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ISSUES OF RELIABILITY INSMART ANTENNAS

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Adaptive digital antenna arrays, also known as smart antennas, are a perspective direction in the development of ground-based command and measurement antenna stations. Smart antennas can significantly improve the efficiency of controlling data exchange between the satellite and ground-based earth station. This benefits the productivity of the technological operations and reduces the time intervals forperforming the technological control cycle. Depending on the requirements, smart antennas containfrom a hundred to several thousand active modules. In this case, the probability of failure of the active module increases. This article discusses the issues of ensuring reliability ofsmart antennas: their ability to maintainin timethe values of their technical parameters within the established limits, which are determined by failures of the equipment included in the antenna, mainly by module failures.

Keywords: adaptive digital antenna array (smart antenna), command-measuring complex, radiation pattern.

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ПРОБЛЕМЫ НАДЕЖНОСТИ АДАПТИВНОЙ ЦИФРОВОЙ АНТЕННОЙ РЕШЕТКИ

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Разработка антенных комплексов командно-измерительных систем (КИС) наземного комплекса управления, непрерывно следящих за космическими аппаратами (КА), является одним из наиболее актуальных направлений в области спутниковой связи. Наиболее перспективным путем развития КИС является применение адаптивных цифровых антенных решеток (АЦАР). Это позволяет улучшить оперативность управления обменом информацией с КА, а также положительно сказывается на производительности технологических операций, сокращая временной интервал проведения технологического цикла управления. В зависимости от предъявляемых требований, такие антенные системы содержат от сотен до нескольких тысяч активных модулей (АМ). В связи с этим вероятность выхода из строя (отказов) АМ повышается. Рассмотрены вопросы обеспечения надежности функционирования адаптивных цифровых антенных решеток, т. е. их способность сохранять во времени значения своих технических параметров в установленных пределах, которые определяются отказами аппаратуры, входящей в АЦАР, главным образом, отказами модулей.

Ключевые слова: адаптивная цифровая антенная решетка, командно-измерительная система, диаграмма направленности.

Introduction. Adaptive digital antenna arrays, also known as smart antennas, are a perspective direction in the development of ground-based command and measurement antenna stations.

The basic principles of building of antennas, which are an assembly of analog digital channels with the same center of radiation with a radiation patterns, formed in a digital way, and without phase shift modules, were given a grounding in 1960s [1].

With the progress of electronics, antennas have made a great way from quite simple facilities to complex controlled systems with active devices. Interference environment is constantly changing, so that the need in adaptive antennas has arisen. Nowadays radio systems are to be able to function under the influence of several heavy broadband interferences in conditions of independent moving of interference sources. In such cases, an adaptive antenna fulfils spatial processing of signal, i. e. it becomes a dynamic spatial filter. The parallel spatiotemporal signal processing in antenna allows increasing the volume of information received from several satellites simultaneously.

The progress of space technology emphasizes development of methods of forming stacked beam patterns able to monitor several spacecrafts and to form nulls in direction of interference sources for a ground-based command-measuring complex. The analysis of modern research, methodical and regulatory literature reveals the concernment of both state institutions and major space engineering corporation in a substantial upgrade of existing command-measuring complexes characteristics [2]. One of the most prospective ways of development of ground control is using of command-measuring complex equipped with adaptive digital antenna arrays.

Such command-measuring complexes would be able, unlike existing stations, to monitor several spacecrafts simultaneously, that will allow increasing the efficiency of data exchange control and performance of technological operations, reducing control time slot.

The development and introduction of smart antennas to ground control systems allow receiving command and telemetric information from all visible satellites. It improves the operational characteristics by elimination of mechanical engineering assemblies of antenna control, and interference immunity of command-measuring complex due to spatial-temporal processing of signals.

