Chapter 8
The Development of Radio Astronomy Research at the Institute of Radio Physics and Electronics of the Academy of Sciences of the Ukrainian SSR

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Abstract The history of the development of radio astronomy in the Ukraine is described. The construction of unique radio telescopes and radio interferometers operating at decameter wavelengths is of special interest. The results of important studies of the Sun, planets and Galactic sources at these wavelengths are presented. The importance of detecting atomic line radio emission is underscored.

8.1 History of the Development of Radio Astronomy in the Academy of Sciences of the Ukrainian SSR

Radio astronomy research at the Institute of Radio Physics and Electronics of the Academy of Sciences of the Ukrainian SSR (IRFE) began with studies of the propagation of radio waves with various wavelengths (from Very High Frequency to medium-wave) above the interface between two media and in a plasma. This work was first carried out in the Department of Radio-Wave Propagation, which was created in 1945 in the Physical Technical Institute of the Academy of Sciences of the Ukrainian SSR under the scientific supervision of S. Ya Braude. Beginning in 1955, when IRFE was organised, based on the Physical Technical Institute, this work was continued in three departments of the new institute. The most noteworthy of these studies conducted at that time (Braude, I. E. Ostrovskii, Ya. L. Shamfarov, I. S. Turgenev, A. V. Megn, A. I. Igrakov, V. F. Shul'ga, O. N. Lebedeva and others) include studies of the propagation of short-, intermediate- and medium-wavelength radio waves above the surface of the sea and the scattering of such waves by irregularities in the sea surface. This led to the emergence of a new area of research, called radio-oceanography, which is still being developed today.

Radio-oceonographic studies required directive antennas to radiate signals and then receive the scattered signals from particular areas of the sea surface, with the possibility of rapidly changing the direction of the antenna beam in space. In contrast to centimetre, decimetre and metre wavelengths, which were used for radar at that time, the need to develop electrical rather than mechanical methods for directing the antenna beam of a radiating system arose for short- and more long-

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wavelength radio waves. At that time, only one highly-directive short-wavelength antenna was known: the "Musa" antenna, with electrical pointing of the beam in hour angle, which was developed in the 1930s for short-wave communications between the USA and England. Research carried out by scientists in the Department of Radio-Wave Propagation (Braude, Megn, Ostrovskii, V. S. Panchenko, Yu. V. Poplavko, Shul'ga) concerned antennas designed for the directed radiation of signals and the reception of such signals scattered by the sea surface operating at short and intermediate wavelengths. Some of these antennas already incorporated electrical pointing of the beam in azimuth. The principles of antenna construction and methods for battling with various types of decametre-wavelength interference that were worked out during this research were subsequently used in the development and construction of a series of decametre-wavelength radio telescopes of the Radio Astronomy Division of IRFE.

Simultaneous with studies of the propagation of radio waves above an interface such as the sea surface, the conditions for the transmission of such waves through a plasma such as the solar corona were also considered. This question is relevant in relation to possible radar sounding of the solar corona. Work dedicated to the idea of radar studies of the Sun was carried out in 1957 (F. G. Bass, Braude). Computations suggested that such studies could be successfully carried out if frequencies from 10 to 40 MHz (decametre wavelengths) were used. A computational effective area for the receiving and transmitting antennas of about 10^5 m^2 was required for a mean transmission power of 10^5–10^6 Watt. This spurred on the desire to carry out work in radio astronomy at decametre wavelengths; the question of designing highly directive antenna systems operating at these wavelengths capable of tracking various cosmic objects was simultaneously addressed. Given the difficulties in building such a powerful transmitter, it was decided in 1957 to first construct only the receiving part of the system, which could also be used for a variety of research in observational decametre-wavelength radio astronomy. A new scientific department was organised at IRFE in 1958—the Department of Cosmic Radio Astronomy, headed by Braude. In that same year, IRFE was given a plot of land 140 hectares by 80 km in size to the southwest of Khar'kov near the Grakovo station, to be used for experimental research.

The main task of the newly created department was the final selection of the main research directions to be pursued, the establishment of a radio astronomy observatory and carrying out observations for various programmes. As is noted above, one possible research direction was connected with decametre-wavelength radio astronomy. A small number of such studies were carried out in Australia and England at the end of the 1960s. In a number of cases, the results of different studies contradicted each other, even those for the most powerful sources (Cassiopeia A, Cygnus A, Sagittarius A, Virgo A). At the same time, numerous data on discrete radio sources, the Galactic radio background, neutral hydrogen, and the Sun, Moon and planets had been obtained at metre and decimetre wavelengths. Together with this direction, the possibility of conducting observations at higher frequencies was also investigated. It was obvious that it would be fruitful to pursue radio astronomy research at metre and shorter wavelengths only if IRFE could acquire an instrument whose capabilities were no lower than those possessed by radio telescopes belonging to other observatories.

By the end of the 1950s, the Large Pulkovo Radio Telescope (see Essay 4) had been built, as well as the fully steerable 22-m parabolic radio telescope of the Lebedev Physical Institute (see Essay 1). These had begun to make observations at decimetre, centimetre and millimetre wavelengths. Several fairly large radio telescopes had also been constructed outside the Soviet Union, including the 76-m radio telescope of the Jodrell Bank Observatory in England, intended for observations at metre and decimetre wavelengths. Therefore, it was decided in IRFE to develop the design for a fully steerable parabolic antenna with a diameter of 200 m. A draft design for such a radio telescope with an equatorial mount intended to operate at metre, decimetre and centimetre wavelengths was produced at Khar'kov by the constructional engineer S. I. Kuz'min. The approximate cost of developing and realising this instrument was estimated to be more than 150 million rubles.

Simultaneous with planning for this instrument, the possibility of creating a radio telescope with a large effective area suitable for observations at decametre wavelengths (a decametre radio telescope) was investigated. At first, when it was proposed to use the receiver antenna system only for radar studies of the Sun, an antenna in the form of a multi-dipole horizontal square grid 300 × 300 m in size was considered, which was to be uniformly filled with horizontal turnstile half-wave dipoles. Since radar measurements of the Sun must be carried out at multiple wavelengths, the antenna system was to be broadband, or at least multi-wavelength, with the ability to tune to a number of decametre wavelengths. It was necessary to provide a means for the antenna beam to track the Sun, which, in the case of such a large instrument, could be done only using electronic pointing of the antenna beam. However, when it was decided to also use this radio telescope for a number of other radio astronomy programmes, the chosen square configuration of the antenna proved not to be optimal, since it provided a resolution at 20 MHz of only $3 \times 3^\circ$. An optimal configuration should provide agreement between resolution and sensitivity, or realise the maximum resolution for a given sensitivity. The requirements can be satisfied by a combination of linear antennas having a cross-, T- or Π-shaped form. Based on the reliability of the antenna system and its stability against interference during measurements for various types of programmes, and also the desire to appreciably increase the volume of information that is simultaneously obtained during the observations, an optimal decametre radio telescope should operate over a range of wavelengths; the chosen range of frequencies was from 10 to 25 MHz.

