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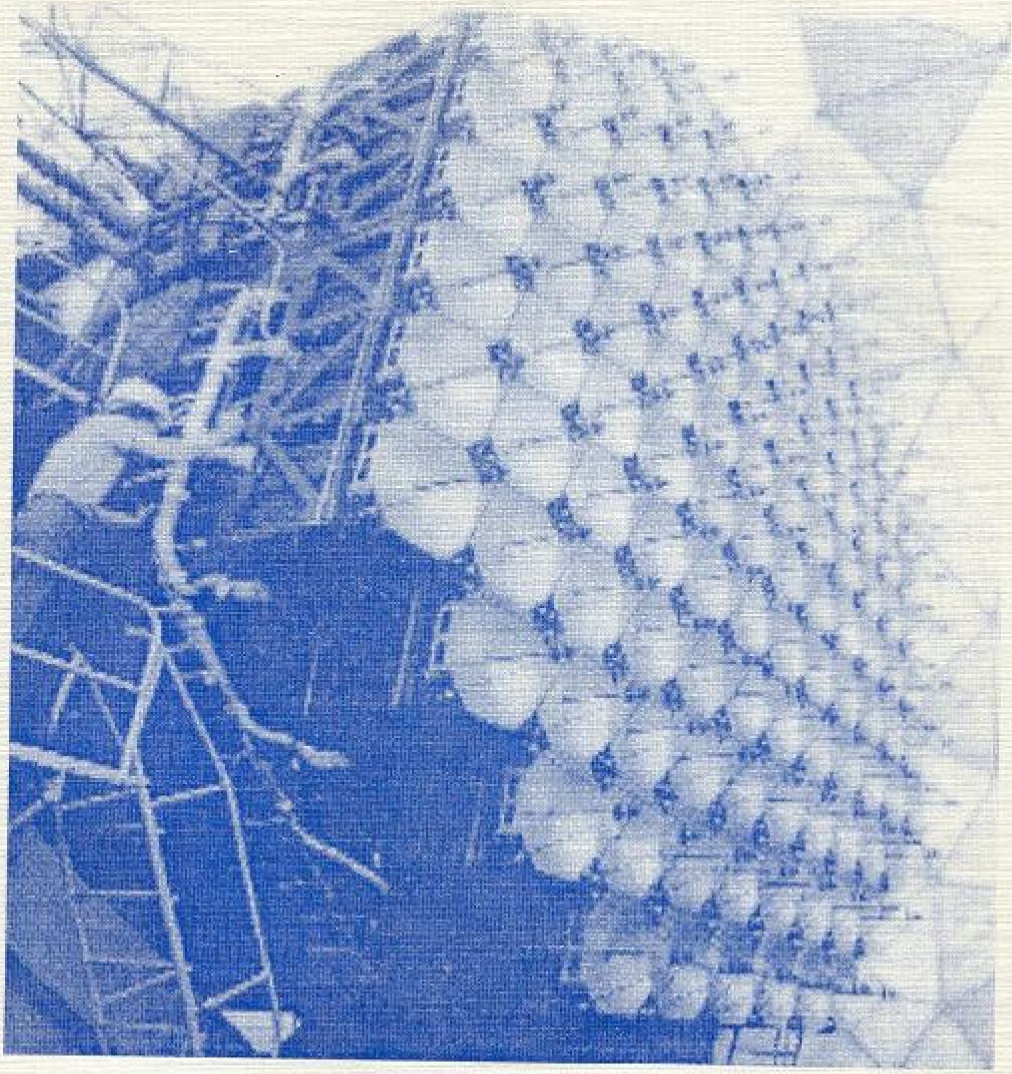

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A LARGE-APERTURED RADAR PHASED ARRAY ANTENNA OF K_a BAND

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Abstract-This paper describes apparently the greatest in the world millimeter wave (MMW) antenna with phased array. The beam steering is combined: electronic in narrow sector and mechanical in wide sector. The technical performances of antenna and their components are presented, the operating features are described.

