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THE SET-UP OF LINEAR FEED ARRAY FOR THE RATAN-600 RADIO TELESCOPE

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ABSTRACT. *The experimental set-up of the linear 8-element feed array is described. First results obtained in the autocollimation radioholographic mode have shown that the elaborated equipment could be used to compensate for scanned-beam deteriorations and surface distortions.*

1. INTRODUCTION

The questions of feed arrays used for increasing the field of view and fluctuation sensitivity of radio telescopes are widely discussed now. First experiments (Condon and Broderick, 1985) made with the help of matrix receivers, allowing to receive the signal independently at each of its inputs, have proved the possibility and give a chance for astronomers to provide deep surveys of the radio sky in an acceptable duration of time. An array of receivers installed near the focus of the telescope reflector makes possible to increase the field of view, accelerates an image forming process of extended objects, increases the coordinate facilities. The use of the phased array gives an opportunity to synthesize the beam scanning, increases the telescope sensitivity, permits to use simple methods to compensate for atmosphere influence.

In the present paper we consider a variant of linear array consisting of 8 receivers with separate front ends installed near the focus of the RATAN-600 antenna system. We see two main directions of using the linear phased feed array at the RATAN-

600 radio telescope: 1) for compensation of scanned-beam deteriorations caused by aberrations and 2) for antenna surface adjustments.

The theoretical base of the first method was described in details by Majorova and Pinchuk (1991). Briefly, the main ideas of it are as follows.

As it is known from the antenna theory, it is possible to change the beam position by displacement of the primary feed from the focus, but it leads to a great beam deterioration. In the case when the observed source is tracked by the primary feed, the output signal will describe the curve determined by antenna aberrations. The examples of such curves are given in Fig. 1.

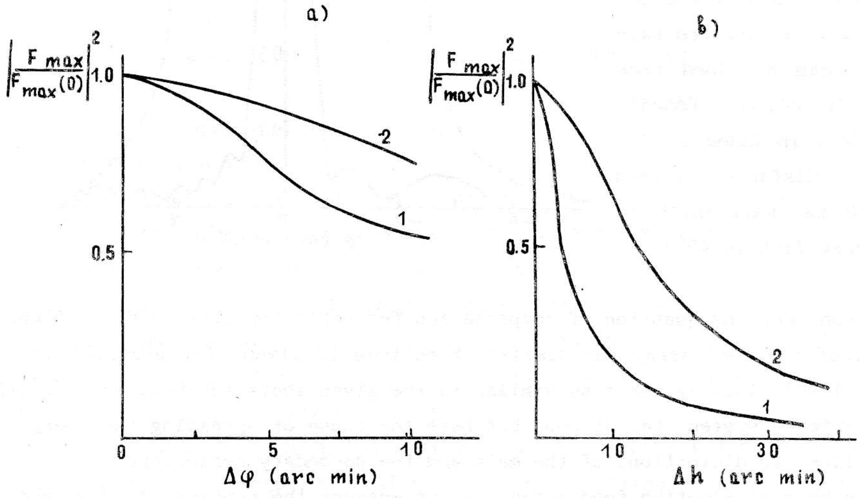

Fig. 1. *RATAN-600 aberration functions in the routine (1) and feed array (2) modes: a) - transversal aberrations, b) - longitudinal aberrations.*

The pattern maximum is decreased for displaced feed and considerable part of energy is concentrated in the sidelobes. It is possible to form an undistorted pattern in the given direction (h – elevation, α - azimuth) with the help of amplitude and phase excitation along the focal line like spread incident field $F(\Delta x)$. The compensation field can be achieved with the help of a special array feed consisting of n elements (horns or open waveguide ends) and controlled attenuators and phaseshifters which provide the $F(\Delta x)$ excitation of the antenna aperture. To provide the compensation of scanned-beam deteriorations, the array feed is to be designed so as to capture the energy spread over the focal line.

Calculations have shown that for tapered amplitude distribution and for observations of low-elevation sources, the array feed with n=8 elements will catch about 80% of spread energy.