A comparison of the two preliminary telescope designs and a final selection of the research directions to be pursued in radio astronomy was carried out in 1961–1962. The following considerations were the deciding factors. The reflector operating at decimetre and centimetre wavelengths could be constructed only with the involvement of industry, and required the allocation of considerable resources.[1] The participation of the IRFE Department of Radio Astronomy in this work could prove to

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[1] As the development of radio astronomy has shown, this path was not the only possible one. High resolution can be realised using synthesised apertures, very long baseline interferometers, diffraction techniques, such as the occultation of radio sources by the Moon and so forth; however, at the

be quite limited, since the design, manufacture and assembly of a large parabolic mirror, as well as the mechanical elements and drive of the telescope would have to be done by specialised constructional and machine-building enterprises. The radio-technical work in outfitting such an instrument, in which the Department of Radio Astronomy could actively participate, would be important, but only a small part of the overall project. In addition—and this was the deciding factor—it was unlikely to be possible to obtain the necessary large-scale allocations of finances and resources.

A completely different situation came about in decametre-wavelength radio astronomy. The setting up of the antenna grid itself, consisting of a large number of identical half-wave dipoles that were individually manufactured and installed in an antenna field with comparatively low accuracy, of the order of tens of centimetres (about $\lambda_{\min}/10$), could be carried out by a specialised constructional–assembly organisation. However, the main efforts in the creation of such a telescope are associated with the necessary radio-technical development, and the design and manufacture of all the radio systems used—broadband symmetrising and matching devices, high-frequency communications devices, a system for electronic control of the beam, antenna amplifiers, various control devices and so forth. This work could be carried out by staff in the IRFE Department of Radio Astronomy and the experimental facilities of the institute. Estimates of the cost of the proposed decametre radio telescope indicated that it would require about 3 million rubles.

Simultaneous with studies of an effective decametre-wavelength instrument, the potential fruitfulness and possible scientific research directions of this wavelength range were also considered. Decametre wavelengths are the longest for which radio astronomy observations can be done from the surface of the Earth, and are of considerable interest in connection with various mechanisms for the radiation, absorption and scattering of radio waves in space. One such mechanism is the absorption of radio waves in the radiating medium itself, made up of relativistic electrons moving in magnetic fields with velocities close to the velocity of light (so called self-absorption). Analogous effects arise due to distortions of the energy spectra of relativistic electrons at relatively modest energies, the group interactions of electron beams with cosmic plasma observed both in our Galaxy and in the Metagalaxy, the absorption of radiation in clouds of ionised hydrogen and a number of other processes. All these processes can be studied by measuring the spectra of cosmic radio sources at decametre wavelengths.

Measurements of decametre radiation together with data obtained at shorter wavelengths can be used to determine the strength and direction of cosmic magnetic fields, and the distributions of the density and energy of the electrons and other particles. A number of very important physical parameters of normal galaxies, radio galaxies, quasars, supernova remnants, the solar corona etc. can also be derived with such measurements. Almost no such investigations were carried out at decametre wavelengths in the 1950s and the beginning of the 1960s due to a whole range of factors, which proved not to be important at higher frequencies. First and

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beginning of the 1960s, these methods were not yet widely used, and so were not considered in detail.

foremost, the low resolution due to the comparatively small size of existing instruments made it difficult to distinguish signals from individual cosmic radio sources, leading to so called confusion, which limited information that could be derived from observations.

Measurements at decametre wavelengths are also complicated by the influence of the Earth's ionosphere, which gives rise to absorption, as well as amplitude, phase and polarisation fluctuations of the received radiation. Ionospheric effects essentially make observations at long decametre wavelengths from the surface of the Earth technically impossible. Considerable difficulties are also associated with various types of interference in this wavelength range, especially with signals from a large number of short-wave radio stations, which often exceed the intensity of the radiation received from a cosmic source by many orders of magnitude (by a factor of a million or more). In radio astronomy observations, we must also deal with the fact that the temperature of the diffuse radio emission of our Galaxy (the Galactic background) reaches several hundreds of thousands of Kelvin, while this background does not exceed 10 K at centimetre wavelengths. All these factors indicate that most radio astronomy measurements at decametre wavelengths can be effectively carried out only using a radio telescope with fairly high resolution and sensitivity, making it possible to weaken the influence of some of these hindrances.

As a result of such analyses, it was decided to develop a series of radiometer studies at decametre wavelengths at IRFE. Since there was no highly directive, broadband, decametre radio telescope that was electronically controlled in both coordinates and had an optimal configuration existing at that time, there was the danger that it would prove unrealistic to realise such a project in full form through the efforts of specialised project-oriented organisations. Through detailed discussions of this question at the Scientific Council on Radio Astronomy of the USSR Academy of Sciences, at the suggestion of the Chairman of the Council Academician V. A. Kotel'nikov, it was decided to approve a large T-shaped decametre radio telescope, subsequently named the UTR-2. The development and technical design of this project was assigned to the Institute of Radio Physics and Electronics of the Ukrainian SSR Academy of Sciences.

8.2 Decametre Radio Telescopes of the IRFE Radio Astronomy Division

The Department of Radio Astronomy Antennas and Instruments was established at IRFE to carry out scientific and technical work associated with the construction of a large decametre radio telescope. The head of this department, A. V. Megn, supervised the development and construction of all decametre radio telescopes in the IRFE Radio Astronomy Division. No previous experience with building the unique antennas needed for such a radio telescope was available either in the Soviet Union or abroad. For this, it proved necessary to develop and construct several comparatively small test instruments operating from 10 to 40 MHz simultaneous with the

Fig. 8.1 Antenna arrays of the second version of the ID-1 interferometer

planning of the UTR-2 telescope, to address a whole series of scientific and technical questions. First and foremost, such questions concerned the construction of broadband phasing systems for the electronic control of the antenna beam, methods for calibrating all the main characteristics of such radio telescopes, the provision of the required high stability of the receiver against interference while simultaneously compensating the high losses of the antennas, accurately taking into account the influence of the Earth's surface on the characteristics of the instrument, the development of the principles behind high-frequency control of the antenna, the creation of the necessary baseline elements etc.

The first of the small radio telescopes (the ID-1—an interferometer operating at decametre wavelengths) was constructed in two forms: antenna rails extending to braces (1960), and grids of freely standing radiating elements (1961). The second (main) version of the instrument, which was used for measurements at 12–20 MHz, was comprised of two identical, 24-element, horizontal antenna grids receiving linearly polarised signals separated along a line East–West by 332 m (Fig. 8.1). Each of the antennas had an area of 24 × 48 m and four rows of six dipoles oriented East–West. All the dipoles were placed at a height of 4.5 m above the ground and were oriented along the interferometer baseline; the distance between the dipole centres along and orthogonal to the rows was 8 m.