1. Introduction

An advancement to the higher frequency ranges is a stable tend of the modern radio electronics progress. The creation of MMW radars allows to get a high energy density of primary signal in space, to expand a bandwidth of radiated signal, to increase a Doppler frequency shift, and thus to essentially improve main radar performances, such as: the radar range with a single target, the accuracy of coordinates measurement, the selectivity and resistance to the different type countermeasures. On another hand the use of MMW opens the possibilities of creation of the more miniature systems, at first by decreasing of the antenna size. This also corresponds to the modern tends of radar development [1].

The most complicated and expensive component of contemporary multichannel radars is the antenna including a phased array as the main integral part. It is true all the more for a big radars with aperture size of a few hundreds or even thousands wavelength. This paper concerns with the technical problems that were overcome during development and operation within the radar of the large MMW phased array antenna.

2. Main tasks

The antenna was developed within the creation of the high power radar of long wavelength part of MMW (K_a range). This antenna had to be of high efficiency closed to the reflector antennas one, but provides with the detection and tracking a few targets independently or under external target indication with the same characteristics as usual centimeter wave radars provide. Simultaneously there were a set of other tasks:

the study of possible decreasing aperture manufacturing accuracy and a compensation of deformations by the array elements electrical phasing;

the study of possible structures of the phased array antennas, including wide angle scanning ones [2];

the development of MMW components for phased arrays;

the development of algorithms and software for MMW phased arrays control, the adjustment procedure, and also the provision of operation monitoring.

The radar with the antenna under consideration had to operate with the satellites, space-crafts and other objects in the near Earth space. The pulse radar potential must be not less than 250 dBm^2 to perform these tasks. It's follows from this the antenna has to operate together with the high power transmitters [3] and provides with the low signal losses from aperture to low noise amplifiers at reception. The MMW antenna of radar from KREMS complex at Kwajalein Atoll based on the 13.7 m reflector [4] is close analog to the described antenna from point of view the operation tasks.

3.Main technical solutions

As the reflector antennas don't correspond to the available requirements, the phase array version was considered and implemented. The reasonable compromise between the cost and abilities of antenna was achieved by the application of transceiver array with great element spacing and narrow electronic scan sector, and the positioner with wide mechanical scan sector. The antenna general view and its simplified block-diagram are presented accordingly in Fig. 1 and 2.