Calculations made for restored pattern have also shown that reduction of side lobes level and increase of pattern maximum take place in all the range of h and α

variations. Fig.2 diagrams a part of the synthesized pattern for the beam declined from the central direction ($\Delta\alpha\neq0$, $\Delta h\neq0$). The aberration curves obtained using the 8-element feed array for both transversal and longitudinal patterns are presented in Fig.1.

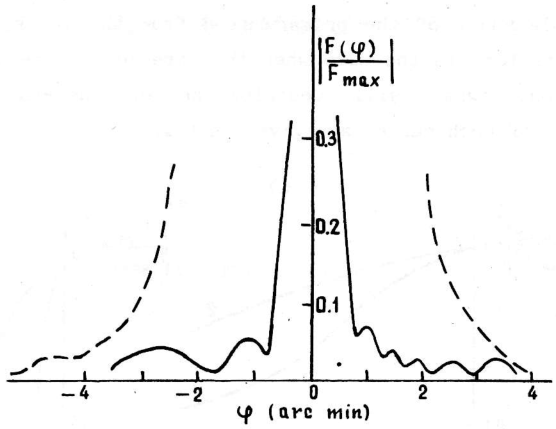

Fig.2. *Central cuts of routine (strokes) and synthesized patterns for beam declined from central direction ($\Delta\alpha=5'$, $\Delta h=10'$) (Feed includes 8 elements, the distance between them is 40 mm, wavelength is 6.2 cm , beamwidth is 40$'$).*

Let us consider the question of compensation for reflector surface distortions.

The use of the feed array for similar objectives is given, for example, in (Rahmat-Samii, 1990). This is the case similar to the given above for beam deteriorations caused by antenna system aberrations, but here the cause of spreading the energy over the focal line is distortions of the main and the secondary reflectors.

With the help of adaptive feed array one can measure the complex field spread near the antenna focus, for example, with the help of "point-like" radio source or in the autocollimation (AC) mode. To do it, the amplitude and a relative phase are to be measured at the outputs of each channel.

To compensate for the surface distortions, the measured conjugated values of the complex field are to be put in the corresponding settings of attenuators and phase-shifters; as a result of this procedure, an undistorted focal beam (spot) will be observed at the output of the beam-forming network.

Here, one can emphasize the principal difference of the given mode with the radio holography (RH) - using the array, it will be possible to compensate for the surface distortions without actual knowledge of the distortions themselves, though, such a variant is also possible.

In our case the AC measurement mode seems to be more preferable for it is more convenient and, besides, has a better angular resolving power (in reconstructed reflecting surface) relative to "point-like" source observations (Pinchuk and Stotskij, 1982).

Also, applying the Fourier transformation to the measured distribution of the complex field in a focal region, the real profile of the reflecting surface can be measured to compensate for. The finite "short" length of the array feed (2m) and the "long" wavelength (6.2cm) predetermine the distortion scales: only large-scale distortions can be properly measured. However, as it can be seen from (Stotskij et al., 1987), distortions with considerable scales prevail at the present time in the total budget of the RATAN-600 reflecting surface's distortions.

2. WAVELENGTH CHOICE

Choosing the wavelength, obviously, it is necessary to proceed from two principles:

- maximum of astrophysical information,
- minimum of expenditures.

Proceeding from the first principle, it is necessary to determine the waveband of the RATAN-600 in which the signal/noise performance is maximum.

Fluctuations connected with the confusion effect grow as $\lambda^{2.7}$ towards long waves, and fluctuations of atmospheric origin grow like λ^{-2} towards short waves (from the wave 6 cm). Besides, minimum of the antenna system noise temperature at average elevations (Parijskij and Korol'kov, 1986) and maximum effective area of the radio telescope correspond to the waves 6-8 cm.

It is necessary to highlight the possibility of spectral line observations at λ 6.2 cm, where the absorption (emission) line of formaldehyde is interesting for astronomers.

Proceeding from the second principle, it is necessary to estimate the cooling efficiency of the first stage of amplifiers for it may be a reason for considerable increase of the system cost and difficulties in its performance. Cooling is important for short wavelengths, because the noises of amplifiers in a "warm" regime are higher for short wavelengths. At the present time, there are enough low-noise amplifiers for 6 cm and longer. The noise temperature for them in a "warm" regime is about 60 K.

Hence, the 6.2 cm wavelength used at many radio telescopes would be the most optimal.