The radiators were horizontal, symmetrical, broadband shunt dipoles. Each dipole consisted of two wire cylinders 1 m in diameter and 3.75 m in length, which were attached to a vertical metal mast with metallic isolators (shunts). The radiator signals were summed using a two-stage circuit, and were phased using a one-stage, parallel circuit. The radio telescope was intended for interferometric measurements on a single baseline, to be used as a meridian instrument (with electronic control of the antenna beam in one coordinate—declination). This radio telescope already made use of antennas consisting of broadband dipoles, with a well matched, screened, parallel circuit for feeding the radiators and very simple broadband sys-

Fig. 8.2 Western ID-2 antenna

tems for matching the input resistances of the radiators and the wave impedance of the antenna, and with electronic control of the beam via hand switching of the time delays in the rows of feeds. However, due to insufficiently good matching between the radiators and the phasing system, and also due to the lack of good isolation for all the high-frequency communication elements, the ID-1 could only approximately be considered a broadband instrument, since its characteristics were very wavelength dependent within the operational wavelength range. The ID-1 radio telescope was immediately followed by the construction of the more modern ID-2 (Fig. 8.2).

The ID-2 radio telescope, built in 1962, was able to carry out measurements at 20–40 MHz. It consisted of two rectangular antenna grids 16.5 × 176 m in size, separated by 470 m along a line East–West. These grids, which each contained 128 broadband radiators, were orthogonal to each other: the western antenna consisted of four rows oriented North–South with 32 parallel dipoles in each row, while the eastern antenna had four rows oriented East–West with 32 co-linear dipoles in each row. The orthogonal mutual orientation of the antennas, each of which was highly directive only in one plane, provided high directivity for the radio interferometer in two planes, corresponding to a pencil beam. The radiators in both antennas were symmetrical, horizontal shunt dipoles 1 m in diameter and 4.75 m long fixed at a height of 3 m above the ground. The distance between neighbouring radiators along and orthogonal to the rows was 5.5 m.

Like the ID-1, the ID-2 radio telescope was initially a meridian instrument, with electronic control of the beam only in declination.[2] In both of the ID-2 antennas, the radiators were fed using multi-stage, matched, unisolated circuits. In the western

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[2] The ID-2 was subsequently modernised to enable simultaneous measurements on two baselines (470 m and 88 m) by dividing the eastern antenna into two identical sections. In this case, the eastern antenna began to also be phased in its second coordinate—hour angle.

antenna, there was first a cophased summation of the signals of the four colinear dipoles (along the short rows from West to East) in 32 identical adders. The electronic pointing of the beam at one of 256 possible positions in a ±90° sector in zenith angle was carried out using a three-stage temporal phasing system consisting of 21 phase transformers, through which the short rows of dipoles were fed. In the eastern antenna, there was a cophased summation of the dipole signals in the rows (from West to East) using a three-stage parallel circuit, with every four added in the first two rows and every two added in the last two. The signals of the rows were phased using a single phase transformer, providing 32 positions of the beam in a ±90° sector in zenith angle. The phasing apparatus for these antennas consisted of discrete temporal delay lines constructed according to the duality principle, that could be switched using high-frequency relays that were controlled remotely. An economical asynchronous means was used in the control apparatus for the beam of the western antenna, when the number of beam positions (multiplicative factors) for various stages of the phasing was chosen to be different—from the minimum for the least directed multipliers for the first stage of the phasing system, to the maximum for the beam of the entire antenna. To optimise the characteristics of the radio telescope, the ID-2 antennas, like the ID-1 antennas, used simple broadband matching of the input resistances of the dipoles and the wave impedance of the system for phasing and feeding the receivers. To reduce the influence of losses on the receiver sensitivity, antenna amplifiers made according to the standard broadband scheme were implemented at the antenna outputs. Although there is no doubt that this radio telescope was more efficient than the ID-1, it had insufficient resolution and sensitivity, and it was not able to provide the accuracy in the calibration of the main characteristics of the antennas required for precision absolute measurements, due to insufficient isolation in the chains for feeding and phasing the dipoles, as well as non-optimal matching with the phasing system.

The third-generation UTR-1 (Ukrainian T-shaped Radio telescope, first model), developed and built in 1963–1964, was appreciably more modern. Its main characteristics were studied in 1965, and the UTR-1 was introduced into regular use beginning in 1966. This instrument, which operated at 10–25 MHz, had a T-shaped configuration that was close to optimal from the point of view of matching its resolution and sensitivity. Its beam was highly directive in two planes, and was formed by multiplying the antenna beams of the two mutually perpendicular antennas, each of which was highly directive in only one plane. The first antenna of the URT-1 was oriented North–South, had a length of 600 m and was comprised of 80 dipoles forming a single row. The second antenna was oriented East–West, had a length of 576 m and was comprised of 128 dipoles forming two rows. Both of the UTR-1 antennas was designed to receive linearly polarised radiation, and was made of individual broadband, horizontal, symmetrical shunt dipoles with a diameter of 1.8 m and a length of 8 m. All the dipoles were fixed at a height of 3.5 m above the ground and were oriented East–West. The dipoles were all separated by 9 m East–West and 7.5 m North–South, including the nearest dipoles in the East–West and North–South antennas (Fig. 8.3).

The radio telescope beam was controlled electronically in both coordinates at a distance: in zenith angle within ±80° and in hour angle within approximately

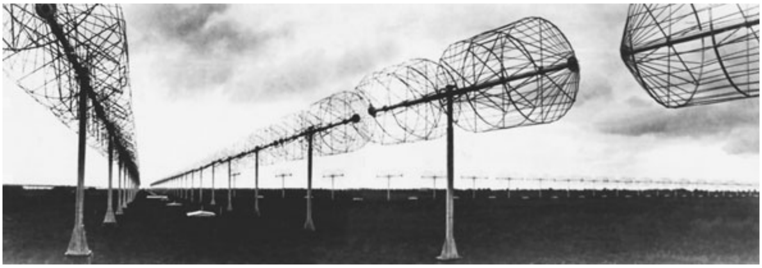

Fig. 8.3 North–South antenna of the UTR-1 radio telescope, comprised of 80 oscillators

±1.5 hours. Broadband, discrete (on temporal delay lines) phasing systems were used for this purpose: two to control the antenna beams and a third for their mutual phasing. A six-stage asynchronous phasing system providing 512 beam positions in zenith angle was used in the North–South antenna. In the East–West antenna, the beam control in zenith angle was carried out using a one-stage circuit that provided 16 beam positions, and the control in hour angle using a five-stage cophased circuit with seven beam positions.

Broadband, hybrid, directive devices were used in all the UTR-1 phase rotators and signal adders, which provided good isolation between all the high-frequency channels. Thanks to this, all of the radiator tracts displayed virtually no reaction to the other high-frequency chains of the antennas, which helped ensure good stability of their characteristics and high reliability in their operation. To optimise the characteristics of the radio telescope (decrease their frequency dependence and realise the maximum sensitivity), broadband matching of the input resistances of all the radiators and the wave impedances of the phasing system was implemented using individual reactive four-terminal circuits with symmetrising dipole devices at their inputs. For this same purpose, high-sensitivity, interference-stable antenna amplifiers based on a multi-terminal circuit were used at the antenna outputs (before the system bringing about their mutual phasing). In the development and construction of the UTR-1, much attention was paid to accurate investigations of its main characteristics (the directive antenna gain, efficiency, effective area, antenna beam, side-lobe level etc.), taking into account all factors influencing the accuracy of measurements (interfaces, the ionosphere). Precision antenna measurements were carried out using a specially developed, automated apparatus and the radiation of strong cosmic radio sources and the background radiation, as well as computational and theoretical methods. Thanks to all these measures, the UTR-1 became an instrument that was suitable for absolute, accurate measurements of the intensities of cosmic radio sources. The maximum effective areas of the North–South and East–West antennas without allowing for losses (when the beam was pointed at the zenith and at the lowest frequency) were 1.5×10^4 and 1.2×10^4 m^2, respectively; the maximum resolution (when the beam was pointed at the zenith and at the highest frequency) was $35'$ North–South and $80'$ East–West.

