UDC 523.164

THE SIBERIAN SOLAR RADIO TELESCOPE

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In 1984, 240 km from Irkutsk (51°45' N, 6^h45^m E) at settlement Badary at one of the SibIZMIR observatories [1] construction work on the Siberian solar radio telescope, a crossed interferometer operated at centimeter wavelengths, was completed. The main design parameters and the principle of operation of this instrument are described in [2-4]. A major merit of the SSRT is its high angular resolution of up to 17" for linear arrays and up to 21" in the crossed mode - with sufficiently frequent recordings of the radio brightness distribution on the solar disk. Systematic observations of solar activity with the SSRT were begun in 1981 with commissioning of the first group of 16 antennas. Such observations with step-like increasing (as the other groups of antennas were incorporated) angular resolution provided new information on space-time evolutionary features of active regions and flares. Some results of the investigations made are presented in [5]. This paper gives a description of the operational instrument, its observing capabilities and of the ways to modernize some radio telescope systems.

The main characteristics and the principle of operation of the SSRT. The choice of the SSRT working wavelength (5.2 cm) was dictated by the intention to investigate active regions with maximum possible effectiveness. Also, consideration was given to wavelength ranges of other large instruments used for investigating solar activity.

The SSRT is made in the form of two orthogonal rows, with 128 antennas in each, installed at steps of 4.9 m in the east-west and north-south directions. These linear interferometers provide the designed maximum resolution of 17" and a minimum distance between the main beam lobes of 35'. The diameter of the dishes (2.5 m) was chosen by compromise between the sensitivity and the duration of observations limited by the shading of the dishes.

In the crossed mode the minimum width of the beam is not worse than 21", and the sensitivity must ensure a reliable recording of active regions with a tenfold (with respect to the quiet Sun) brightness temperature.

For constructing a two-dimensional map of the solar radio brightness distribution in the crossed mode, the method of frequency scanning is used (the dependence of the position of main maxima of the beam on the frequency of the received radiation) [6]. In this case the discrete scanning in height is made by using the mul-

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ti-frequency method and along the trajectory of motion of the solar disk center - as a consequence of terrestrial rotation.

The multi-frequency receiver unit of the SSRT features 180 channels spaced in frequency by 622 kHz [7]. For certain directions the overall frequency band of the receiver cannot ensure the desired coverage of the solar disk by the beam fan; in the worst case, 2 or 3 passages or a time of no more than 20 min is required for synthesis of a complete solar map. The questions related to the choice of the number of frequency channels and their spacing are considered in detail in [2,8].

Scientific objectives of the SSRT. One of the main problems for whose solution the SSRT is intended, is systematic daily diagnostic of the state and evolutionary features of solar activity at microwavelengths.

On such a basis, using data obtained in other ranges of the solar spectrum as well as data on particle fluxes, the solar wind and geophysical disturbances, research is being done on:

- the structure and evolution of active regions at all stages of their development;
- dynamical peculiarities and transient processes in the atmosphere of active regions;
- buildup signs and geoeffectiveness criteria of flare processes;
- space-time peculiarities of the development of flares;
- the relationship of the morphological and temporal development of the microwave emission range and of other ranges in order to study the three-dimensional picture of the structure and development of active regions and flare processes; and
- processes of emergence of magnetic fields into the solar atmosphere, the interaction of them with previously evolved magnetic configurations, magnetic field energy accumulation and release, and acceleration and escape of geoeffective high-energy particle fluxes.

The problems which require high time resolution can be solved through observations on linear interferometers forming the SSRT, by use of frequency scanning. This observing mode is suitable for investigating rapidly occurring nonstationary processes (bursts and quasi-periodic oscillations) and the inclination of the spectrum of bright sources [9]. Interesting possibilities of investigating short-period processes of weak intensity are provided by observations with the east-west interferometer in the direction to the east and west and with the north-south interferometer in culmination, where during several minutes the sources lie in the knife-edge beams [10]. In observations of sufficiently bright flares the SSRT provides a technical capability to increase the distance between the elements

F i g. 1. A general top view of the SSRT from the south

in the interferometer in order to decrease the period of the interference beam, which does not cause any ambiguity of the result due to the small angular size of the burst and its significant brightness as compared with the level of the quiet Sun. In this case there is a significant increase of the possibility of continuous observation of the burst with the SSRT linear interferometers [9].