The fluctuation sensitivity, depending on confusion noises, for the "South + Flat" antenna system, single sector and the entire circular aperture of the RATAN-600 radio telescope are some mJy, some portions of mJy, and μJy, respectively .

The expected estimate of the system noise temperature gives a value of about 100 K that corresponds to a fluctuation sensitivity of 6 μK with a frequency band of 500 MHz and a postdetection integration time of 1 s. Cooling of the amplifier down to "hydrogen" temperatures leads only to a two-fold improvement of the fluctuation sensitivity.

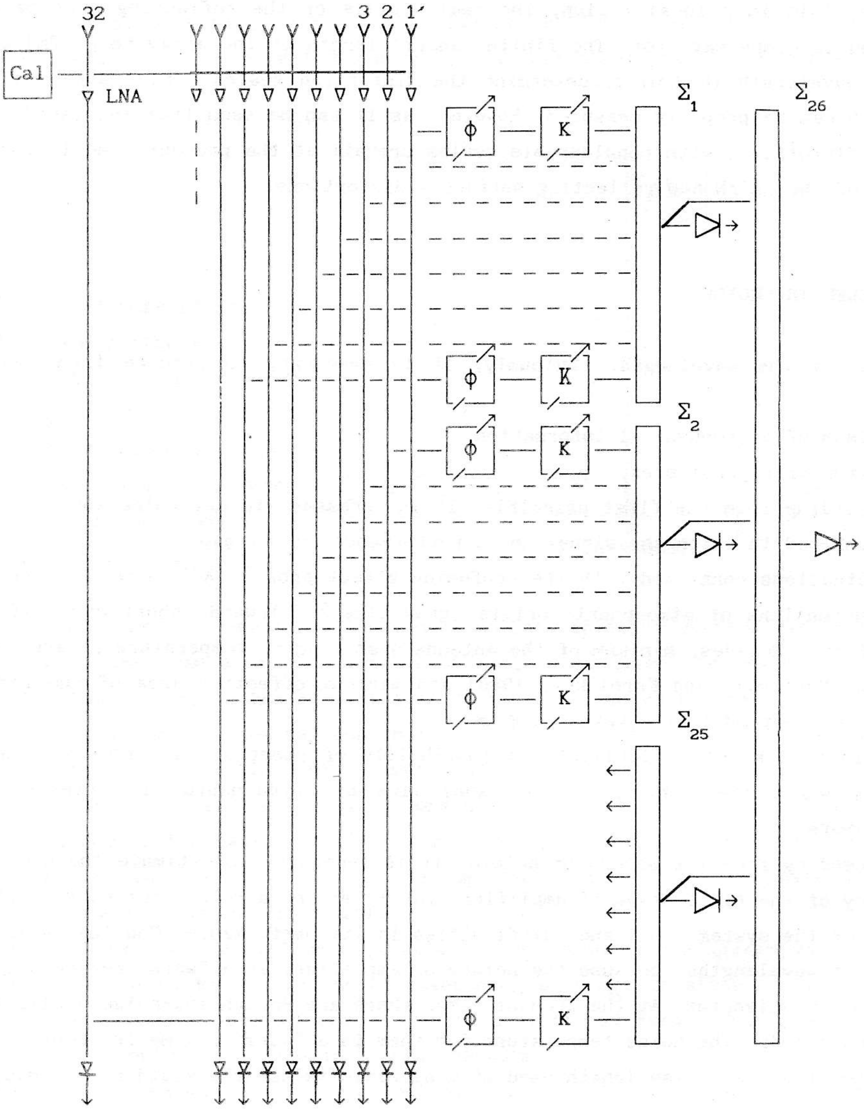

Fig.3. *Proposed apparature perfomance for the 32-element feed array*

(∇ - receivers, K *attenuators,* φ *- phaseshifters,*
Σ - summators).

3. THE SCHEME OF LINEAR FEED ARRAY

The possible scheme (Fig.3) of the array's apparatus design for the multibeam observational mode was briefly discussed by Pinchuk et al. (1989). Feed elements (N=32, from constructive and economic considerations) are installed along the focal line and connected to low-noise amplifiers. Each of k beams is formed by n channels (with appropriate amplitude and phase calculated previously). As has been estimated earlier, n is equal to 8. Hence, there are k=N-n+1=25 independent registrations of a radio source passing through the pattern undistored beams.