The advantages of digital antenna arrays are [3–5]:

– presenting digital synthesis of a radiation pattern in a receiving mode and forming of specified distribution of electromagnetic field in an antenna array face in transmitting mode;

– the ability of digital antenna arrays to perform multisignal transmit and receive signals in a spatial angle;

– the ability to perceive all the information contained in the structure of spatial-temporal electromagnetic fields in an antenna array face and transform it into data almost without any losses;

– the digital formation of the requested radiation pattern in receivers input provides deep spatial cancellation. When combined with the volume expansion it provides interference immunity unreachable before.

Smart antennas allow implementing of special types of gain-phase distribution in an antenna array face and applying for different methods of processing of signals received by every single antenna radiating element. Therefore, it is possible to gain low side lobes of the radiation pattern, to extract more data out of the received from different satellites radio waves, to use adaptive algorithms of optimal spatial-temporal filtration of signals against a background of interference, that all in all improves characteristics of navigational facilities of a consumer [6].

Modern hardware components allow producing smart antennas with unique specifications along with the trend towards components miniaturization and reducing of their aggregated cost. The nearest future of antenna arrays and especially smart antennas seems to be prospective, while their further development of hardware components will help to solve those problems that suppress mass use of such systems.

Reliability of smart antennas is its ability to keep values of technical parameters in set limits in time. It is defined by failures of facilities of smart antennas, mainly, by failures of modules.

The requirements to reliability of smart antennas are strict. MTBF is to be at least fifty thousand hours, while assured life should be not less than 10 years.

Faultiness of electronic components in the modules determine the appearance of both sudden failures and gradual failures. The first lead to the fact that the emitters of smart antennas connected to the failed modules have a zero amplitude of excitation, the second causes a change in the complex amplitudes of the excitation emitters. Since smart antenna is a statistical system, which includes a large number of parallel channels, it potentially has high reliability. Indeed, both types of failures of the modules lead not to failure of the whole system, but only to a deterioration of energy and the directivity characteristics of the antenna: reducing the effective area, increasing the error of the beam, increasing the level of side lobes, reducing the transmission power of the transmitting smart antenna [7–9].

The failure rate of the modules $\lambda(t)$ is a function of time. With good accuracy we can assume that after screening tests the failure rate of the modules is constant, i. e. $\lambda(t) = \lambda = \text{const}$. The percentage of modules failed for the time t, is given by the following ratio:

$$n(t)/N = 1 - \exp(-\lambda\, t), \qquad (1)$$

where $n(t)$ is the quantity of failed modules; N is the total quantity of modules, $T_0 = \lambda^{-1}$ is MTBF. $n(t)/N \approx \lambda\, t = t/T_0$ is true for $t << T_0$.

The value T_0 of the electronic components of the electronic equipment specified in the specifications.

The failure rate of the modules essentially depends on the operating temperature of the crystals of semiconductor devices included in the modules. Description of temperature dependence of MTBF is based on the Arrhenius equation:

$$\lambda(T) = A\exp(-\varepsilon / kT), \qquad (2)$$

where T is the absolute temperature; k is the Boltzmann's constant; ε is activation energy; A is the constant of proportionality. Test results show that at temperatures of the crystal of 100–200 °C, the failure rate increases about 2 times by increasing the working temperature to 10 °C. That is, when the temperature increases, for example, from 100 to 150 °C operating time to failure is reduced by more than 30 times. In this regard, when considering reliability issues, the first thing to pay attention are transmitting adaptive digital antenna arrays having elevated operating temperature due to large heat generation and therefore lower reliability [10].

From the above it follows that a major problem in the design of transmitting adaptive digital antenna arrays is to ensure the normal thermal regimes of high-power transistors with the purpose of increasing their reliability.

If dissipation is large, a liquid cooling system is used, at relatively low heat an air cooling system is applied. Cooling systems working on different physical principles may be used as well. Here is the example of reliability calculations for smart antennas.

Adaptive digital antenna arrays with large heat generation use liquid cooling systems. Some smart antennas are made of tile-typed modules with metal thermal busses, in which heat from the power transistors is transmitted to the piping with the coolant fluid, located on the rear side of smart antenna. In order to remove high heat generation module structures with embedded channels for flushing of cooling liquid are used.