The antenna array. A general view of the SSRT is given in Fig. 1. The location of the SSRT in an area with considerable freezing of soil (up to 2.8 m) required a special foundation for each antenna. The structure of the equatorial support-rotation device (SRD) provides a possibility of small linear displacements of the antenna and of corrections of the position of its polar axis (Fig. 2). A dedicated high-precision geodetic network [11] made it possible to achieve the accuracy of:

a) the orientation of the SSRT beams in cardinal points not worse than 2.5';

b) setting of the SRD axes in the three coordinates, on the average, not worse than ±1 mm; and

c) setting of the SRD polar axes not worse than 2'.

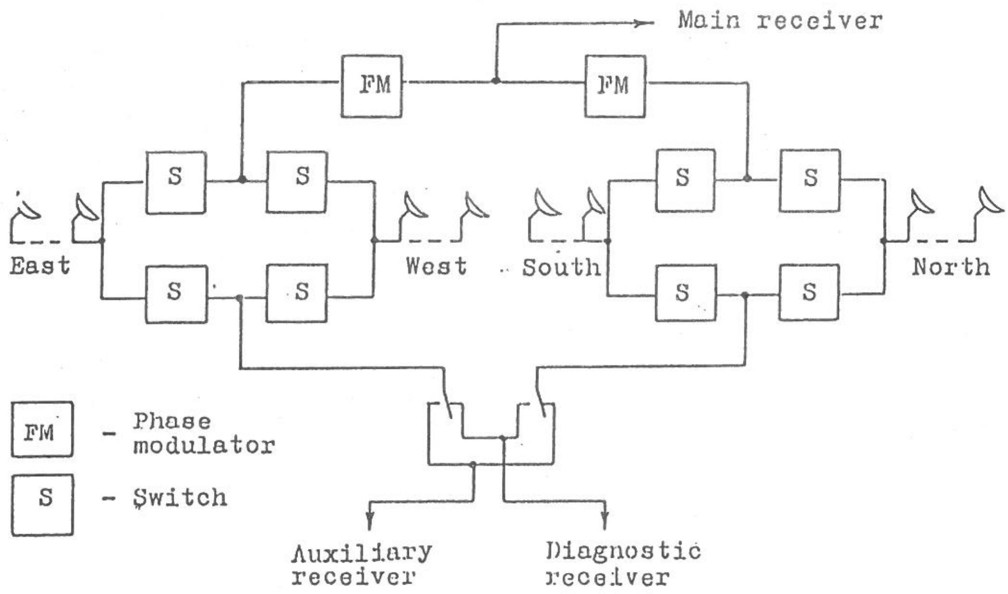
The geodetic network is checked and the SRD coordinates are mea-

F i g. 2. A general view of a separate antenna element of the SSRT

sured every day. The results show a satisfactory stability of adjustment. A minor correction was made once in the last three years for a part of the antennas.

The SSRT antenna elements consist of parabolic dishes 2.5 m in diameter, with the Cassegrain reflector system. The polarized emission is separated with the help of modulators working by the principle of Faraday rotation of the plane of polarization. The SRD drive is based on stepping motors.

Signals are added according to a classical stage-parallel circuit via rectangular waveguides. For equalizing electrical lengths, the first 4 stages of the adding circuit utilize waveguide inserts



F i g. 3. Scheme of remote control of the connection of the antenna arrays and of receiver input switching of the SSRT

and phase shifters with manual control. The other stages contain phase shifters with remote control.