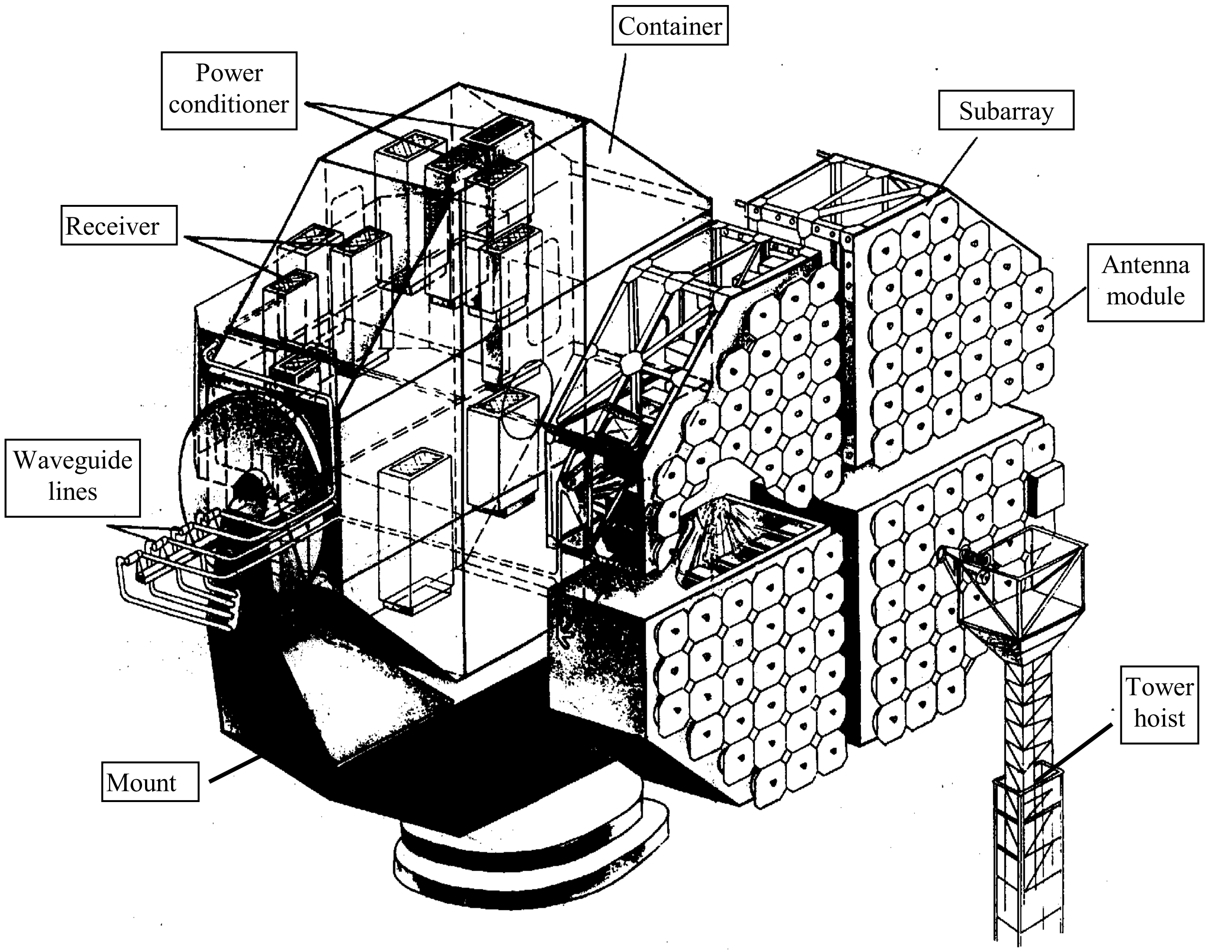

Fig. 1. The antenna general view.

So far as the high power gyroklystron transmitter may be placed only stationary the antenna scheme on transmission is passive with waveguide feeding. The antenna scheme on reception is active with the use in every antenna module the two stage low noise parametric solid-state amplifier. The microwave energy transmission to the antenna and signal in phase lay-out over array on transmission and reception are implemented with the use of overmoded