For smart antenna of K-range communication system (18.8–19.3 GHz) RaytheonSystemsCompany designed a cooling system, based on using phase transitions of the refrigerant. The heat exchanger in the form of a metal cylinder filled with porous aluminum “foam”, impregnated with paraffin wax. The volume of the heat exchanger and modules are connected by heat pipes. When you enable the modules the heat supplied to the heat exchanger volume goes into melting the paraffin. The process occurs at almost constant temperature. After turning off the modules, the process is reversed – the paraffin sets solid. The heat exchange device provides the junction temperature of the transistors about 100 °C when temperature gradients on the surface of the array is less than 10 °C.

Changes in the characteristics of smart antennas due to failures of modules can be described by statistical methods. An average radiation pattern of power of a system consisting of N emitters has the form:

$$\overline{\left|F(\vec{k},\vec{k}_0)\right|^2} = \overline{\left|f(\vec{k})\right|^2}\;\overline{\left|\sum_{n=1}^{N} I_n(1+A_n)\,e^{i(\vec{k}-\vec{k}_0,\vec{r}_n)}\,e^{i\Phi_n}\right|^2}, \qquad (3)$$

where $\vec{k}$ is the wave vector directed towards the observation point; $\vec{k}_0$ is the wave vector directed towards the system phasing point; $\overline{\left|f(\vec{k})\right|^2}$ is an average radiation pattern of power; $\vec{r}_n$ is the vector assigning location of emitter *nth*; I_n is the deterministic part of the amplitude excitation of the *nth* radiator; A_n, Φ_n – random amplitude and phase errors of the excitation of the *nth* emitter. The relation (3) allows by averaging the ensemble of realizations of the random radiation patterns of smart antennas to find the dependence of its parameters from the parameters of a random amplitude-phase errors [11; 12].

If the amplitude and phase errors in the channels are independent and small, i. e. they have a zero average and small variance $\alpha = (\overline{A_n^2} + \overline{\Phi_n^2}) << 1$, and average values of the amplitudes are the same (I_n = 1), then degradation of smart antennas parameters is described by the following approximate relations.

The gain is determined by the ratio:

$$G = G_0 - \Delta G \approx G_0\, e^{-\alpha} \approx G_0(1-\alpha). \qquad (4)$$

The average error of the maximum of a radiation pattern $\delta\theta$ related to the width of the half power radiation pattern $\Delta\theta_{05}$ (for the case of square pattern) is given by:

$$\delta\theta / \Delta\theta_{05} \approx 0.3\sqrt{\alpha / N}. \qquad (5)$$

The distribution of the side lobes of the radiation pattern obeys the generalized Rayleigh law. Average level of side lobes is described by the ratio:

$$\overline{f_б^2} = f_{б0}^2 + \alpha\pi / N, \qquad (6)$$

where $f_{б0}^2$ is the relative significance of any side lobe of power in the absence of amplitude-phase errors; $\overline{f_б^2}$ is the average value of the same side lobe if there are errors. In a separate implementation level of the side lobe can be more. With a probability almost equal to one, the maximum level of lateral radiation does not exceed values:

$$f_1 = f_{б0} + 3\sqrt{\alpha\pi / 2N}. \qquad (6a)$$

In 80 % of implementations, the level of the side lobe does not exceed the value

$$f_2 = f_{б0} + \sqrt{\alpha\pi / 2N}. \qquad (6b)$$

To assess the level of first side lobe of a smart antenna with a square aperture under equiamplitude excitation of the emitters in the formulas (6) should be considered $f_{б0} = 0.217$.

The degradation of the gain depends only on α, and the side radiation caused by random errors, decreases with increasing N. Thus, the maximum level of the first side lobe (6a) of the array with a rectangular aperture that is 13.2 dB with no errors (α = 0) is increased in the presence of the error α = 0.3 to –8.8 dB in the array with N = 200, and only up to 12.7 dB in the array with N = 20000. For the same parameters relative error of the maximum radiation pattern (5) is approximately 1 % of the beam width at N = 200 and only 0.1 % when N = 20000.