The attenuation in the channels is compensated via 16 transistor amplifiers installed at the output of each 16-antenna group and 4 amplifiers at the output of each 64-antenna arm of the SSRT. The amplifiers feature a noise temperature of less than 800 K and an amplification of about 20 dB. In conjunction with the amplifier, there is an attenuator for accurate equalization of the responses from the antenna groups. In front of the amplifiers of the groups the amplitude modulators are installed.

The connection of the SSRT arms and the switching of the receiver inputs is done by remote control via the mode control circuit (Fig. 3). Each of the orthogonal arrays has two outputs - for operation with the linear interferometer and for forming the crossed interferometer.

In the crossed mode the signal multiplication uses a phase modulator 0-π realized according to a two-channel scheme with circulators and diaphragms with nipin-diodes. The achieved results on minimizing the spurious amplitude modulation in the working frequency range of 0.5% do not permit some undesired effects to be eliminated when operating in this mode. Therefore, provisions are made for operation of two modulators at different modulation frequencies which complicates the receiver circuitry but removes the spurious modulation problem. The beam adding system makes it possible to operate simultaneously several receivers.

F i g. 4. One of the parts of the waveguide conduit

For convenience of servicing and to improve the phase stability, the waveguide transmission line of the SSRT as well as control cables are laid in the underground tunnel 2.5 m in diameter (Fig. 4), whose base lies at a depth of 3.5 m. The control peripherals and secondary power sources are also installed in special holes there. The holes are located at geometrical centers of each of the 16 antenna groups. The receiver systems and the computer complex are installed in a building separated from the SSRT center by 30 m.

Receivers. The principal receiver of the SSRT with the overall transmission band of 112 MHz contains 180 channels. Each channel with the transmission band of 500 kHz features two subchannels for separating the intensity signal (at the modulation frequency of 1000 Hz) and the circular polarization signal (at the 70 Hz frequency). In order to expand the dynamic range, an SHF-attenuator with steps of switching the attenuation of 1 dB and with total attenuation of 40 dB is installed at the input, and an attenuator operating at steps of 4 dB is installed in the intermediate-frequency transmission line. The time constants of the channels are 0.2; 0.6 and 1.4 s. The second receiver features the same parameters but covers only one-fourth of the principal receiver band (28 MHz) and contains 45 channels.

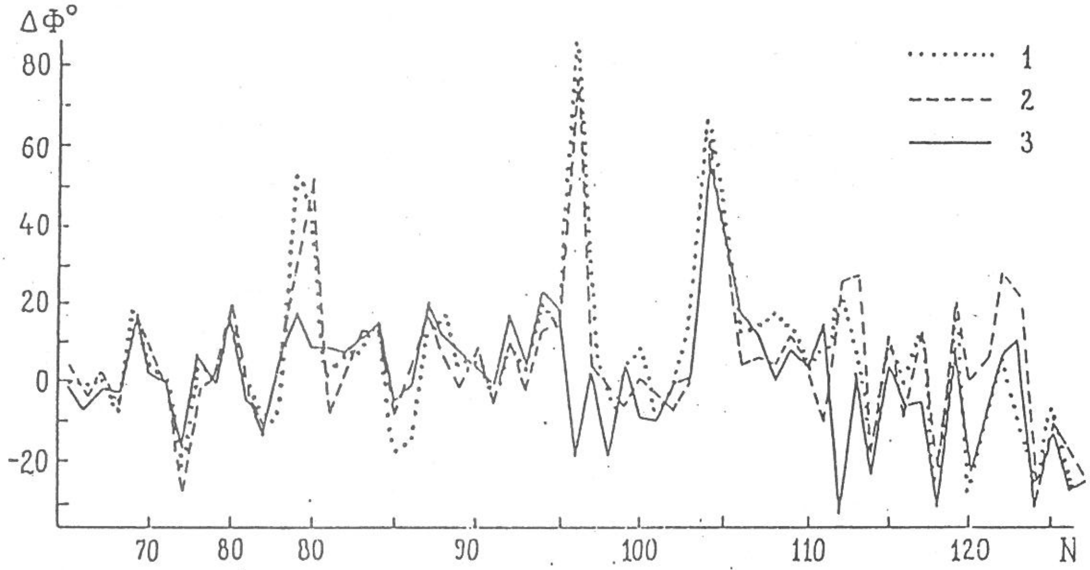
The diagnostic receiver that is designed to control the antenna-feeder system parameters, includes 4 wide-band channels covering the 112 MHz band. Low-frequency units of the receiver contain special filters and demodulators for separating the signals under investigation.

