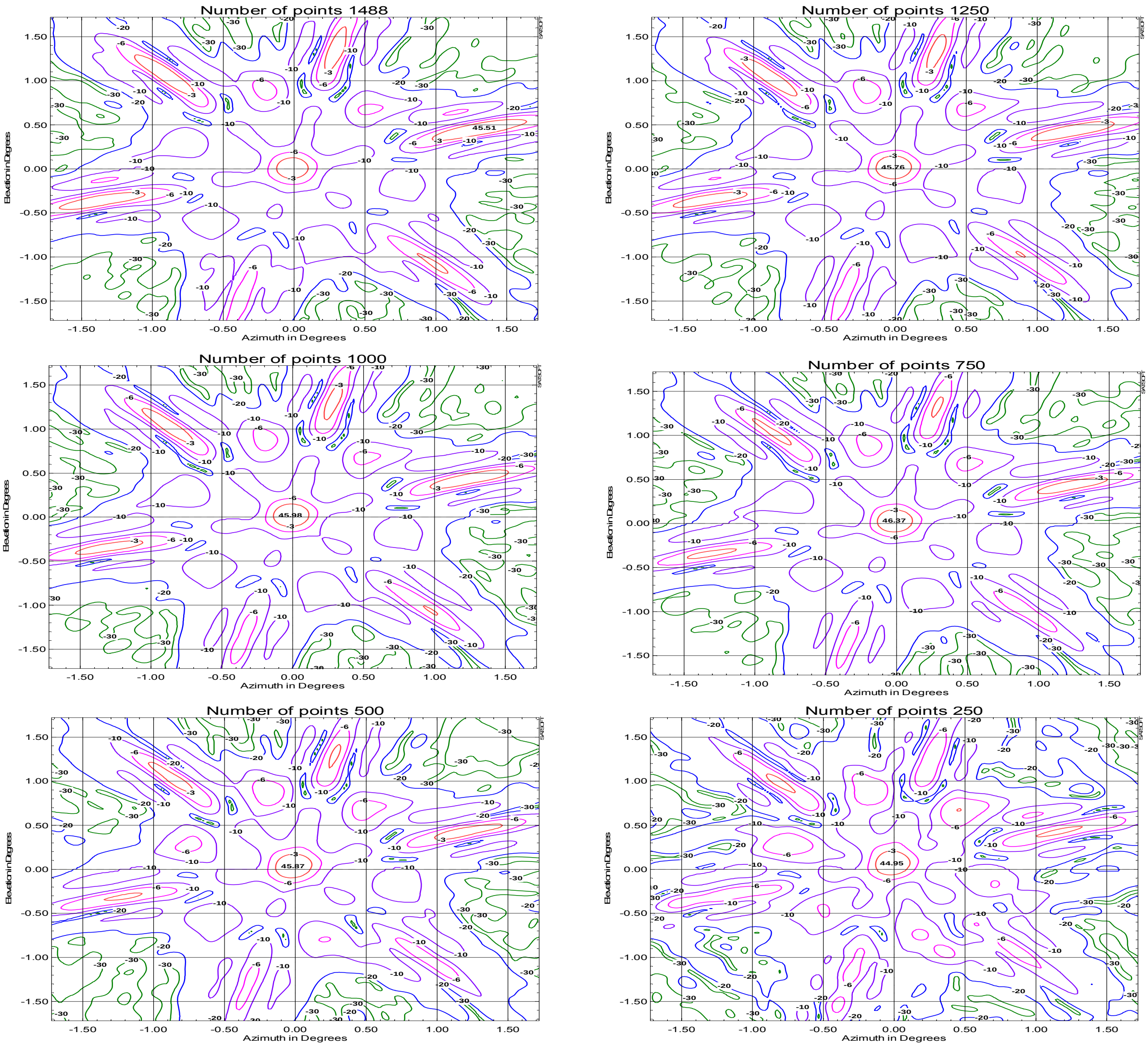

Fig. 7. Focal beam pattern at the lower operational band frequency
with different numbers of the deformed reflector profile points

Рис. 7. Контур фокального луча на нижней частоте рабочего диапазона
при различном количестве точек деформированного профиля рефлектора

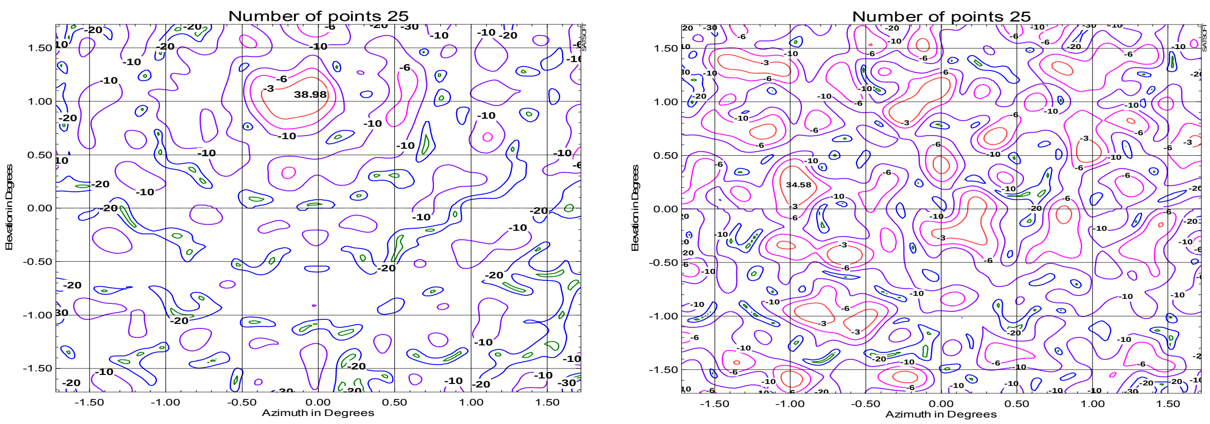

Fig. 8. Focal beam pattern at the lower operational band frequency
with 25 points for both reflector profiles

Рис. 8. Контур фокального луча на нижней частоте рабочего диапазона
при 25 точках для двух профилей рефлектора

Table 3

Directive gain of the antenna focal beam at the upper operational band frequency for different reflector profiles

Number of points	DG, percent	
	Reflector profile without deformation	Deformed reflector profile
1488	100	74.77
1250	99.83	75.15
1000	99.75	75.52
750	99.62	76.17
500	99.26	75.33
250	97.79	73.83
25	64.03	56.80

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