After these instruments were built, each was used to investigate various questions associated with the construction of optimal, precision, broadband, decametre radio telescopes with electronically controlled beams, as well as for a wide range of radio astronomy programmes. The results of this work were published in more than a hundred articles and reviews; some of the results will be presented below. We emphasise that the series of theoretical and experimental (including technical) studies carried out by researchers at IRFE on radio astronomy antennas (Megn, L. G. Sodin, Yu. M. Bruk, N. K. Sharykin, P. A. Mel'yanovskii, G. A. Inyutin, N. Yu. Goncharov, V. P. Bovkun) and radio astronomy (L. L. Bazelyan, I. N. Zhuk, B. P. Ryabov) during the construction of the antennas and radio apparatus for the decametre radio telescopes, especially the UTR-2, led to a complex of new electronically controlled antennas. The principles of constructing such antennas proposed in these works can be used to built precision decametre instruments that are technically comparatively simple and reliable. The most characteristic properties of these antennas are their use of multi-element antenna grids consisting of broadband radiators with optimal configurations; an electronically controlled broadband beam in either one or two angular coordinates created using temporal phasing systems; isolated, multi-stage, parallel circuits for feeding and phasing the radiators with synchronous and asynchronous methods for pointing the beams; and discrete remote switching of the temporal delay lines, constructed according to the duality principle. The investigations carried out included theoretical calculations of the directive gains and efficiencies of large antennas near the semi-conducting interface (Sodin); development of a method for matching the frequency-dependent input radiator impedances in broadband, electronically controlled antennas in two angular coordinates and the wave impedances of the phasing system (Megn, Mel'yanovskii); theoretical analyses of electronic, asynchronous systems for beam control (Bruk, Sodin); and the creation of optimal, multi-stage distributive antenna-gain circuits based on interference-stable, multi-terminal amplifiers (Megn, Bovkun, K. A. Babenkov). In addition, principles for the accurate high-frequency control of large electronically controlled antennas were developed (Megn, Mel'yanovskii), and work was carried out on the creation of broadband baseline elements, discretely switchable temporal delay lines (Bruk, Inyutin, Mel'yanovskii, Sharykin, Goncharov) and new automated measurement technology (A. V. Antonov, Bovkun, Megn), as well as a number of other topics. The results of these studies have wide applicability in receiver and measurement technology and the technology of long-distance, short-wavelength links.

The most recently constructed decametre-wavelength telescope of IRFE—the UTR-2—was planned and erected from 1964–1969, was tested in 1970–1971, and began to be used for regular scientific observations in 1972. The technical work on the development of the UTR-2 (Braude, Megn, Sodin) foresaw the creation of a highly sensitive instrument that had a high directivity in two planes, a resolution (at its highest frequency) of about $30 \times 30'$ and an effective area (without taking into account losses) no lower than 10^5 m^2. The calculated sensitivity of the radio telescope (5–10 Jy) was expected to yield a volume of scientific information at decametre wavelengths for its main programs that was comparable to that obtained in the better studied metre- and decimetre-wavelength regimes.

Carrying out precision absolute measurements required referencing of the main instrumental characteristics in a broad field of view and over the full range of operational frequencies. Due to the influence of the refraction of radio waves in the

Fig. 8.4 North–South antenna of the UTR-2 radio telescope, comprised of 1440 oscillators

ionosphere in the case of highly directive antennas, the radio telescope was to have a multi-beam (in terms of zenith angle) antenna beam. The use of the UTR-2 for various scientific research required a rapid and operative change in the beam orientation in both planes, in accordance with a specified programme. The radio telescope was to be distinguished by high reliability and a simple construction.

Like its smaller cousin the UTR-1, the UTR-2 radio telescope was intended for operation at 10–25 MHz, and had an optimal T-shaped configuration that ensured matching of its resolution and sensitivity. The antenna systems, which occupy about 16 hectares, consist of two multi-element grids placed so as to enable regulation of the beam sidelobe level in both planes. The first antenna is oriented North–South, has a length of 1860 m and a width of 54 m and contains 1440 radiators forming 6 rows from North to South with 240 parallel dipoles in each (Fig. 8.4). The second antenna is oriented perpendicular to the first antenna (East–West) at its centre, has a length of 900 m and a width of 40 m and consists of 600 radiators placed in 6 rows from North to South with 100 co-linear dipoles in each row. The resulting pencil beam for the radio telescope as a whole is formed by multiplying the beams of the two individual antennas. The size and arrangement of the dipoles is the same as for the UTR-1. The maximum total effective area of the antennas (at 10 MHz with the beam pointing at the zenith) without taking into account losses is 152 000 m^2, and the minimum half-power beam width (at 25 MHz with the beam pointing at the zenith) is $30 \times 30'$.

The circuit for feeding the dipoles of both antennas is multi-stage and parallel with good broadband isolation of all the high-frequency tracts. The broadband input resistances of each dipole are optimally matched to the wave impedances of the feeding and phasing system, taking into account the dependences of the input resistances on the frequency and the two angular coordinates determining the pointing direction of the beam. The radio-telescope beam is pointed electronically in the sector from -30 to $+90$ in declination and from ± 3.5 hr to ± 12 hr (depending on the declination) in hour angle. This is brought about by five phasing systems: two are used in each of the antennas to point its beam in the two angular coordinates, and the fifth is used to mutually phase the antennas. All these systems are broadband, constructed according to the duality principle, and make use of temporal delay lines with discrete remote control. The two most complex phasing systems, which control the highly directed multipliers of the antenna beam, are based on a multistage, asynchronous circuit, while the remaining phasing systems use a single-stage, synchronous circuit. In the field of view indicated above, $2^{21} = 2\,097\,152$ beam positions can be used: 2^{11} in declination and 2^{10} in hour angle. The beam position can be changed from the control panel either by hand or by computer, ensuring virtually continuous tracking of a selected object over no less than 7 hours. To allow for refraction in the ionosphere and to ensure stability against interference and efficiency of observations, the resulting UTR-2 antenna beam is formed with five beams separated by half a beam width in declination, each having independent outputs. Observations can be conducted simultaneously on these five beams, and within each beam, at the six decametre frequencies 10, 12.6, 14.7, 16.7, 20 and 25 MHz. In this case, measurements can be taken simultaneously in 30 receiver channels, whose output signals are recorded on tape and then also sent to a computer, where the reduction is carried out in real time by a series of specialised programmes.

To realise the maximum sensitivity of the instrument while maintaining the required stability against interference, compensation for losses in the UTR-2 antennas is performed by a two-stage antenna-amplification system consisting of 21 broadband amplifiers developed specially for this purpose using an optimal multi-band circuit. The UTR-2 beam shape can be adjusted to decrease the effect of confusion, making it possible to decrease the sidelobe level in declination by the introduction of the necessary current distribution, and the sidelobe level in hour angle through appropriate processing of the data.