The control complex. The complex controls the solar tracking by the antennas as well asgathering and processing data for SSRT diagnostic systems. The control complex of antenna tracking includes a central computer and a sequential CAMAC branch. A group control method is chosen (a group includes 16 antennas). Controllers of the sequential branch in the groups control, via drive units of the stepping motors, the antennas of a relevant group in two coordinates [12]. Owing to the high reliability of the stepping motors, it was possible to manage without the feedback in the system. The software of the tracking subsystem includes both the antenna array control programs themselves and the test support which makes it possible to determine the serviceability of separate elements. The functions of the control programs include the tracking, the return to the desired position, control of separate groups in the chosen mode, and entering accompanying data into the protocols.

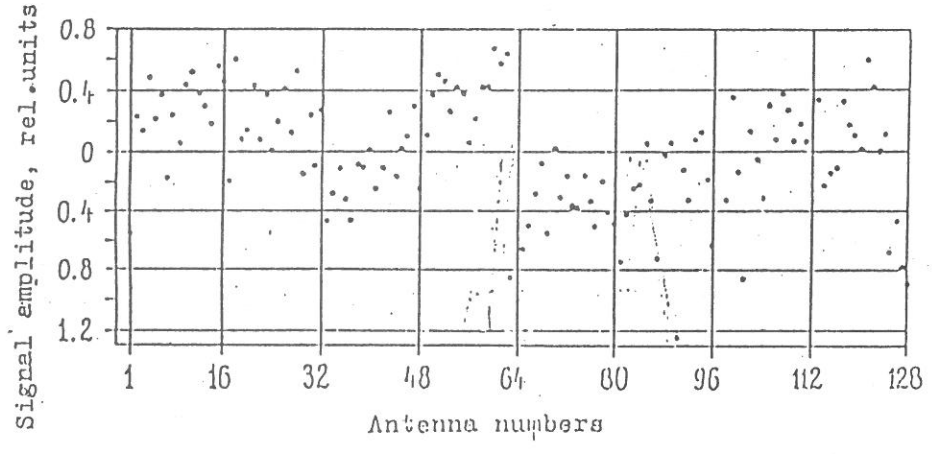
The large number of SSRT antennas, combined with the use of waveguide transmission lines with amplifiers, have dictated the need to generate a system of operative checking of the amplitude-phase distribution in the instrument aperture.

In order to measure the phase difference of the interferometer antennas, it is the most convenient to use the adjustment method based on cosmical radio sources. For improving the efficiency of measurements, it is appropriate to use the most powerful radio source, the Sun, but in such a case it is necessary to take account of the variability of radio brightness distribution over its disk.

The adjustment method adopted for the SSRT [13] virtually excludes the influence of the above factors. It is based on comparing the phases of the pair of antennas investigated and the primary standard, which is represented by the fundamental harmonic of the linear array response: in the case of a large number of antennas the phase of the fundamental harmonic differs little from zero even at a significant value of phase defocusing of separate antennas. The array response and the signal of the chosen pair of antennas are measured simultaneously; for this purpose, an additional modulation of the signal of these antennas is introduced. In order to improve the sensitivity, the receiver uses a sufficiently wide frequency band - 40 MHz. As a result, the r.m.s. error of measurement of the phase in the aperture of the 64-element arm, with the modu-



F i g. 5. Differential phase distribution of the field in the aperture of the 64-element antenna array. 1 - 29 September, 2 - 30 September, 3 - 1 October 1986



F i.g. 6. Amplitude distribution of the field in the aperture of the 128-element antenna array lation depth of the interference pattern in the two-antenna interferometer response, equal to 0.3, is about 4° (according to experimental data). Fig. 5 gives an example of the results of measurements of the differential phase distribution by the eastern arm for three days. The curves in Fig. 5 coincide rather well, which indicates the stability of the phase distribution (separate large deviations of the phase are attributable to the conduct of repair).