The suggested scheme could also be used in the scanning mode (or electronic tracking with motionless array) - single-beam operational mode. In that case the energy of all channels is added and registered at the common exit (summator Σ_{26}). The settings of amplitudes and phases are made in real time according to the field spread over the focal line. The values of amplitudes and phases calculated previously are kept in the computer memory.

With the help of the suggested scheme the multibeam mode could be combined with the tracking one within the limits of the carriage motion zone. In that case the tracking by single beam is made within 4-5 meters.

It is possible to restore the radio images of extended regions (at any azimuth different from the meridian) by means of multibeam pattern with independent signal registration of each of channels. Such a method is similar to the rearranging one (of the secondary mirror), but unlike it, it has equal convolution functions in all field.

The registrations at P_1-P_{32} outputs are also possible if we observe the near-zenith sources, when the "nonaberrational" zone is longer than the array feed.

The array possibilities permit to create the RH observational mode: the measurement of amplitudes and phases of the received signal with the following reconstruction. One of applications of such a method could be, for example, diagnostic of the RATAN-600 system's quality.

It is suggested to create a radiometer based on the scheme with a pilot signal for noise balance or beam switching. The "software beamswitching" is a convenient method to remove the atmosphere influence that determines the receiver instabilities when observing for a long time. More than two beams provide a good possibility to restore extended sources (Emerson et al., 1979). Also, we look for a quasi-zero compensation method (or a total power receiver) for it can improve the sensitivity $\sqrt{2}$ times.

The amplitude and phase calibration of each channel is foreseen. The entire radio astronomical observational process from the preliminary amplitude and phase calculations and its settings to data processing is to be automated. It is suggested to control all elements in real time.

To check all estimations and computation results connected with the feed array implementation at the RATAN-600, the experimental 8-channel feed array has been made. The experimental set-up includes: 8-element array feed (it is described above), 8-channel receiver, beam-forming network, system for data processing, evaluation, etc.

Below, the mentioned experimental set-up is briefly described.

3.1. Array feed

The main requirements placed on such an array feed are as follows:

1) Good matching and low coupling between feed elements.

This is particularly important for radio astronomical signal reception, when a low noise temperature and a low coupling, allowing to provide an independent acquisition each of the channels, are needed. In its turn, for low coupling the additional noise temperature from neighboring channels will be minimum. It is clear, that for T_{res} = 60-70 K and T_{ant} = 40 K an array feed noise temperature of 10 K will be acceptable.

2) The partial diagrams (patterns) of each channel are to be matching with antenna system configuration, i.e to provide the high gain/low side lobes level performance of the antenna pattern. Ideal would be the characteristics of the routine mode which provided the highest ratio of gain/side lobes level and lowest noise temperature of the antenna.

3) All array feed characteristics are to be the same for 10% frequency bandpass (4.55-5.05 GHz).

4) Identity of electrodynamical characteristics of such array feed elements.

5) If possible, the smallest gaps between the feed elements. It follows from the demand to create the scanning beam without deteriorations, when the "smooth" excitation field has to be equal to a wave incident on the focal line. It is clear, that possible gap will be determined by sizes of waveguides constituting such a multielement feed.

Proceeding from these demands, the linear 8-element feed consisting of H-plane waveguides loaded on E-plane corrugated horn was suggested, calculated and made. The distance between the nearest feed elements determined by constructive features is 44 mm.

At the first stage, the characteristics of such an array feed based on the periodical structure theory (Amitay et al., 1974) were calculated, moreover, the approximation of infinite model was used. Considering a problem of plane wave diffraction on a periodical structure of open-end waveguides, one can obtain the expression both for partial pattern and for coupling coefficients (Γ_{00}, Γ_{0i}...) between the feed elements. The theoretical model permits to create the suggested design of the array feed with the parameters mentioned above. Specifically, the coefficient Γ_{00}=-21 dB corresponds to a noise temperature of 2 K.

The difference between the real array feed and H-plane waveguide array is the field structure in E-plane. The measurements carried out for different types of corrugated horns have shown that for the best patterns both in E and H planes and for lowest coupling the corrugated horn with a flare angle of 120° will be the most optimal (Fig.4).