The good condition of the numerous radio devices incorporated into the UTR-2 is tested using two specialised high-frequency control systems, enabling the operational remote verification of the condition of the antenna networks, and of the entire antenna and receiving apparatus of the radio telescope.

The efficiency and reliability of the UTR-2 have been verified over a decade of nearly continuous use of the telescope. This instrument remains unique to this day in terms of its design, characteristics and abilities, and is fundamentally different from other instruments operating in this wavelength range. However, the resolution provided by the UTR-2 is insufficient for a number of scientific tasks, such as studies of the angular structure of cosmic radio sources. These and other such measurements require a resolution at decametre wavelengths of the order of several arcseconds. Although such resolutions can be provided under specific conditions, such as analysis of scintillations of the intensities of radio sources due to inhomogeneities in the interplanetary medium or observations of the occultation of a source by the disk of the Moon (indeed, such observations are carried out on the UTR-2), the most effective means to obtain this higher angular resolution is by using an array of radio interferometers with sufficiently long baselines. With this goal in mind, the Radio Astronomy Division of IRFE began the development and construction of the URAN system in 1973. The main element of this system was the UTR-2, which forms an interferometer array together with four relatively small radio telescopes, yielding a maximum resolution of about 1 arcsecond. The first interferometer of this system is URAN-1, with a baseline of 42.6 km and a resolution of about 30 arcseconds, and is comprised of the North–South UTR-2 antenna and a second URAN-1 antenna located near the town of Gotbal'd. This instrument was already completed by the end of 1975, after which test observations began. The Odessa Division of the Main Astronomical Observatory of the Academy of Sciences of the Ukrainian SSR (scientific supervisor V. P. Tsesevich) and the Poltav Gravimetric Observatory (scientific supervisor V. G. Bulatsen), in collaboration with IRFE, began the development and construction of the URAN-4 antenna near the village of Mayak in the Odessa region in 1975 and the URAN-2 antenna near Poltav in 1979. These radio interferometers have baselines of 592 and 176 km, and should provide resolutions of about two and about seven arcseconds. The maximum resolution (of about one arcsecond) will be provided by the baseline to the URAN-3 antenna, which will be located near Lvov.

The specialised antenna systems of all the URAN radio interferometers are designed to operate from 12.6 to 25 MHz, and are each comprised of a multi-element, equidistant, rectangular array with an electronically controlled beam in both coordinates. The arrays consist of 128 or 256 radiators. To enable elimination of the influence on the interference measurements of the rotation of the plane of polarisation of linearly polarised radio waves in the ionosphere (ionospheric Faraday rotation), which is very substantial at decametre wavelengths, all the URAN antennas are equipped to receive simultaneously two linear or circular polarisations. For this purpose, tourniquet radiators are used in the URAN antenna arrays, each consisting of two orthogonal, linear, horizontal, broadband dipoles. The dipoles for each linear polarisation have their own broadband feed and phasing systems, based on a multi-stage, synchronous circuit. These phasing systems are controlled in parallel, so that each antenna is made up of two superposed multi-element arrays for the reception of linearly polarised waves, with separate outputs. Photographs of the dipoles of the URAN-1 antenna and the entire antenna array have been taken from an aircraft (Fig. 8.5).

The URAN-1 radio interferometer is intended for interferometric observations in real time, while the remain URAN interferometers are designed for use as a Very Long Baseline Interferometry system.

8.3 Radio Astronomy Studies

As was already noted above, a variety of radio astronomy observations were carried out on all the decametre instruments of the Radio Astronomy Division of IRFE beginning in 1960. Most recently, an especially wide range of observations have

Fig. 8.5 Antenna grid of the URAN-1 system

been conducted on the UTR-2 (from 1972) and the URAN-1 interferometer (from 1975). Of all the decametre-wavelength scientific programmes carried out over these years, the main ones are

(1) measurements of the flux densities of discrete radio sources and compilation of a catalogue of these values;
(2) determination of the angular structures of radio sources (radio imaging) using various methods;
(3) observations of the radio emission of pulsars;
(4) studies of the Galactic background, in particular, of regions of ionised hydrogen (H II regions);
(5) radio spectroscopic observations and searches for various radio lines;
(6) studies of the radio emission of the Sun, as well as of the scattering of radio waves in the solar corona;
(7) searches for and studies of non-thermal emission from planets in the solar system.

We will now briefly discuss some results of these studies.

Among the various objects that are studied in radio astronomy, discrete radio sources are of special interest. About 30,000 such sources are currently known, and this number will, of course, grow with the sensitivity and resolution of radio telescopes. Some of these sources have already been identified with either Galactic (supernovae, gaseous nebulae etc.) or extragalactic (normal, radio, Seyfert and N-type galaxies, quasars etc.) objects. These sources had been studied in the radio primarily at metre through centimetre wavelengths, while observations at decametre wavelengths were much rarer. It was therefore of considerable interest to compile a catalogue of discrete radio sources at decametre wavelengths. Such a catalogue was created using the UTR-2 at 5 to 6 wavelengths from 12 to 30 m. More than 1500 sources have currently been investigated in the area of sky with declinations from $-13°$ to $+20°$ and from $+50°$ to $+60°$, 60 of them discovered for the first time.

Although some of these sources are thermal, the vast majority are non-thermal, especially the extragalactic sources. The main mechanisms giving rise to this non-thermal emission are Bremsstrahlung and the synchrotron mechanism. This is testified to by the frequency dependence of the emission intensity, which usually falls off with increasing frequency in accordance with a power law. In the case of thermal mechanisms, the radio intensity first grows with frequency in proportional to the square of the frequency, then becomes nearly constant at very high radio frequencies. If we plot the spectrum of a non-thermal source—the dependence of the spectral flux density on the frequency—on a logarithmic scale, this dependence is linear, with the slope, called the spectral index (α), being different for different discrete sources. It turns out that the energy spectrum of relativistic electrons whose motion in the source magnetic fields gives rise to the radio emission is also a power law, with index γ. According to the theory of synchrotron radiation, these two indices are related by the simple expression $\gamma = 2\alpha + 1$.

If we proceed from this position, which has been confirmed by observations over a wide range of wavelengths (from centimetres to metres), we can use various theoretical models to predict the frequency spectra of non-thermal sources at decametre wavelengths. In general, we would expect spectra of two types: linear if there are no factors altering the source spectrum, and curved, with negative curvature of the spectrum at decametre wavelengths. The latter type of spectrum should be observed, for example, if there is self-absorption in the source, absorption due to H(II) or some other similar mechanism. Theoretically, there should be many sources displaying self-absorption, since measurements at higher frequencies show quite a few sources where this effect is clearly visible. Observations carried out in the USA and Canada first seemed to support this picture.