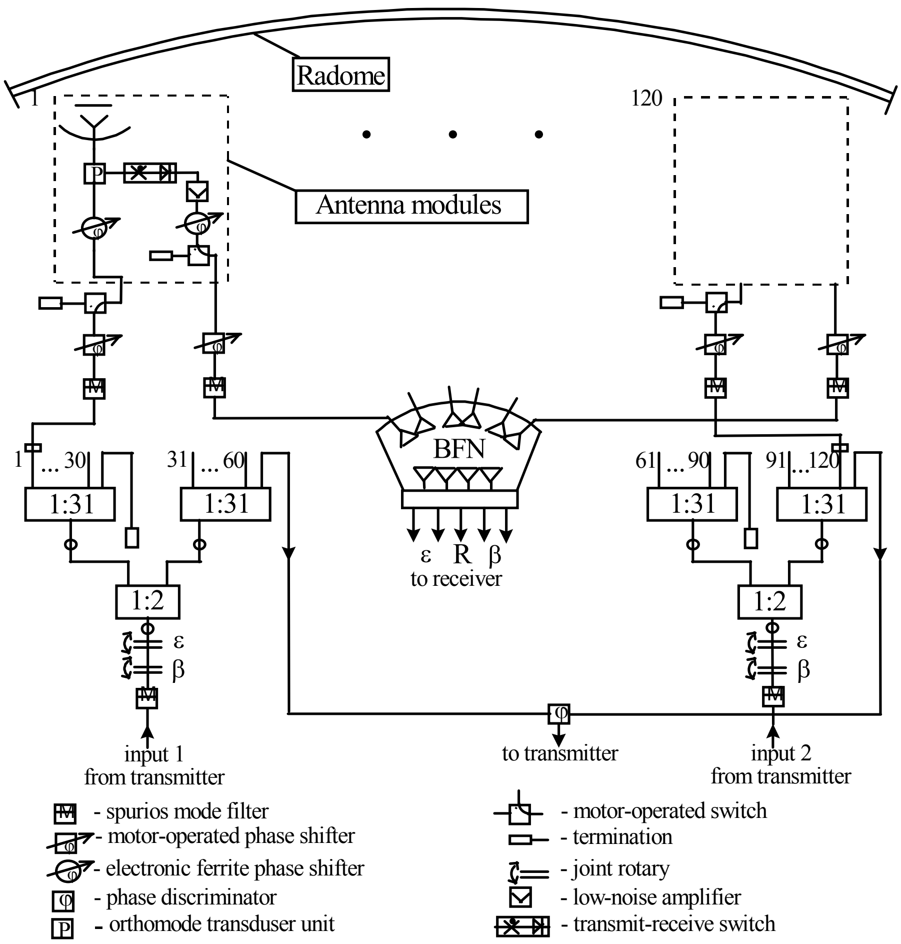

Fig. 2. The simplified block-diagram of antenna.

waveguides. The original spatial microwave devices perform microwave power division and reception monopulse beam forming. The array antenna module consists of the high efficiency reflector antenna and transmission-reception apparatus, including ferrite phase shifters, orthomode transducer, transmit-receive switch for low noise amplifier protection, control and monitoring elements. The antenna operates with two transmitters. So waveguide lines include the carrier frequency phase discriminator for automatic phase equalization of both transmitters output signals. The technical antenna performances are presented in Table 1.

4. Phased array

Phased array was developed in the form of octagonal prism of about 2 m depth divided into 4 subarrays. The easily removed antenna modules are placed in nodes of square lattice of ~0.6 m spacing. The array view from the aperture side is presented in Fig. 3. The receiving beam forming network (BFN), four waveguide splitters, and other components are disposed behind of the array structure. Antenna modules are connected with BFN and waveguide splitters by the waveguide lines. BFN is the spherical waveguide lens with the four-horn monopulse feed. The BFN transmission gain is -3.6 dB under the partial patterns crossing at half power level. The electronic beam steering is performed by the row-column manner with digital row and column phase summation. There is a possibility of individual phase correction to avoid phase drifts in transmission and reception channels.

Table 1. The technical performances of antenna

Name	Value	
	at broadside beam position	at the edge of electronic scan sector
Frequency band	33.75 – 34.25 ÃÃö	
Electronic scan sector	50'	
Mechanical scan sector	±135° in azimuth 0-180° in elevation	
Polarization	Left hand circular for transmission Right hand circular for reception	
Axis ratio	0.92	0.91
Half power beamwidth for transmission	3.6'	4.2'
Gain for transmission G_T: without the circular waveguide line with the circular waveguide line	 60 dBi 56 dBi	 56.5 dBi 52.5 dBi
Half power beamwidth for reception	4.4'	5.0'
Gain for reception G_R: at the inputs of the transmit-receive switches at the output of BFN (receiver input)	 62.5 dBi 69.5 dBi	 59 dBi 66 dBi
Reception radiation patterns	1 sum pattern (range channel) 4 difference patterns (angular channels)	
Maximum grating lobes level	–10 dB	0 dB
Maximum other sidelobes level in the transmission pattern	–16 dB	–12 dB
Maximum other sidelobes level in the sum reception pattern	–20 dB	–16 dB
Beam position error	< 20"	
Beam switching rate	15 kHz	
Noise temperature T_R: at the inputs of the transmit-receive switches at the output of BFN (receiver input)	 840 K 4200 K	
G_R/T_R ratio	33.3 dB/K	28.8 dB/K
Peak power at the antenna input	1.0 MW	
Maximum pulse width	100 μs	
Average power at the antenna input	10 kW	
Face position error	< 6"	
Maximum rotation velocity	4 deg./s	
Aperture size	7.2 m on every axis	
Radome diameter	20.5 m	
Operating Environment		
Temperature Relative humidity Operation wind velocity	–50 to +50° C 5 to 100% 0 to 30 m/s	

The element spacing d is big and equal to 68λ. So there are large grating lobes in the radiation pattern in directions

$$\theta_{gr.\ lobe} = arcsin(sin\theta_0 \pm \lambda/d),$$

where θ_0 is the beam deflection angle from broadside. The grating lobes level monotonically increases from -10 dB to the main beam level when the beam deflects from broadside θ_0=0 to the scan sector edge θ_0=±25'. The radar can lock on a target by grating lobe, so its algorithms include this effect protection.