The phase distribution in the SSRT aperture is taken systematically several times per season as well as upon performing repairs which distort the amplitude-phase distribution. The amplitude distribution is also measured from the solar radio emission through the alternative modulation of the antenna signals, with the outputs of all the other antennas switched off. These measurements are done 1 or 2 times a day. The time required for controlling the amplitudes of one SSRT arm is about 3.5 min. Fig. 6 presents a typical amplitude distribution in the interferometer amplitude.

The result of operation of the diagnostic subsystem includes the obtained data on the state of the antenna array on magnetic tape, the graphical representation of the operational system, and a control package for the SSRT elements.

<u>The recording system</u>. The recording system is organized on the basis of micro-computer "Elektronika-60" with the pertinent set of CAMAC-modules. The complex consists of two identical systems, one of which is connected to the principal receiver, and the other is connected to the other two receivers. Data digitizing uses 12-digit analog-to-digital converters. The prepared information is written from the buffers on magnetic tape or a disk. The recording program algorithm makes it possible to introduce, in the interactive mode, the service data, choose the required frequency channels for the recording, vary interrogation intervals of the channels, and to choose the needed set of apparatuses. In order to secure an improved reliability, the program is contained in the permanent memory.

<u>In-line processing and storage of data</u>. The in-line processing of data at the SSRT is conducted in three directions:

1) diagnostics of the SSRT systems;

2) obtaining primary data on active regions (their structure, dynamical features, coordinates, the degree of polarization), including those for evaluating the operation of the antenna array and of the receivers;

3) sorting, packaging and coding of data designed for long storage.

Data entering the recording system are written on magnetic tape in blocks of 1016 bytes each. Each block contain data from different channels of the receiver; therefore, at the beginning of any processing program, unpack and sorting of records for the channels and the individual processing of each channel are made [14].

The results of observations during the day are used to construct, by the method of synthesis from the various SSRT arms, a radio map of the Sun [15] which is employed for in-line analysis of the location of active regions and for constructing synoptic maps. Other kinds of the processing associated, for example, with the study of dynamical features, the location and radio emission fluc-

F i g. 7. Solar radio brightness distribution, integrated over 60 one-dimensional scans

tuations of active regions are carried out occasionally by some interested investigators, for example [16].

Since 1988 the "Solnechnye dannye" Bulletin of the Main astronomical observatory (Pulkovo) has published daily scans obtained in the East-West line during culmination.

The SSRT archive contains, as a rule, records of one-or-two frequency channels taken mainly with the help of the East-West line on magnetic tape in files with blocks of 512 bytes each.

Conclusions

It is planned to commission the SSRT in a complete configuration for observation with a two-dimensional directivity pattern in 1990. However, the availability in the SSRT facility of two mutually orthogonal 128-antenna arrays has made it possible to do systematic observations of the Sun with high one-dimensional resolution during the day for a number of years. The results of such observations enable us to investigate the structure and space-time peculiarities of the development of active regions [17,18], transient processes in their atmospheres [19-21], flare buildup and evolution processes [22], and signatures and criteria for their geoeffectiveness [23]. As has already been mentioned, an overview of some of these results is presented in [5].

The effective response of the microwave emission to emergence into the solar atmosphere of new magnetic fluxes and their interaction with those which emerged earlier, the origination and development of active regions, and their flare activity and fluctuations have demonstrated the promising prospects for research using the SSRT in a number of crucial directions of solar physics. The SSRT has received a high appreciation and recognition by leading specialists in the field of solar physics and solar-terrestrial relationships.