The ratio (4)–(6) can be used to assess the impact of the modules breakdown on the performance of smart antennas.

In the statistical theory of antenna arrays it is shown that the failure of n randomly located in the array of N elements can be considered equivalent to the impact of uniformly distributed over all elements of the array of random amplitude and phase errors with variance $\alpha = n/N$. Expressing the fraction of the failed elements as a function of the failure rate (1), we get:

$$\alpha = \alpha(t) = n(t) / N = 1 - e^{-\lambda t} \approx \lambda t = t / T_0. \qquad (7)$$

It should be borne in mind that the failure of modules of the transmitting adaptive digital antenna arrays not only leads to deterioration of the gain and radiation pattern, but will also reduce the radiated power, so the potential of smart antennas when $n << N$ is described by the following ratio:

$$\Pi = PG = \Pi_0(1-\alpha)e^{-\alpha} \approx \Pi_0(1-\alpha)^2 = \Pi_0(1 - t / T_0)^2. \qquad (8)$$

Time to failure T_0 of modern transistor transceiving modules of smart antennas of X-range is up to 100 000 hours (over 11 years). Receiver modules, made by hybrid technology have a life 2–3 times longer, and receiver modules based on integrated circuit can take $T_0 > 1\ 000\ 000$ hours, that is orders of magnitude larger.

From ratios (7)–(8) it follows that the smart antenna with $N = 20\ 000$ modules and $T_0 = 100\ 000$ hours, will undergo the following changes of parameters after one year operation without repair (about 8600 hours): decrease of the gain and effective area of the aperture (about 0.4 dB), the reduction of potential (about 0.8 dB), maximum growth of the first side lobe (not more than 0.3 dB), the maximum error of the beam (about 0.2 %, without taking into account the error, associated with the discreteness of the phase shifters and errors in the calibration of the channels of the array).

Given parameters are achievable, if the correct thermal operation mode of power transistors is chosen. This is achieved through the optimal mode of operation at a reduced power level, rational choice of materials for bodywork and its design maximizing heat dissipation from the crystals, a sufficient flow of cooling air or fluid in the cooling system [13–15].

Practically, the modules located at the edges of the aperture have a lower temperature than the modules located in the central part due to heat transfer to the environment. For example, in the literature there are the results of tests of a 17-element active array with air cooling. Power consumption of DC power in each channel is 9 watts. In conditions of the absence of forced cooling central elements of the array have a temperature of about 100 °C while the extreme ones – 60 °C. When enabled forced airflow, those temperatures are 40 °C and 20 °C, respectively [16].

Increased temperature in the central part of the aperture leads to a higher failure rate of the modules located here in accordance with the aforementioned ratio (2). This, in turn, leads to higher growth of side radiation than it follows from (6). Simulation of smart antennas parameters with variable temperature distribution can be performed using the ratio (3), while the failure rate of the modules in the aperture is described by the ratio (2).

Conclusion. Thus, for a more accurate description of the smart antennas characteristics it is necessary to create a model of its reliability. Such a model should take into account energy parameters of the modules and their elements, the dependence of the efficiency (and hence operating temperature) from the output power level, the temperature dependence on structural parameters of the cooling system, the above mentioned dependence of MTBF on the temperature, a more accurate description of the failure rate of the modules based on the analysis of the failure rate of their elements.

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References

1. Sliusar V. I. [Smart antennas are becoming mass-produced], *Elektronika: nauka, tekhnologiia i biznes,* No. 2, P. 62–65.

2. Huang P., Xu, W. Analog beamforming and digital beamforming on receive for range ambiguity suppression in spaceborne SAR. *International Journal of Antennas and Propagation*, 2015, Vol. 2015, Article number 182080.

3. Lin C., Li G. Y. Adaptive beamforming with resource allocation for distance-aware multi-user indoor terahertz communications. *IEEE Transactionson Communications*, 2015, Vol. 63, Issue 8, Articlenumber 7116524, P. 2985–2995.