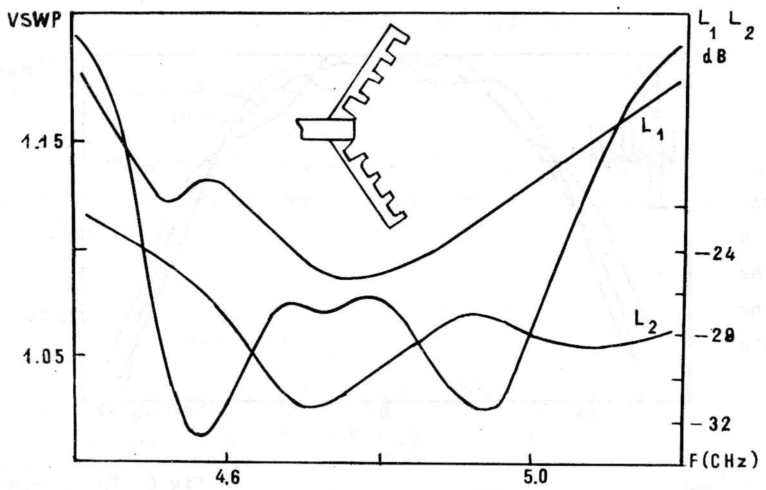

Fig.4. *The VSWR and mutual couplings (L_1, L_2) for feed elements.*

In the array feed construction, the matching elements, inductive diaphragms and capacitive screws are invisaged. Besides, an ability to compensate for the coupling between the elements is also foreseen as holes in the partitions connecting the waveguides. The distance between hole center and waveguide open-end is 0.7 λ. The voltage standing-wave ratio (VSWR) of the feed elements and values of coupling obtained in a frequency band of 10% are given in Fig.4. The final partial patterns for E and H planes (two curves) are given in Fig.5. The last two are for the central and extreme feed elements. The difference between them can be explained by different coupling of elements in the finite 8-element feed. The additional noise temperature will be not more than 5 K for the achieved coupling.

Note, that all given characteristics were calculated both for the central and extreme frequencies of the 10% band; they correspond to all requirements placed upon the array feed.

3.2 Receiver

The block diagram for one of the array receivers based on the pilot-signal balancing method is presented in Fig.6. Three thermostats are used for receivers location:

2 thermostats (4 channels in each) for the first stages of amplification (low-noise amplifiers - LNA) and a common one for the next stages. The temperature level inside the thermostats is 310±0.1 K. LNA (FET-transistors) are locally cooled down to a temperature of 213 K with the help of a thermoelectric system. T_{amp} = 60 K, the gain over the operating frequency band is 30 dB.

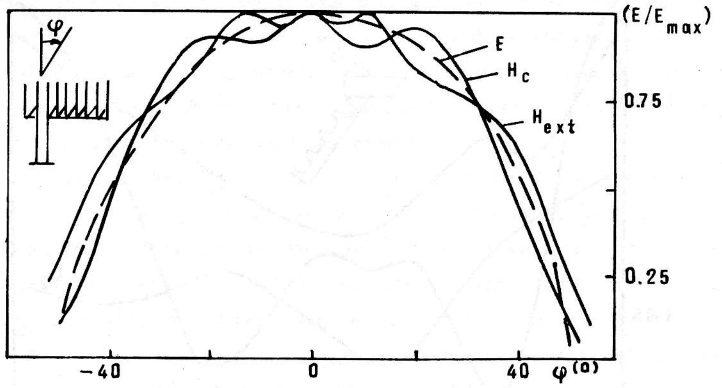

Fig.5. *Partial patterns in E and H planes (for H: the central and the extreme element's patterns).*

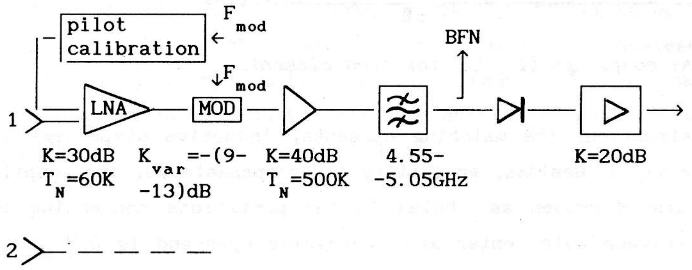

Fig.6. *The scheme of single receiving channel of realized 8-channel set-up.*

The modulator of gain (p-i-n diode) installed for noise balance of the receiver may vary the value of gain from 9 to 13 dB with an accuracy of 10^{-3} that is provided by digital system of diode-current setting.