The antenna module consists of the radiator and components for phasing and amplification. The radiator is a two-reflector antenna of four side 0.6x0.6 m aperture with the cut off corners. The radiator photo is shown in Fig. 4. The main parabolic reflector was produced by casting of aluminum allow with subsequent machining. The maximum profile error is 0.25 mm. The radiator efficiency of 0.73 was achieved by feed horn optimization, subreflector shaping [5], and conical booms use in its support. The beamwidth corresponds to the array scan sector and equals to 50' at half power level. The performances of the rest main components of antenna module are presented in table 2. The mass of antenna module is about 65 kg.

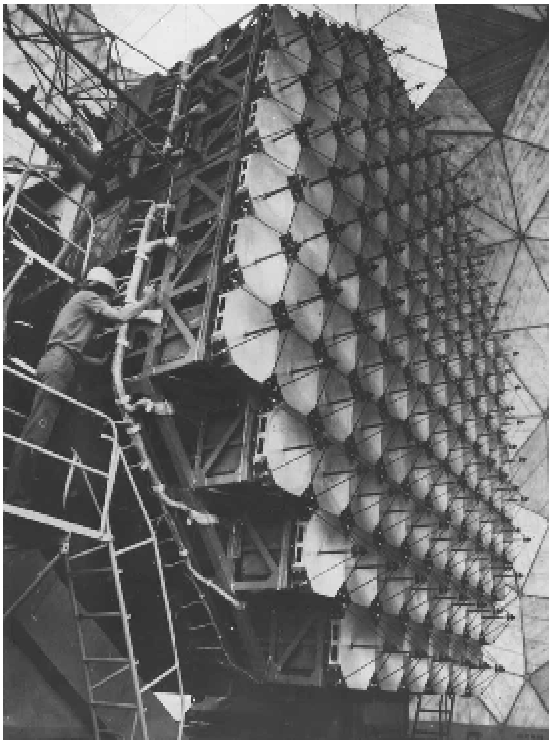

Fig. 3. Phased array.

Fig. 4. Array element.

Table 2. Main components of antenna module

Name	Type	Main parameters
Orthomode transducer unit	Waveguide	Isolation: ≥20 dB Axial ratio: ≥0.75
Low-noise amplifier	Two-stage parametric amplifier with solid-state pump	Gain: 21 dB Noise temperature: 550°K
Transmit-receive switch	Two-stage (gas-discharge and semiconductor) controlled	Leakage power: ≤50 mW Loss: ≤2 dB
Electronic phase shifters	Ferrite phase shifters with the longitudinal magnetization	Loss: ≤1 dB Phase discrete: 45° Switching time: 60 μs
Motor-operated switch	Waveguide, DPDT	Loss: ≤0.2 dB Isolation: ≥60 dB

The parametric amplifiers have a higher power handling than polar transistor ones and almost the same noise temperature. The applied technical solutions provide with the rather high temporary stability of these amplifiers' amplitude and phase performances. Fig. 5 shows the transmission and reception antenna patterns in broadside beam position.

