Chapter 1
Radio Astronomy Studies at the Lebedev Physical Institute

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Abstract The history of the development of radio astronomy studies at FIAN is described, beginning with the first theoretical (1946) and experimental (1947) studies of the solar radio emission. Information about the development of the Crimean station of FIAN, then the establishment and development of the Radio Astronomy Station in Pushchino is presented. Work on the construction of large radio telescopes, including the FIAN 22-m, DKR-1000 and BSA telescopes, is described, together with important results obtained during observations of the Sun (including the discovery of its “supercorona”), planets, line radio emission and studies of pulsars and other discrete sources.

1.1 The First Steps[1]

The important radio physicist Academician Nikolai Dmitrievich Papaleksi (Fig. 1.1) is justifiably considered the founder of radio astronomy research in the Soviet Union. Nikolai Dmitrievich was interested in astronomy and meteorology even in his youth. Before the Second World War, he and Academician Leonid Isaakovich Mandel’shtam considered the possibility of measuring the distance to the Moon using radar methods, by detecting the time delay of a radio pulse sent from the Earth and reflected off the lunar surface. The level of radio technology available at that time (1925) made this appear unpromising. Papaleksi and Mandel’shtam returned to this problem during the years of the Second World War. Their new calculations, published at the beginning of 1946, showed that such measurements were realistic, and indeed, they were carried out in that same year in Hungary and the USA. When it came to thinking of radar measurements of the Sun, Papaleksi gave the young theoretician of the Lebedev Physical Institute (FIAN) V. L. Ginzburg the problem of carrying out the necessary calculations.

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[1] Section 1.1 was written by N.L. Kaidanovskii and A.E. Salomonovich, Sect. 1.2 by V.A. Udal’tsov, Y.L. Kokurin and R.L. Sorochenko, Sect. 1.3 by Y.P. Ilyasov, A.E. Salomonovich and A.D. Kuz’min, Sect. 1.4 by V.A. Dogel’ and Sect. 1.5 by A.E. Salomonovich.

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Astrophysics and Space Science Library 382,
DOI 10.1007/978-94-007-2834-9_1,

Fig. 1.1 Nikolai Dmitrievich Papaleksi (1880–1947)

Academician Ginzburg describes this occurrence as follows: "N. D. Papaleksi, naturally, had thought about radar measurements of the planets and Sun. In this connection, he asked me at the end of 1945, or more likely the beginning of 1946, to elucidate the conditions for the reflection of radio waves from the Sun. It stands to reason that, in essence, this was a typical ionospheric problem, and I had all the corresponding formulas to hand. The results of the calculations did not seem especially optimistic, since they indicated that, for a broad range of parameters, many of which were unknown then (the number density of electrons, the temperatures in the corona and chromosphere), radio waves should be strongly absorbed in the corona or chromosphere, so that they should not even reach the level where they would be reflected… But a more interesting conclusion followed directly from this: the sources of solar radio emission should not be in the photosphere, but instead in the chromosphere, or even in the corona in the case of longer waves. Further, it was already supposed at that time that the corona was heated to hundreds of thousands, or even a million, degrees. Thus, even under equilibrium conditions (in other words, in the absence of any perturbations), the temperature of the solar radio emission emitted by the corona (waves with wavelengths longer than about a metre) should reach about a million degrees for a photospheric temperature of 6000 degrees" [2, p. 289].

These results were laid out by Ginzburg in a paper published in the Reports of the Academy of Sciences in 1946. The conclusion that the corona must be the source of solar radio waves at metre wavelengths was also drawn nearly simultaneously and independently by I. S. Shklovskii in the Soviet Union and by D. Martin in England.

Papaleksi had also been interested earlier in the problem of solar–terrestrial connections, including the important question of the influence of solar activity on the Earth's ionosphere and the stability of radio communications. One of the methods he adopted was making observations during solar eclipses, when it was possible to distinguish the influences of the photon and particle fluxes from the Sun. During the eclipse of July 9, 1945, Papaleksi had already carried out a broad set of studies of phenomena in the ionosphere accompanying the eclipse. He intended to continue these investigations during the total solar eclipse of May 20, 1947, which it was possible to observe from Brazil. For this purpose, he began to prepare a large, multi-faceted expedition. Now, after the estimates of Ginzburg, it was planned for the first time to make not only ionospheric observations, but also direct observations of the radio emission of the Sun at metre wavelengths. Papaleksi hoped to detect not only the steady-state emission of the quiescent Sun, but also (thanks to the high resolution attained during eclipse observations) regions of sporadic radio emission. Information about this radiation obtained abroad during the war years was just starting to appear in literature at that time.