The frequency bandpass of the filter is 4.55-5.05 GHz (central frequency - 4.8 GHz), the stopband rejection is greater than 40 dB.

The detector is the tunnel diode. The total gain from the front-end up to the detector input is 65 dB.

The preliminary amplifier of video frequencies (PAVF) may vary the gain (17-23 dB) and provides the matching between receiver and registration system.

The FET-transistors are loaded on the array feed described above. The size of the waveguide is 20x40 mm, the distance between the feed elements is 44 mm.

The feed spatial characteristics correspond to calculated ones: the partial diagrams in a vertical plane are similar and cosine-type; in a horizontal plane, the diagrams of extreme elements differ from the central one, that is the result of finite-size array feed using. Matching of the elements is -20 dB, the coupling between the neighboring elements is -21 dB. The warming of the waveguide system by air stream with a temperature higher than the dew point is allowed for.

The balance (compensation) of the receivers is provided with the help of thermostated noise diode through 8-element power splitter.

3.3 Beam-Forming Network

The scheme of Beam-Forming Network (BFN) is given in Fig.7. The phaseshifters are 4 bits with a ferrite memory. The limits and accuracy of phase settings are $(0^\circ-360^\circ)\pm11^\circ.25$.

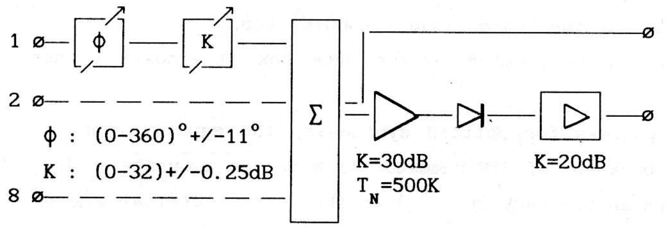

Fig.7. *Beam-Forming Network.*

The attenuators are made on the basis of p-i-n diodes. The limits and accuracy of amplitude settings are (0-32)±0.25 dB (6 bits) that is provided by a digital system of diode-current settings.

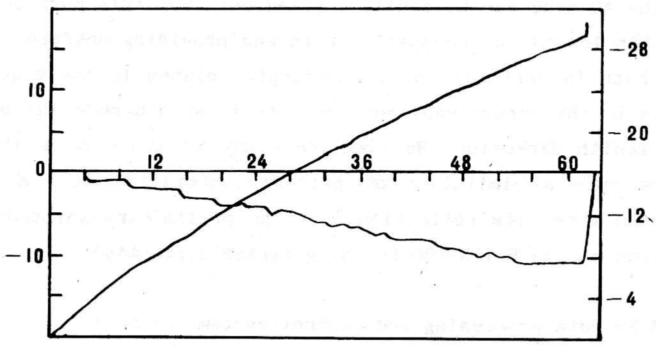

Fig.8. *Measured attenuations for 1-st channel in depend on control system signals - right; the additional coupling between phase and amplitude - left.*

In Fig.8 one can see the curves of amplitude depending on remote control system signals (0-63). The curves of mutual couplings between amplitude and phase are given there also. The same data for phase are also in the computer memory. The additional phase change when varying the amplitude does not exceed 10° that is less than the accuracy of its setting. The duration of a new setting for phaseshifters is determined by duration of its remagnetization and does not exceed 1 ms, the time characteristics for attenuators are much better.

With the objective to compensate for the power loss (20 dB) from the input of every channel up to the output of 8-channel summator (divider), the amplifier loaded successively on the detector and PANF is provided for.

All HF elements are thermostated at the level of 310±0.1 K.

3.4 Calibration

In the system, both the absolute (amplitude) and relative (amplitude and phase) calibrations are envisaged. For the first case, the special matched load cooled down to the liquid nitrogen temperature was made. The load is connected to the array feed front end. Provision is made for the "warm" load (T=300 K) too.