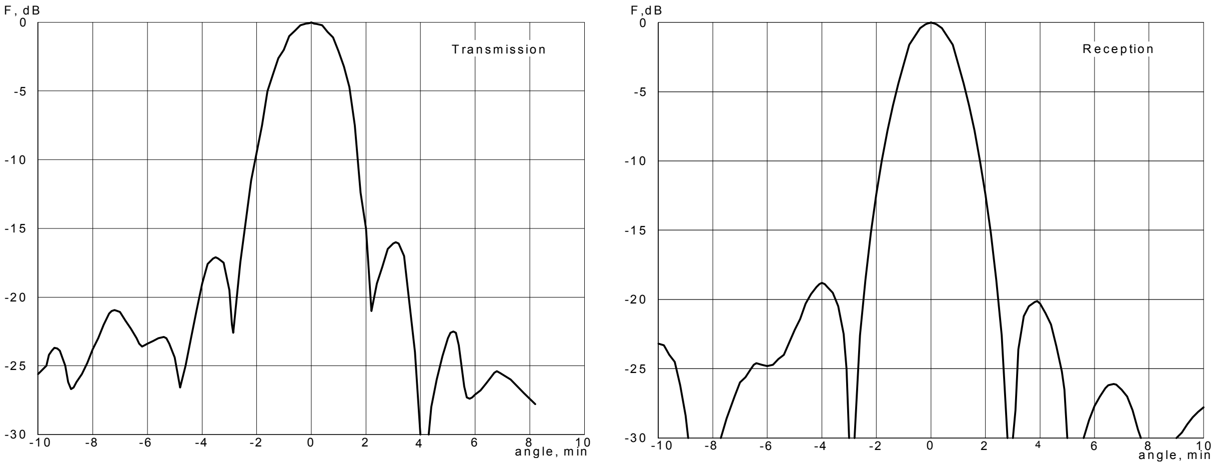

Fig. 5. Radiation patterns in broadside beam position

5. Waveguide lines

The radar contains a few waveguide systems. The most important ones are the following: 2 waveguide lines from transmitter to subarrays, 4 waveguide lay-outs of transmit signal over subarray, *i.e.*, to 30 antenna modules, 120 waveguide equal length lines from antenna modules to BFN, the 2.3 km line to the test tower.

The first system is the most complicated and crucial. There are three determinative technical requirements: the minimum losses, high power handling, mating with the gyroklystron output of TE_{02} operating mode. Every line has to include two rotary joints, divider 1:2, some additional elements, and must be of complicated path along the construction of two axes positioner. We chose the TE_{01} mode circular waveguide as the most satisfied to the available requirements. It's well known that this waveguide is of anomalous low loss per meter [6], but overmoded. The power handling of TE_{01} mode circular waveguide is very high. This waveguide can be matched with the gyroklystron output (the converter $TE_{02} \rightarrow TE_{01}$ was used). Notwithstanding the available experience of TE_{01} mode circular waveguide application in a communication and in the short distance high power transmission lines, their use in the radar required the solving a set of unprecedented problems. We found the transmission losses mainly occur because the mode conversion in the waveguide elbows. These elbows are disposed at a short distances one from another and strongly interact. The mode interference at the elbows and other line elements lead to the high ripple of transmission-frequency response and transmission gain variation when the array is rotated. The microwave breakdowns are occurred with the spurious asymmetrical modes when their power is by a few orders lower than TE_{01} mode power. The waveguide line development was based on three simple principles: the straight path when it's possible; the use of the components with low mode conversion loss only; the spurious mode suppression immediately after their rise. To implement these principles we had to develop waveguide elbows of 0.2-0.25 dB operated mode loss, effective spurious mode filters [7, 8], the T-type divider 1:2 based on the semitransparent dielectric reflector. The scheme of the one high power waveguide line is shown in Fig. 6. Its length is 40 m. It provides with the stable operation with 400-500 kW input peak power, about 4 dB losses, and transmission gain variation of 0.3-0.5 dB when array rotation. The some waveguide components are shown in Fig. 7.

The waveguide in phase layouts of transmit signal over subarray were developed with the use of radial type waveguide splitter 1:31 (one output is used for array adjustment) and 16×8 mm rectangular waveguide with TE_{01} operation mode. This waveguide is also overmoded. The signal loss in it is about 0.3 dB/m. One may bend this waveguide in H-plane without mode conversion. It permits to provide with the necessary length equality of all branches. The length of every branch is 2.5 m, the loss is about 1.5 dB and may be reduced to 0.8-1.0 dB when apply the better transitions and mode filters as shown in [9]. Fig. 8 shows the waveguide splitter 1:31. The waveguide lines from antenna modules to BFN were developed with the same waveguide.