In a public lecture in January 1947, Papaleksi said the following about radio astronomy: “This new area of research, which is currently in its infancy, will undoubtedly be of extreme interest for physics of the Sun. There is every reason to believe that the application of radio astronomy methods in astronomy will open a new era, whose importance can be compared to the discovery of Fraunhofer lines and the application of spectral analysis in astrophysics, and which will help us penetrate more deeply into the mysteries of the Universe.”

Radio observations of the Sun during partial eclipses began abroad starting in 1945, but these observations did not yield conclusive results. The total eclipse of May 20, 1947 could potentially provide important new information.

The Brazilian expedition was organised by the Scientific Council of the USSR Academy of Sciences on Astronomy under the supervision of Academician Papaleksi, who was then the Head of the Oscillation Laboratory of FIAN. The well known polar explorer G. A. Ushakov was the administrative assistant to the head of the expedition. The expedition included researchers from optical, radio astronomy and ionospheric groups. Papaleksi supervised the last two of these groups, and M. N. Gnevyshev the optical group.

In the period of preparation for the expedition, it was necessary to acquire and adapt all the equipment, develop the methods to be used for the observations, carry out the necessary calculations of the conditions for the eclipse and prepare a program for the reduction of the observations.

The expedition members included the now well known scientists V. L. Ginzburg and I. S. Shklovskii. The radio astronomy observations were to be carried out by Papaleksi’s student B. M. Chikhachev (Fig. 1.2), formerly of the Central Radio Laboratory, who was an experienced specialist on radio technology and electronics. Before the Second World War, he had studied the technology of preparing metallic radio lamps in the USA, and, during the war, he was the chief technician at a radio factory. After the war, he became a PhD student of Papaleksi in FIAN. Workers under Academician A. I. Berg were assigned as assistants to Chikhachev. This group was responsible for the radio astronomy equipment for the expedition.

The planned observations of the radio emission of the Sun at a wavelength of 1.5 m required a radio telescope with a fairly high sensitivity, since, according to calculations, the intensity of the signal might be decreased by more than a factor of ten during the eclipse. An antenna with a large receiving area that was capable of tracking the Sun over the entire period of the eclipse (about three hours) was required, as well as a broad-band receiver with a good noise coefficient. A large

Fig. 1.2 Boris Mikhailovich Chikhachev (1910–1971)

number of Soviet and foreign radar equipment with suitable parameters were left after the war. A radar receiver operating at a wavelength of 1.5 m was selected for the eclipse observations.

However, Papaleksi was not able to realise his plan; he died suddenly on February 3, 1947. At a memorial service dedicated to N. D. Papaleksi in April 1947, the President of the Academy of Sciences Academician S. I. Vavilov said, "Death has claimed Nikolai Dmitrievich during his preparations for an expedition to Brazil, for which he and his students, as always, prepared meticulously and at the head of which he stood. He was not fated to live to see the realisation of this expedition, and now his orphaned students will sail on a Soviet ship to the shores of Brazil without their teacher.[2]"

The supervision of the expedition was given to Corresponding Member of the Academy of Sciences A. A. Mikhailov, and his scientific assistant and supervisor of the radio astronomy and ionospheric groups became Semen Emmanuilovich Khaikin (Fig. 1.3)—a student of L. I. Mandel'shtam, who can be considered a co-founder of Soviet experimental radio astronomy. At that time, he was the head of a group in the Oscillation Laboratory of FIAN, and was working on studies of the physical properties of solid bodies and electrolytes using radio methods.

The experience acquired by Khaikin during the Second World War with the construction of radar systems helped him develop a method for observing the radio emission of the Sun during an eclipse.

The expedition began with an unpleasant surprise; a shelf of heavy ice with a width of 5 km formed in the usually unfrozen port of Liepaya from which the ship *Griboedov* (Fig. 1.4) was to set sail for Brazil. The icebreaker *Sibiryakov* was called from Riga, and was supposed to make a passage through the ice in order to lead the ship to clear water. After the war, there were many mines left in the port, and there was a real danger of getting blown up by one. The *Griboedov* arrived in Sweden only

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[2] Izvestiya Akademii Nauki SSSR, Seriya fizika, 1948, 12, No. 1, p. 5.