The noise diode (generator) is located in the same box (thermostat) where the balance noise diode is.

During the calibration process for pattern synthesis, the equalization of gains from the noise diode up to back-end of BFN summator is made (as accurate as 0.25 dB); also, the equalization (with an accuracy of 11°) of absolute electrical signal paths is carried out. For the last case it is important to emphasize that due to the wide frequency band (10%), we must provide the mentioned accuracy within the limits 2π. The parameters of the calibrating power splitter, the alone element does not taking part in the signal reception, are taken into account when calibrating and adjusting the array.

In the RATAN-600 antenna system, calibration and adjustment of the array elements in the AC mode can be easily carried out. For this purpose, the additional noise generator loaded on the special horn and providing uniform excitation of the main mirror both in vertical and in horizontal planes is envisaged. The AC horn is located close to the array feed, and the work in such a mode is identical to observations in the zenith direction. Besides the array adjustments in the AC mode, one may easily carry out: a) imitation of pattern restoration (the distorted incident field is created after its reflection from the preliminary shifted main mirror), and b) correction of the RATAN-600 focusing system distortions.

3.5 Data processing and control system

The block diagram of the data processing and control system is given in Fig.9. As the base, the PC/XT "Amstrad" computer including a special plate with A/D converter (10 bits) and input/output ports are used. That allows to carry out in turn the registration of 16 analog signals and code control with bus (24 bits) organization of data streams and addresses.

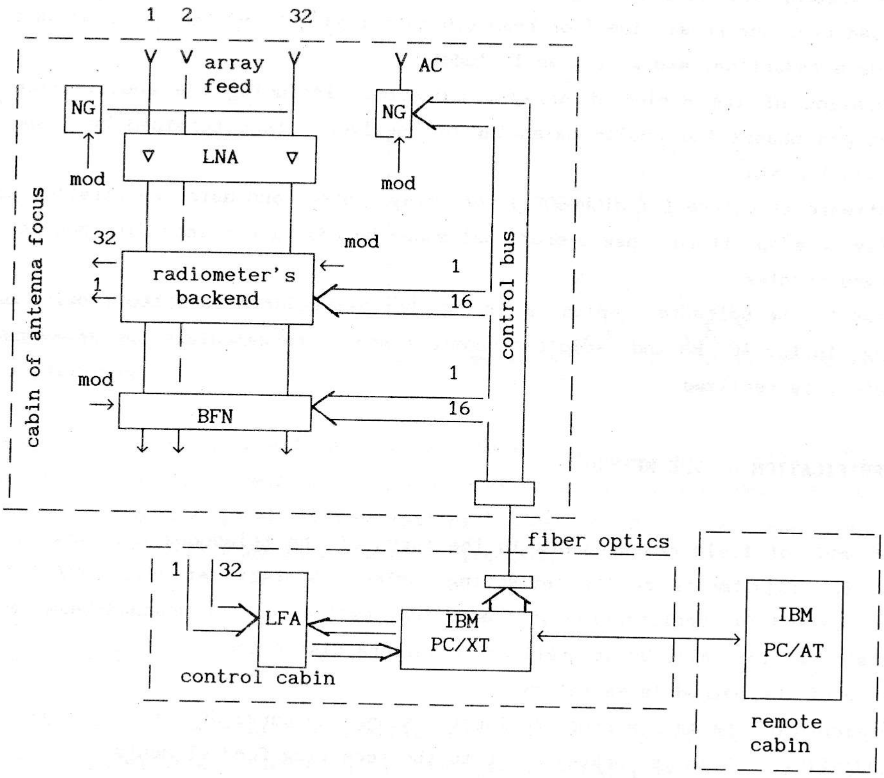

Fig.9. *Data processing and control system.*

The transmission of control signals is carried out by optical fibre with a length of 30 m.

As was described earlier, for the 32-element array, it has to control 25 independent beams that corresponds (for n=8) to 200 pairs of phaseshifter-attenuator. Proceeding from this fact, the address bus contains 8 bits. Besides, 2 bits are needed for the strobe (phaseshifter or attenuator) and 6 bits - for setting of the corresponding state of phaseshifter or attenuator (6 bits - for attenuators and 4 bits - for phaseshifters).