A series of investigations were carried out at IRFE, whose goal was to measure the flux densities of discrete sources in order to construct their spectra at frequencies 10–25 MHz (Braude, Zhuk, Ryabov, K. P. Sokolov, Sharykin and others). There are currently data enabling the construction of spectra at frequencies 10–1400 MHz for about 700 sources. The number of such sources will be increased to 1000 in the near future. It turns out that, in addition to the expected two types of spectra described above, two more qualitatively different types of spectra are also observed. The data showed both linear (I) spectra and curved spectra with negative (II), positive (III) and sign-variable (IV) curvature. The relative numbers of sources in these categories are

Type of spectrum	I	II	III	IV
Number of spectra, %	86	3.5	10	0.5

As we can see, the vast majority of sources in this frequency range have linear spectra (type I) and rather few have type II spectra, in contrast to the expectations based on higher-frequency data. A fairly large group of sources has type III spectra, which were not previously observed (with an increase in the spectral flux density with decreasing frequency more rapid than linear behaviour).

To elucidate how discrete sources with different types of spectra differ from each other, the spatial distribution of radio galaxies, quasars, supernova remnants and unidentified objects with type I, II and III spectra were compared. It turns out it is not possible to establish a connection between type of spectra and either spatial location or type of source. The same is true of other properties that were investigated.

This led to the suggestion that, independent of the type of radio source, there exists some common factor leading to these various types of spectra. It was shown (Braude, Zhuk, Megn, Ryabov) that one possible such factor was a deformation of the energy spectrum of cosmic-ray electrons with energies of 10^7–10^8 electron volts. It is precisely at these energies, in magnetic fields of 1–10 milliGauss, that decametre radio waves are generated in discrete sources.

Thus, based on our observations, it was possible to show that, contrary to theoretical predictions, sources with type II spectra are encountered only rarely, while quite a few sources with type III spectra are observed.

A very important conclusion flows from these studies: the vast majority of sources that high-frequency observations show to have features with small angular sizes should show signs of self-absorption. However, as our data show, self-absorption is not observed in most of these sources, right to decametre wavelengths. One possible explanation for this is that decametre radio waves are intensely scattered on inhomogeneities in the plasma in the sources themselves. This scattering could lead to an appreciable increase in the angular size of a source, and so sharply weaken the effect of self-absorption. It is also possible that these sources have extended features or a halo whose spectra are characterised by large spectral indices, and that these features make a substantial contribution to the total radio flux at decametre wavelengths. In this case, we should also observe a corresponding change in the radio images with decreasing frequency. This leads to the need for independent measurements of the angular structures of various types of radio sources at decametre wavelengths.

Four different methods for resolving extended radio sources are being used at IRFE to attack this problem: UTR-2 observations with a narrow antenna beam; analysis of scintillation of the intensity from radio sources on inhomogeneities in the interplanetary plasma; observations of radio sources occulted by the disc of the Moon; and interferometric observations. All of these methods have been intensely applied under the scientific supervision of Braude and Megn, and information about decametre-wavelength angular structure is already available for a number of objects (Vovkun, Zhuk, A. L. Bobeiko, Yu. Yu. Sergienko and, in recent years, S. L. Rashkovskii, I. S. Fal'kovich, Sharykin, V. A. Shepelev and A. D. Khristenko).

For example, results obtained on the UTR-2 using the last three methods have been used to study the decametre angular structure of the important radio source the Crab Nebula. Strip radio brightness distributions at several frequencies have been determined from these observations. The coordinates of the compact source in the Crab Nebula have been measured for the first time at decametre wavelengths, and coincide within the errors with the position of the pulsar NP0532. The relative contributions of the compact source to the total radio flux, measured with very high accuracies for the decametre range, are 0.32 ± 0.03, 0.42 ± 0.04 and 0.55 ± 0.08 at 25, 30 and 16.7 MHz, respectively. This source has a linear spectrum (on a logarithmic scale) at 16.7–122 MHz, with spectral index $\alpha = 2.09 \pm 0.04$. A flattening and turnover of the spectrum at low frequencies is observed for the spectrum of the Crab Nebula without its compact source.

Observations of the quasar 3C196 on the URAN-1 interferometer together with measurements of scintillation of its intensity were used to identify the best model from a number of models that had been considered earlier. At decimetre and centimetre wavelengths, this quasar has two features with angular sizes of no more than $2 \times 2''$ separated by about $5''$ on the sky, while it displays an extended region of radio emission at decametre wavelengths, with the intensities of compact features and extended emission being nearly equal. The extended emission in 3C196 spans about $18''$ in right ascension and $25''$ in declination.

Similar measurements aimed at establishing good models for radio sources for which new and interesting data were obtained have also been made for the supernova remnant Cassiopeia A, the radio galaxy 3C280 and a number of other cosmic radio sources.

Pulsar studies on the UTR-2 began in 1972 (Bruk, B. Yu. Ustimenko). For a number of reasons, it had been considered very doubtful that useful observations of pulsars could be carried out at decametre wavelengths. Nevertheless, using original instruments, it was possible to detect for the first time pulsed structures in the signals for 7 of 12 nearby pulsars observed at 10 to 25 MHz. It was found that the decametre radiation of pulsars is very different from their radiation at higher frequencies. In particular, a larger number of interpulses are observed at low frequencies, which are virtually completely absent at high frequencies. The spectra of the main pulse and interpulses are different, as well as the character of their time variations.

The interpulses arise sporadically, but their location between two neighbouring main pulses is fairly fixed. Interpulses were observed for all pulsars that were detected at decametre wavelengths, with the intensities of the main pulse and interpulses being comparable. Moreover, it was found that the intensity of the main pulse falls with decreasing frequency in the range 16.7–25 MHz, while the intensity of the interpulse grows.

Simultaneous observations of 5 pulsars were obtained over a wide range of frequencies, from 16 to 1400 MHz. These studies were carried out at the Grakovo (Ukrainian SSR), Pushchino and Jodrell Bank (Great Britain) observatories. The frequency spectra of the main pulses and interpulses were measured. The main pulses of the five studied pulsars had their maxima at frequencies of 80–120 MHz, while no such maxima were observed for the interpulses.

The structure of the decametre radiation of pulses is very complex. In addition to the main pulse and interpulses (up to 5 can be observed, with amplitudes form 20 to 100% of that of the main pulse), an extended component was observed, as well as flares of the interpulse emission lasting 30–60 minutes, whose amplitudes and energies could sometimes appreciably exceed those of the main pulse. Although the amplitude fluctuations for the interpulses and the variability of their structures are substantially greater than for the main pulse, the mean profile of the signal proves to

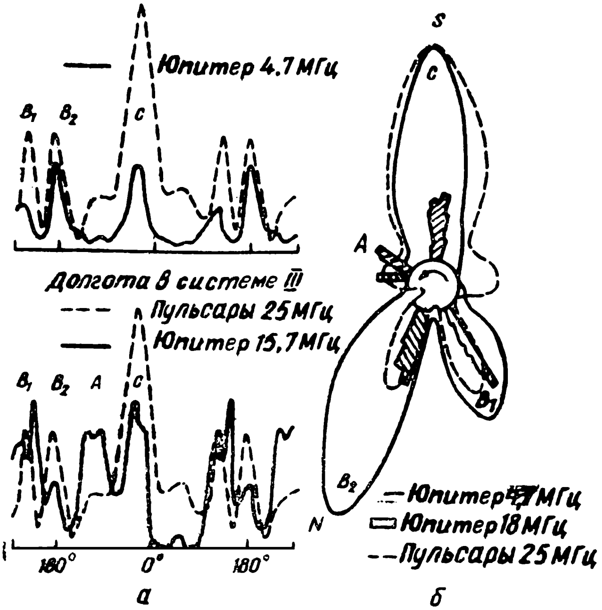

Fig. 8.6 Comparison of the longitude structure of the emission of pulsars and Jupiter. The *upper left text* reads "Jupiter 4.7 MHz," the *middle left text* "Longitude in the system," "Pulsars 25 MHz," and "Jupiter 15.7 MHz," *from top to bottom*, and the *lower right text* "Jupiter 4.7 MHz," "Jupiter 18 MHz," and "Pulsars 25 MHz," *from top to bottom*

be very stable. For many pulsars, it is possible to identify structural elements in the received signals that repeat often and are stable. A comparison of these structures at decametre and shorter wavelengths suggested the presence of common characteristics of all pulsars. As was noted above, there are symmetrically placed zones in the pulsar period where the signal is received.