The forced nonoptimal realization of some SSRT systems (for example, the 180-channel receiver with fixed frequency characteristics), many-years' experience of adjustment, observations and investigations as well as new technical capabilities govern our plans of modernization and development of the SSRT complex. Work has already begun on the optimization of the receiving-and-recording system on the basis of acoustic optoelectronics [24]. A system of automatized diagnostics of the amplitude-phase distribution of the field in the aperture of the antenna array is near completion [13]. With renovation of computer facilities, the control of the SSRT systems, recordings and processing of data are improved. The development of the program software in this case would increase the frequency of obtaining solar radio maps from observations with the pencil beam. At the same time, work will continue on synthesizing radio maps using one-dimensional scans. Possible modes of observations are run in for various scientific objectives (for example, recording of second pulsations, bursts, etc.) [9]. A complex of auxiliary instruments (radio interferometers with a small baseline for wavelengths of 3.5 and 5.2 cm, radiometers for centimeter and meter wavelengths, a radio spectrograph for the range 70-140 MHz, a photoheliograph, etc.) has been constructed and is further developed, which are required for calibration of the SSRT observations, for achieving high time resolution and for choosing the target and mode of observation on the basis of the state of solar activity as well as obtaining additional information on the development of activity in the solar atmosphere.

The authors express their gratitude to the staff-members of the Radio Astronomy Department for their active and interested involvement in carrying out activities on putting the SSRT in operation,

running it in, modernization and development, the conduct of systematic observations, and the development of investigations in the above-mentioned directions of solar activity physics. Without their help the unique instrument and, all the more, the present paper would be non-existent.

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Scientific objectives of SSRT

- systematic daily diagnostic of the state and evolutionary features of solar activity at microwave range
- the structure and evolution of AR at all stages of their development
- dynamical peculiarities and transient processes in the atmosphere of AR's
- buildup sign and geoeffectiveness criteria of flare processes
- space-time peculiarities of development of flare
- the relationship of the morphological and temporal development of microwave emission range and other ranges in order to study the three-dimensional picture of the structure and development of AR and flare processes
- processes: of emergence of magnetic field into the solar atmosphere

  : of the interaction of them with previously evolved magnetic configurations

  : magnetic field energy accumulation and release

  : acceleration and escape of geo-effective high-energy particle fluxes

I Requires to SSRT

1. only for solar activity
2. monitoring of state of s.a.
   - all AR's simultaneously
   - full disk of Sun
   - sufficiently interval of space frequencies
     - .. all solar disk
     - .. large-scale phenomena
     - .. complexes of AR
     - .. AR
     - .. ditail of structure of AR
       - ... at least main its parts
3. Monitoring of development of s.a.
   - all AR's simultaneously
   - full day observations
   - every day
   - dynamic interval ~ 10^4
     - .. for flare phenomena
     - .. from QS to flares
4. fine structure of radioemission of AR
   - angle resolution limited pase instability
     we reach - size of linear array up to $1.2 \cdot 10^4 \lambda$
     - space resolution 17''
5. work wavelength 5.2 cm
   - take into acount λ's of other instruments
   - suffient effective mani-festation of AR's and Flares in microwave range

6. Supplementary instruments

- to understanding of development of s.a. on other levels of solar atmosphere
- to choice of programe and mode of observations
  - radio: - Ri and RP's on 3, 5, 8, 10 cm and m λ
    - RISB on 3.2 and 5.2 cm
    - RS on 40-20 MHz
  - optical: - photoheliograph on SSRT
    - SMO, BAO (photo-, chromosphere, corona, mf's, fv's ...)