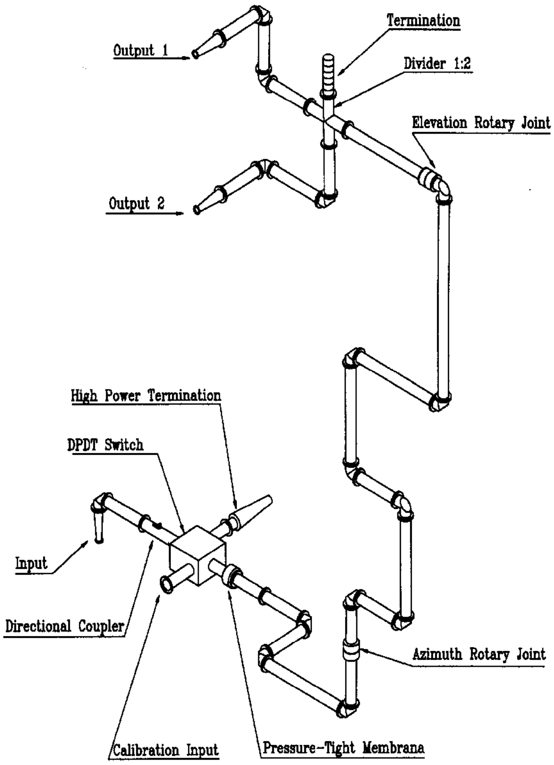

Fig. 6. Scheme of waveguide line from transmitter to two subarrays

Fig. 7. TE_{01} mode waveguide components.

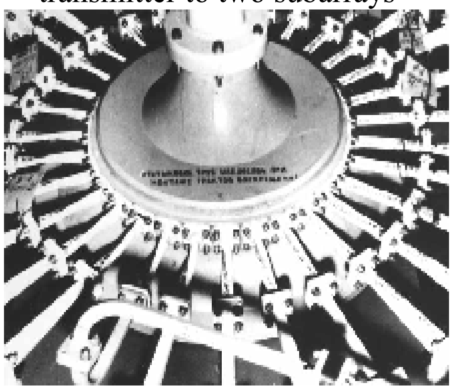

Fig. 8. Waveguide splitter 1:31.

The line to the test tower was implemented with the use of a mode self-filtering helix waveguide of 60 mm diameter. The path repeats a lay of the ground and have two Π-type sections over crossed roads. The waveguide line contains 19 elbows and inserts 20 dB losses.

6. Antenna design

The antenna consists of the three main parts: mount, phased array, and radome (see Fig. 1).

The mount is an elevation over azimuth positioner providing with the upper hemisphere survey. The octagonal rigid container is placed on the elevation axis. Its front face is used for phased array connection. The BFN, beam steering controller, power supply equipment, and microwave portion of the receiver are disposed inside this container. The rotary joints of TE_{01} mode waveguide lines are placed along the positioner axes.

The phased array consists of four subarrays, each of theses includes 30 antenna modules with waveguide lay-outs. The subarray mass is 4 tons. Due to the applied through phasing we could reduce the requirement to the metal frameworks dimensional accuracy. In particular the nonflatness tolerance of container and subarray frameworks was defined as 2 mm. The permissible total waveguide branches inequality is 3λ. The replacement of antenna modules is carried out from the aperture face with the use of the fast-unwrapped tower hoist.

The frame-membrane radome of the 20.5 m diameter provides with the necessary operating environment. The double light semitransparent membranes of 0.2 mm thickness composite film material were used. The signal loss in the radome is no more than 0.8 dB. The air conditioner maintains the temperature condition in the space under radome.

7. Maintenance

The described antenna is a complicated apparatus system. The necessity of continues aperture coherence and phasing when use in antenna modules the parametric amplifiers, ferrite phase shifter and other unstable components under condition of season and daily temperature and humidity differences, and mechanical disturbances, required the development of the maintenance procedure. It includes the real-time monitoring (RTM), which is making permanently during radar operation; equipment condition test (ECT), which is making during pauses between operation periods; and fast faulty antenna modules replacement.

The RTM is carried out due to built-in sensors and devices and continuously signalize about healthy and unhealthy components.