The presence of such structures suggested there might be a similarity between the decametre radiation of pulsars and of Jupiter (Fig. 8.6). The decametre radiation of Jupiter is manifest as intense, sporadic outbursts with various characters and origins. Above 20 MHz, the structure of the radiation is subject to strong influence due to Jupiter's moon Io.

The longitude structure of the radiation of pulsars and Jupiter was compared. The influence of Io was excluded using longitude profiles of Jupiter at frequencies below 20 MHz. Supposing that the radio emission of pulsars originates at their magnetic poles, the emission regions for Jupiter and pulsars were compared after shifting the centre of the main pulsar pulses to their South poles. The results show that the structures of the impulsive emission of these two completely different types of astronomical bodies are quite similar. This resemblance could be associated with similar configurations for the magnetic fields of these objects (Braude, Bruk). Jupiter has a close to dipolar magnetic field, with the dipole inlined by 10° to the rotational axis of the planet and shifted relative to the centre of gravity. In some theories, the radio emission of pulsar is also explained by the presence of a dipolar magnetic field that is inclined and shifted relative to the centre of the object. Of course, the strengths of the magnetic fields, the inclinations of these fields to the rotation axis and a host of other physical properties are very different for pulsars and Jupiter, but the similarity in the emission structure provides hope that further detailed studies of the radio emission of Jupiter will help bring us closer to an understanding of the physical processes giving rise to the radio emission of pulsars as well.

Stars can form in regions of ionised hydrogen (H II regions). The radio emission of these regions have been studied mainly using so-called recombination lines. Such studies have been carried out primarily at centimetre and decimetre wavelengths. This emission arises fairly deep inside the H II regions, and the derived information characterises precisely the inner parts of the region of ionised hydrogen (see Essay 1).

Observations of H II regions with the UTR-2 radio telescope, which has relatively high angular resolution, open new possibilities for studies of these regions. Some of the background radiation is absorbed as it passes through such regions. Observations of this absorption at decametre wavelengths can be used to determine a number of important parameters of the H II regions, and also to study the non-thermal radiation of the Galaxy. Since the optical depth of an H II region is rather high at decametre wavelengths, the main role in such absorption studies is played by the outer parts of the H II region. Decametre measurements supplementing measurements of recombination lines enable more complete analysis of the structure of such regions of ionised hydrogen.

A specialised method for measurements and calibration on the UTR-2 was developed for such observations (V. V. Krymkin). H II regions were observed using the five-beam UTR-2 antenna beam in a transit mode, with the studied regions passing through the beams due to the rotation of the Earth. Measurements were carried out at 5 frequencies from 12.6–25 MHz. The data obtained were used to estimate the electron density, n_e, and electron temperature, T_e, for a number of H II regions, as well as quantities characterising the distribution of non-thermal Galactic emission. Six H II regions were studied using the UTR-2 images obtained, including NGC1499, for which the values $T_e = 4400$ K and $N_e = 9$ cm^{-3} were derived. These values are in good agreement with measurements carried out at other frequencies, testifying that the outer and inner structures of NGC1499 are similar. The results of such observations of various regions were used to estimate the mean density of non-thermal radio emission along the lines of sight from the Earth to these objects. These estimates coincide with previously determined values, and confirm that there is a higher density of radiation in the arms of the Galaxy than in the inter-arm regions. Thus, observations at decametre wavelengths can provide independent information about the temperatures and densities of H II regions, thereby verifying various conclusions about these structures based on observations at shorter wavelengths.

The methods developed for studies of H II regions were also used to investigate old supernova remnants. One example is the detection and explanation of the low-frequency turnover in the spectrum of a source in the Monocerous Loop. It was concluded that this turnover is due to the presence of ionised material, which directly absorbs the source radiation, as well as the background emission generated along the line of sight toward the source. The resulting drop in the brightness temperature of the background is balanced by the remaining source emission, giving rise to an apparent turnover in the spectrum.

Until recently, studies in the intensely developing area of radio spectroscopy were carried out from millimetre to metre wavelengths. The construction of the UTR-2 radio telescope made possible radio spectroscopic observations at decametre wavelengths. Through such studies (A. A. Konavalenko, Sodin) indicated the possibility of detecting recombination lines of hydrogen with very high principle quantum numbers $n = 630$–650, whose wavelengths are in the decametre range. A special spectrometer with a frequency resolution of 1 kHz and a sensitivity of $\Delta T/T \simeq 4 \times 10^{-4}$ for an integration time of 10 hours was developed for such observations. However, the numerous observations carried out in various areas of the sky did not give positive results, and no such hydrogen recombination lines were detected.

This same equipment was used to attempt to detect a line of neutral nitrogen, ^{14}N. Back in the 1950s, I. S. Shklovskii indicated the existence of two lines of ^{14}N at decametre wavelengths, with frequencies $f_2 = 26.127$ MHz and $f_2 = 15.676$ MHz. Calculations showed that these lines should be observed in absorption with very small optical depths, $10^{-4} - 10^{-5}$. As we can see, these theoretical calculations were not very encouraging; nevertheless, observations were conducted on the UTR-2 with the aim of attempting to detect the presence of nitrogen in space (Sodin, Konavalenko). The experiment was set up to try to detect nitrogen in our Galaxy. It is known from the literature that strong absorption in the 1420-MHz line of neutral hydrogen HI is observed in the direction of the strong radio source Cassiopeia A, which occurs in the spirals arms of our Galaxy—in particular, the so-called Orion and Perseus arms. It was logical to look for nitrogen absorption in this same direction. Thus, the observations made use of a spectrometer, and were carried out on the UTR-2 in the direction of Cass A. Absorption was detected close to 26 MHz, both in the nearer Orion arm and the more distant Perseus arm. The radial velocities in the two arms were different, with the velocity in the Orion arm being about 42 km/s and that in the Perseus arm being near zero. This line was found to be fairly intense for the Perseus arm, but weak for the Orion arm. The Galactic origin of the detected line is confirmed not only by the coincidence of the radial velocities for this line and for the HI absorption in this direction, but also by the presence of periodic variations in the frequency of the line, which coincide with the Doppler shift due to the revolution of the Earth around the Sun. If the detected line is taken to be the sought-for ^{14}N line, the data obtained can be used to determine the nitrogen abundance in these two arms in our Galaxy. In the case of the Perseus arm, the observed optical depth of the line turned out to be 2×10^{-3}, appreciably higher than predicted by the theoretical calculations. Assuming that the spin temperatures for the HI and ^{14}N are the same, for the observed ratio of the densities of HI and nitrogen, the abundance of ^{14}N to HI is about 130–140, instead of the commonly adopted value of 2000.