Control of all elements is made successively. Hence, for the full data/addresses bus 16 bits are just enough.

With the help of the same bus, control (10 bits) of balance of each of radiometers, switching (on/off) of AC and calibration noise generators are made. The system permits to control the position of the cabin housing the set-up. and also to control gain (3 bits) and integration time (τ = 1 or 0.1 s) of 8-element back-end. The

LF device is made in the CAMAC-standard.

In the system, the data exchange with the HOST PC/AT-386, which calculates the field spread over the focal line (for beam synthesizing), stores the data, makes preliminary data reduction, etc., is also included.

The duration of the 8-element array calibration, including the equalization of amplitudes and phases and noise balancing of receivers, is determined by τ and is equal to about 2 min.

The software structure (CI/MICROSOFT) for array control and data registration permits easily to adapt it for new operational modes by adding corresponding modules of the software complex.

At present, the software complex, allowing, besides calibrations, to provide data processing in the AC, RH and radio astronomical modes, to calculate the array parameters, etc., is realized.

4. AC VERIFICATION OF THE METHOD

The AC mode of field measurements in the focus of the telescope used now at the RATAN-600 for adjustments of its reflecting surface (Stotskij et al., 1987) is a convenient method for verification of theoretical estimations of scanned-beam restoration distorted initially by aberrations or antenna distortions.

The base of the method is as follows:

1. The elements of the main mirror are located along the curve of a ring cylinder.
2. The radiating AC horn is located close to the receiving feed elements.
3. The reflected field is formed along the focal line of the secondary mirror. Displacing the portion of the main mirror elements by a value of $\Delta\lambda$ relative to its initial positions, one can obtain the beam deteriorations.

As a result, the incident field is spread along the feed elements. It is clear, that for the purpose of energy focusing to a single point, which means the AC pattern restoration, the feed elements must be excited according to a calculated (or measured) amplitude-phase distribution of incident wave.

The measurements (for the second occasion) can be carried out in the RH mode (amplitudes are measured directly, phases - in a comparison with one of the channels). Besides, it is possible to apply the Fourier transformation to the data measured and to restore the profile reflectivity of the main mirror.

There are two AC focal diagrams depicted in Fig. 10: 1) measured by means of one of the feed elements and 2) restored when measuring the spread field along 8-elements of the array feed.

The main mirror is consisted of 30 reflecting panels, half of which are displaced by the value $\lambda/4$. In such a case, the measured AC diagram is a curve with two main lobes out of phase by 180°. Unfortunately, in this experiment the feed did not capture all energy spread along the focal line, that is why we have a high level of side lobes for the restored beam.

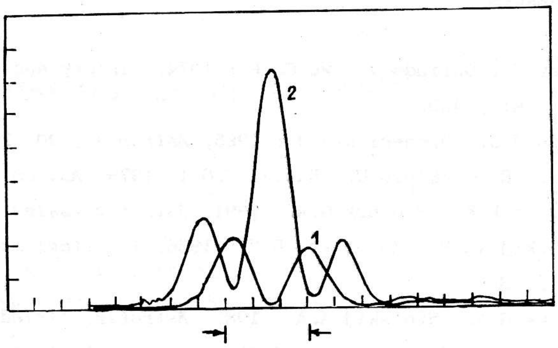

Fig. 10. *AC verification of beam restoration (1 - initial beam, 2 - restored beam).*

Besides, the use of the AC mode allows to provide the adjustments of the array's elements, for in the AC mode all signals received by the feed elements are equal that is explained by the great "nonaberrational" zone in this mode (equivalent to the routine observational mode in the zenith direction).

5. CONCLUSIONS

In the paper, the main requirements placed on the multielement feed array designed at the RATAN-600 for improving its observational possibilities are presented. The parts of the constructed experimental 8-element feed array assembly and its measured characteristics are described. First antenna measurements made in the AC operational mode have shown that the combination of reflector with feed array installed near the focus of radio telescope may considerably increase its facilities. The elaborated equipment could be used for radio astronomical observations at the RATAN-600, but the best results, it is clear, will be achieved using the 32-element feed array.

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system.

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