The ECT performs the antenna modules diagnostics, and tests the main antenna characteristics (patterns and gains) in transmission and reception modes. The ECT block diagram is presented in Fig. 9. The ECT is carried out with the use of radar apparatus portion, central computer, special software, and the test reflector antenna on the tower situated 2.3 km

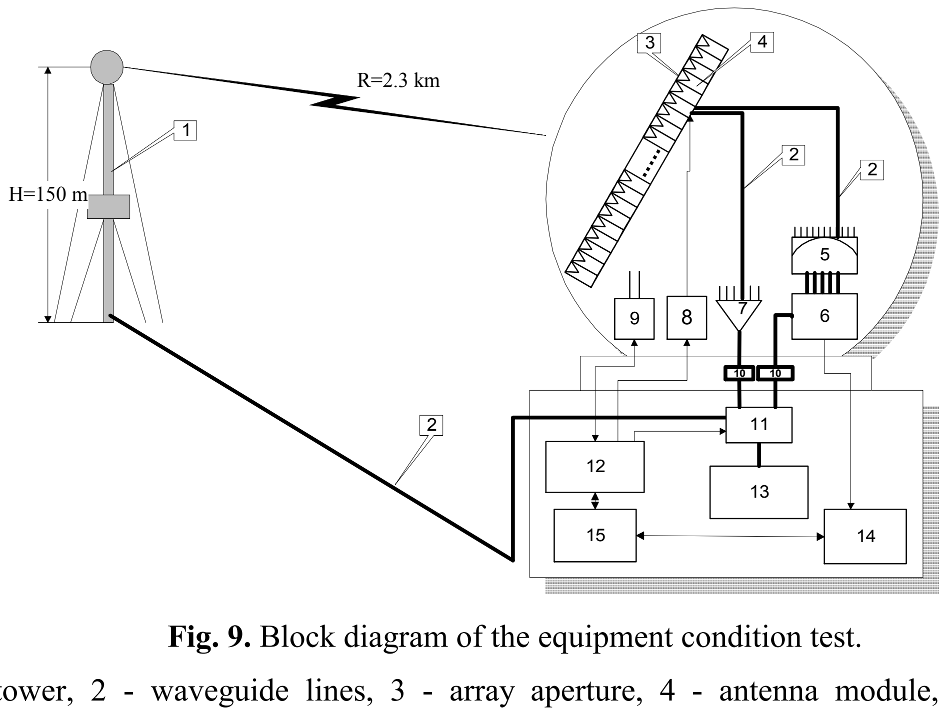

Fig. 9. Block diagram of the equipment condition test.

1 - test tower, 2 - waveguide lines, 3 - array aperture, 4 - antenna module, 5 - BFN, 6 - receiver, 7 - waveguide dividers 2:124, 8 - beam steering controller, 9 - drives, 10 - rotary joints, 11 - waveguide switches, 12 - control equipment, 13 - master oscillator, 14 - signal processing chain, 15 - central computer.

distant from the radar antenna. Signals for test antenna transmission and signals received by the test antenna are transmitted accordingly to the tower and return through the special waveguide line. The radar antenna is immovable during ECT. Its geometrical axis is directed to the test antenna on the tower. The electronic beam steering carries out the pattern tests. The test antenna is in the near field of the radar antenna, so the array is focused to the test antenna by automatic introduction of the individual phase shifts in every antenna module. The test of amplitude and phase distribution over aperture is carried out for the antenna module diagnostics. All array elements are switched-off by the waveguide switches except the tested one. In this test the phase corrections for every module are measured, the faulty antenna modules are defined, and the dispersions of amplitude and phase distribution are calculated. As a result of this test the array phasing is performed by the introduction of the corrections in phase shifter control codes. The duration of this test is about 20 minutes separately for transmission and reception. The antenna exploration shows the necessity of array channel phasing every week to maintain the satisfied phase distribution over aperture.

To follow the RTM and ECT results the faulty antenna modules have to be replaced. The replacement is carried out when the number of faulty antenna modules exceed 5% on transmission or reception separately. The antenna is in turn off condition during the replacement of course. The special tower hoist providing with 20 minutes module replacement was developed to repair the aperture. Usually a few modules fail during a month. The antenna maintenance required about 5 men team.

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