4. Dmitriev D. D., Kartsan I. N. [Adaptive antenna arrays with digital beamforming]. *Reshetnevskiye tchteniya* [Proceedings of XVII International. Scientific. Conf. “Reshetnev reading”], Krasnoyarsk, 2016, Vol. 1, No. 20, P. 263–265 (In Russ.).

5. Tyapkin V. N., Kartsan I. N., Dmitriev D. D., Goncharov A. E. Spatial Filtering Algorithms in Adaptive Multi-Beam Hybrid Reflector Antennas. *International Siberian Conference on Control and Communications (SIBCON), 2015*. DOI: 10.1109/SIBCON.2015.7147244.

6. Dodychina E. M., Kol’tsov, Yu. V. *Tsifrovye antennye reshetki v bortovykh radiolokatsionnykh sistemakh* [Digital Antenna Array in Onboard Radar Systems]. Moscow, MAI Publ., 2013, 160 p.

7. Dmitriev D. D., Tyapkin V. N., Kremez N. S. [Methods of adaptation of the phased antenna array to noise in satellite radio navigational systems], *Radiotekhnika*. 2013, № 9. P. 39–43 (In Russ.).

8. Tyapkin V. N., Kartsan I. N., Dmitriev D. D., Goncharov A. E. Interference Cancelling Responses for Various Configurations of Antenna Arrays for Angular Measuring Navigation Equipment. *2015 International Siberian Conference on Control and Communications (SIBCON),* DOI: 10.1109/SIBCON.2015.7147245.

9. Kartsan I. N., Zelenkov P. V., Tyapkin V. N., Dmitriev D. D., Goncharov A. E. Spatial suppression of interference in hybrid reflector antennas. *IOP Conf. Series: Materials Science and Engineering,* 2016, Vol. 122, P. 012010. DOI: 10.1088/1757-899X/122/1/012010.

10. Sliusar V. [Digital antenna arrays in mobile satellite communications], *Pervaya milya*. 2008, No. 5, P. 16–21 (In Russ.).

11. Tyapkin V. N., Fateev Y. L., Dmitriev D. D., Kartsan I. N., Zelenkov P. V., Goncharov A. E., Nasyrov I. R. Using GLONASS for precise determination of navigation parameters under interference from various sources. *IOP Conference Series: Materials Science and Engineering,* 2016, Vol. 22 (1). DOI: 10.1088/1757-899X/122/1/012035.

12. Tyapkin V. N., Kartsan I. N., Dmitriev D. D., Goncharov A. E. Correcting non-indentity in receiving channels in interference-immune systems for Glonass and GPS. *International Siberian Conference on Control and Communications*, *SIBCON 2015*. 2015. DOI: 10.1109/SIBCON.2015.7147246.

13. FateevYu. L., Dmitriev D. D., Tyapkin V. N., Kartsan I. N., Goncharov A. E. Phase methods for measuring

the spatial orientation of objects using satellite navigation equipment. *IOP Conference Series: Materials Science and Engineering*, 2015, Vol. 94 (1). DOI: 10.1088/1757-899X/94/1/012022.

14. Kartsan I. N., Zelenkov P. V., Tyapkin V. N., Dmitriev D. D., Goncharov A. E. Adaptation algorithms for satellite communication systems equipped with hybrid reflector antennas. *IOP Conference Series: Materials Science and Engineering,* 2015, Vol. 94 (1). DOI: 10.1088/1757-899X/94/1/012010.

15. Serenkov V. I., Kartsan I. N., Dmitriev D. D. [Method for the synthesis of amplitude-phase distribution of hybrid-mirror download]. *Vestnik SibGAU*. 2015, Vol. 16, № 3, P. 664–669 (In Russ.).

16. Tyapkin V. N., Garin E. N., Ratushniak V. N., Gladyshev A. D. [The spatial noise suppression in various configurations goniometric of navigation equipment]. *Naukoenkie tekhnologii*. 2016, Vol. 17, № 8, P. 52–56 (In Russ.).