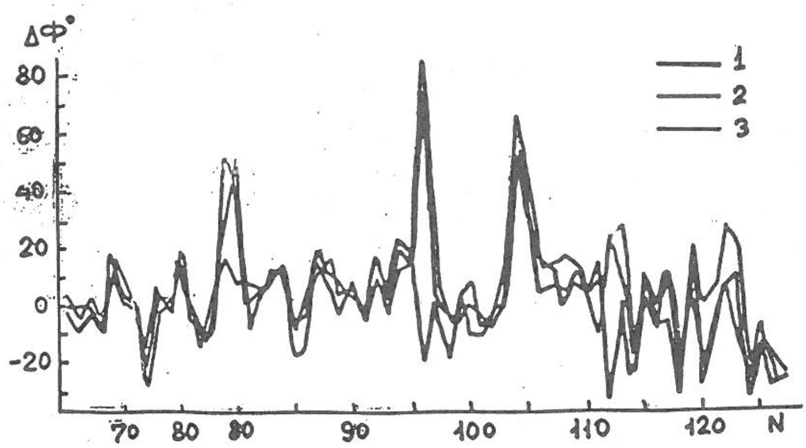
7. Stability in work

- Stable amplitude and phase distribution of field along all base line of array
- high-precision geodetic network provide the accuracy:
  - orientation of beams of array ≤ 2,5'
  - setting of SRD axes in 3 coordinates ≤ ±1mm
  - setting of SRD polar axes ≤ 2'

8. Limitation for SSRT

- large temperature interval ± 40°C
- depth of freezing of soil ~2,8 m
- latitude ~ 52°N

  limite time observation in winter upto 02-08 UT (in summer 23-11 UT)
- Seismological activity near Lake Baikal up to 10 balls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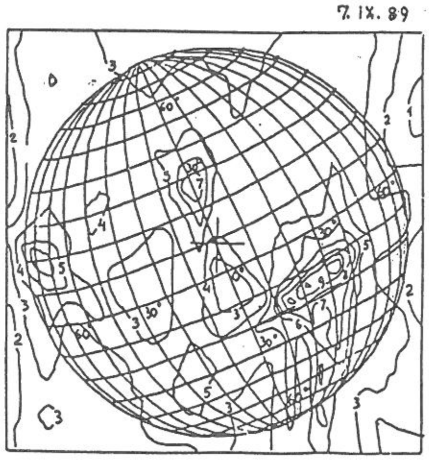
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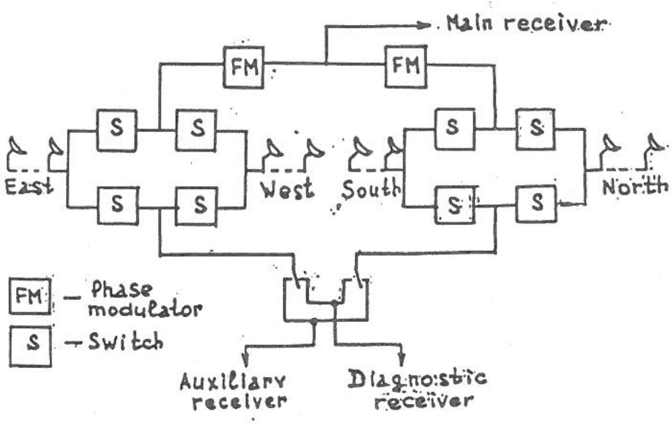
Main receiver
FM
FM
S
S
S
S
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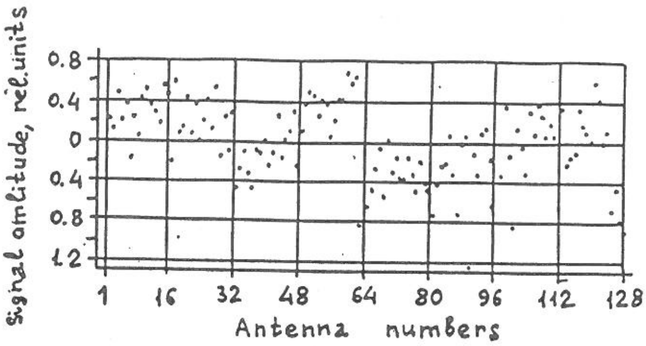
S
S
S
East
West
South
North
FM — Phase modulator
S — Switch
Auxiliary receiver
Diagnostic receiver


Signal amlitude, rel.units
0.8
0.4
0
0.4
0.8
1.2
1 16 32 48 64 80 96 112 128
Antenna numbers