This discrepancy led American radio astronomers to suggest that the absorption line observed on the UTR-2 was a recombination line of carbon with principle quantum number $n = 631$. They pointed out that this line, in contrast to all recombination lines known at the time, should be observed in absorption rather than emission. If this was the observed line, all the observational data would be in agreement with generally accepted abundances.

Experiments carried out at IRFE in 1981–1982 fully confirmed this point of view. It was possible to push the measurements toward longer wavelengths, and recombination lines of carbon corresponding to transitions from levels with principle quantum numbers up to $n = 732$ were detected.

The solar corona is another very interesting object. Measurements at decametre wavelengths can be used to study high layers in the corona, out to two solar radii. This region is of considerable interest, since it is here that the solar wind is generated, and it is currently poorly studied. Thanks to its large effective area (sensitivity), broadband receivers and antenna beam adjustable in two coordinates, the UTR-2 could be used to derive the two-dimensional distribution of the radio brightness of the Sun. This telescope was thus used to carry out detailed studies of the Sun during partial eclipses.

Studies of the solar corona at distances from 5 to 25 solar radii were conducted by analysing the radiation of discrete background sources that had passed through the solar plasma, and deriving the radio images of these sources distorted by scattering and refraction in the corona. It was found that the increase in the effective sizes of sources inversely proportional to the square of the wavelength observed at metre and shorter wavelength slows at decametre wavelengths. This made it possible to explain some properties of scattering of radio waves on inhomogeneities in the solar plasma near caustics (Bazelyan, Braude, Megn, V. G. Sinitsyn). The observational data that were obtained were used to refine certain parameters of the solar corona.

A large amount of time in the UTR-2 observing programme was dedicated to studying the sporadic component of the solar emission. Together with flares with durations from several seconds to several hours, the decametre observations revealed short-lived flares with lifetimes from several seconds to tenths of a second. These were new manifestations of type III outbursts characteristic only of the decametre range. These flares are elementary events, and are often subdivided in frequency or time, forming chains. In a number of cases, these phenomena were observed to precede ordinary type III outbursts. These observations were carried out on the UTR-2 in collaboration with radio astronomers of IRFE and the Radio Physics Research Institute in Gorkii (Balezyan, E. P. Abranin, Zaitsev, V. A. Zinichev and others).

As is noted above, the theoretical possibility of radar studies of the solar corona was investigated at IRFE as early as 1957; the required power was estimated and an optimal frequency range was selected. These calculations were confirmed by the successful realisation of radar sounding measurements at 25 and 38 MHz in the USA, however the new results were never adequately explained. In 1968–1974, a series of studies was carried out at IRFE (I. M. Gordon, N. N. Gerasimova) dedicated to creating a new theory for the formation of radar signals reflected from the solar corona.

It was shown that all important features in the structure of the reflected signal could be explained if it was supposed that the signal was formed and amplified in turbulent zones of the corona by induced scattering on turbulent pulsations of the coronal plasma. It turned out that the signal was reflected only from regions of the corona above active regions, whereas they were absorbed by the "quiet" corona.

Attempts to use the UTR-2 to detect decametre radiation of planets in the solar system were also made. Such radiation was detected only from Jupiter, which was known to be a powerful source of decametre radio emission. The fine structure of this emission is currently being studied.

Together with experimental work, a large amount of attention has also been given to theoretical studies, which encompass a wide range of questions, from the processes occurring in discrete sources to phenomena in the solar corona (V. M. Kontorovich, A. V. Kats, A. E. Kochanov, Ya. M. Sobolev, Yu. A. Sinitsyn, N. A. Stepanova, V. N. Mel'nik, V. I. Vigdorchik and others).

It is known that astrophysical objects are rarely in a complete state of thermodynamical equilibrium, but nevertheless, many of these objects display nearly universal power-law spectra. For example, power-law energy (frequency) distributions are characteristic of many cosmic-ray sources, for cosmic rays themselves and, in a number of cases, for the optical, X-ray and sometimes gamma-ray emission of sources.

The theoretical studies carried out established a general mechanism for the appearance of power-law spectra, which are characteristic for Kolmogorov turbulence. It was shown to be of considerable interest to study possible ways to form Kolmogorov spectra in astrophysical sources. A number of general properties of power-law spectra in weakly turbulent systems of waves and particles were elucidated. The relationships between equilibrium and power-law spectra were studied, and the corresponding power-law distributions in a strong magnetic field derived. Non-linear spectra obtained due to synchrotron or Compton losses in the case when there is a localised injection of hard particles (in other words, when the source of relativistic electrons is a localised region of high energy) were also studied. It was shown that, in an inhomogeneous source under these conditions, the radiation flux that diffuses outward forms a non-linear spectrum with linear power-law sections, including sections with the "universal" power-law with spectral index equal to two. At the same time, spectra with both positive and negative curvature could be formed. The role of inhomogeneity of the magnetic field and diffusion in "core + halo" sources was studied, and it was shown that the spectra of galaxies with low-frequency turnovers whose rises were not too steep could be explained in this scenario.

In addition to questions associated with the formation of power-law spectra, a number of problems connected with the physics of the solar-corona plasma were studied. In particular, the propagation of electron beams in the corona was analysed, taking into account the inhomogeneity of the plasma. It was shown that a beam of electrons ejected from the region of a solar flare propagates toward regions of lower plasma density. As a result, plasma waves "lag" behind the beam, and come out of resonance with it. Due to this movement of ejected clumps of plasma from resonance in the inhomogeneous corona, the characteristic relaxation length for the beam grows to scales of the order of the dimensions of the corona. This stabilises the beams observed during type III outbursts.

Theoretical studies also examined the role of non-equilibrium conditions in plasma in the solar interior arising due to the nuclear reactions occurring there. It was shown that such conditions are associated with the existence of power-law energy “tails” in the velocity distribution for the elements; due to these high-velocity “tails,” the rates for nuclear reactions involving elements with high Coulomb barriers turn out to be higher than for a purely Maxwellian velocity distribution. Hydrodynamical stability and interactions of surface and internal waves with turbulence was also studied, as well as wind instability in the lobes of radio galaxies.

In this essay, we have briefly examined the results of studies carried out from 1959 through 1980. In 1980, the Radio Astronomy Division was organised in the Institute of Radio Physics and Electronics, by a resolution of the Presidium of the Academy of Sciences of the Ukrainian SSR (L. N. Litninenko was appointed chairman of the Division). In this Division, radio astronomy studies at millimetre wavelengths were begun, alongside continued work at decametre wavelengths. A quantum amplifier operating at 45 GHz that has increased the sensitivity of radiometers in this range by an order of magnitude (to $\Delta T = 0.05$ K) has already been developed and installed on the RT 25-2 radio telescope of the Institute of Applied Physics of the Academy of Sciences.