Библиографические ссылки

1. Слюсар В. И. Smart-антенны пошли в серию // Электроника: наука, технология, бизнес. 2004. № 2. С. 62–65.

2. Huang P., Xu W. Analog beamforming and digital beamforming on receive for range ambiguity suppression in spaceborne SAR // International Journal of Antennas and Propagation. 2015. Vol. 2015. Article number 182080.

3. Lin C., Li G. Y. Adaptive beamforming with resource allocation for distance-aware multi-user indoor terahertz communications // IEEE Transactions on Communications. 2015. Vol. 63, iss. 8. Articlenumber 7116524, P. 2985–2995.

4. Дмитриев Д. Д., Карцан И. Н. Адаптивные антенные решетки с цифровым формированием луча // Решетневские чтения : материалы XX Юбилейной междунар. науч.-практ. конф., посвящ. памяти генерального конструктора ракетно-космических систем академика М. Ф. Решетнева. В 2 ч. Ч. 1 / Сиб. гос. аэрокосмич. ун-т. Красноярск, 2016. С. 263–265.

5. Spatial filtering algorithms in adaptive multi-beam hybrid reflector antennas / V. N. Tyapkin [et al.] // 2015 International Siberian Conference on Control and Communications, SIBCON 2015 (21–23 May 2015, Omsk). 2015. DOI: 10.1109/SIBCON.2015.7147244.

6. Добычина Е. М., Кольцов Ю. В. Цифровые антенные решетки в бортовых радиолокационных системах. М. : МАИ, 2013. 160 с.

7. Дмитриев Д. Д., Тяпкин В. Н., Кремез Н. С. Методы адаптации фазированных антенных решеток к помехам в спутниковых радионавигационных системах // Радиотехника. 2013. № 9. С. 39–43.

8. Interference cancelling responses for various configurations of antenna arrays for angular measuring navigation equipment / V. N. Tyapkin [et al.] // 2015 International Siberian Conference on Control and Communications, SIBCON 2015 (21–23 May 2015, Omsk). 2015. DOI: 10.1109/SIBCON.2015.7147245.

9. Spatial suppression of interference in hybrid reflector antennas / I. N. Kartsan [et al.] // IOP Conf. Series: MaterialsScienceandEngineering. 2016. № 122. DOI: 10.1088/1757-899X/122/1/012010.

10. Слюсар В. И. Цифровые антенные решетки в мобильной спутниковой связи // Первая миля. 2008. № 5. С. 16–21.

11. Using GLONASS for precise determination of navigation parameters under interference from various sources / V. N. Tyapkin [et al.] // IOP Conference Series: Materials Science and Engineering. 2016. № 22 (1). DOI: 10.1088/1757-899X/122/1/012035.

12. Correcting non-identity in receiving channels in interference-immune systems for GLONASS and GPS / V. N. Tyapkin [et al.] // 2015 International Siberian Conference on Control and Communications, SIBCON 2015 (21–23 May 2015, Omsk). 2015. DOI: 10.1109/SIBCON.2015.7147246.

13. Phase methods for measuring the spatial orientation of objects using satellite navigation equipment / Yu. L. Fateev [et al.] // IOP Conference Series: Materials Science and Engineering. 2015. № 94 (1). DOI: 10.1088/1757-899X/94/1/012022.

14. Adaptation algorithms for satellite communication systems equipped with hybrid reflector antennas / I. N. Kartsan [et al.] // IOP Conference Series: Materials Science and Engineering. 2015. № 94 (1). DOI: 10.1088/1757-899X/94/1/012010.

15. Серенков В. И., Карцан И. Н., Дмитриев Д. Д. Метод синтеза амплитудно-фазового распределения гибридно-зеркальной антенны // Вестник СибГАУ. 2015. Т. 16, № 3. С. 664–669.

16. Пространственное подавление помех при различных конфигурациях антенной решетки угломерной навигационной аппаратуры / В. Н. Тяпкин [и др.] // Наукоемкие технологии. 2016. Т. 17, № 8. С. 52–56.