Fig. 1.3 Semen Emmanuilovich Khaikin (1901–1968)

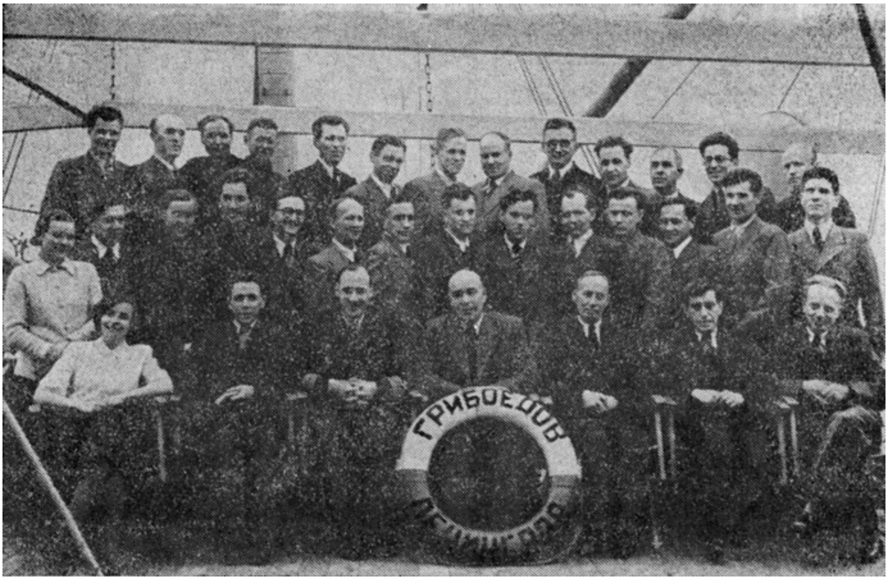

Fig. 1.4 Participants of the Brazilian expedition of the USSR Academy of Sciences on the desk of the "Griboedov". Included in the picture are the well known scientists and engineers S. E. Khaikin (*bottom row, first on the right*), G. A. Ushakov (*lower row, fourth from the right*), V. L. Ginzburg (*middle row, fourth from the left*), B. M. Chikhachev (*middle row, sixth from the right*), and I. S. Shklovskii (*upper row, second from the right*)

on April 15, where it underwent demagnetisation over the course of two days. The ship arrived at the Brazilian port of Salvador on May 10, 1947, only ten days before the eclipse. The optical and ionospheric groups set out by train to the city of Arasha.

There was now little time to set up and test the equipment. In spite of its characteristics, which were quite good for that time, the radar station was not usable for observations of solar radio emission during the eclipse without certain adaptations. When mounted in the usual way, the antenna had a vertical axis that could rotate in azimuth, and was not able to carry out observations at large elevations—and the centre of the Sun during the eclipse would be at elevations of approximately 35 to 57°.

Khaikin solved this problem in the following very clever way: the surface of the antenna was laid on the deck and inclined about its horizontal axis using winches. Rotation in azimuth was achieved by rotating the ship itself. Since the measurements were carried out in a bay whose bottom would not take a secure hold on the anchor, lines for rotating the vessel were strung to the shore. This provided tracking of the Sun during the observations with an accuracy of about 2°—quite sufficient for this purpose.

The receiver was calibrated using the intensity of its own noise, and was estimated in units of the maximum noise with an accuracy of 5%. The output electromagnetic recorder worked poorly, and there weren't chart recorders at that time. And of course, the results of the observations must be absolutely trustworthy. At Khaikin's suggestion, output pointer-display instruments were added in parallel, and placed in isolated cabins where observers could independently write the readings from these instruments each minute, using clocks checked against the ship's chronometer. The position of the ship was also noted each minute. Corrections for the deviation of the antenna and monitoring of the noise correction were carried out every five minutes.

The emission received could include a contribution from the Galaxy as well as the Sun. Therefore, measurements of the radio emission from the same region of the sky were carried out 15 days later, when the Sun was offset by 15° and was outside the beam of the antenna. It turned out that Galactic emission comprised only about 5% of the receiver noise, in other words, it was at the sensitivity limit, so that no correction to the eclipse curve was needed. The eclipse curve (Fig. 1.5) showed that the minimum intensity of the solar radio emission was only 40% lower than the maximum intensity—the eclipse was annular, or ring-like, rather than total for radio waves with 1.5 m wavelength. The intensity was higher in the first than in the last phase of the eclipse, indicating that the distribution of the solar radio brightness was not uniform. If we suppose that the radio brightness distribution over the solar disk was uniform, the radiating layers of the Sun should reach distances from the solar centre of about 0.35 times the radius of the Sun ($\sim 0.35 R_\odot$) above the photosphere. Since this was clearly not correct, the derived radio diameter of $2.7 R_\odot$ was only approximate. Nonetheless, this value was in good agreement with the theoretical calculations of Ginzburg.

The brightness distribution derived from the observations agreed with the arrangement of spots on the Sun. An eclipse curve constructed by E. I. Mogilevskii based on data for protuberances and filaments from a number of observatories proved to be close to the observed radio curve.

The results of these solar-eclipse observations carried out under Khaikin became classic—the theoretically predicted coronal radio emission at metre wavelengths had been detected. Some 23 years after the observations (on April 28, 1970, with the discovery date given as October 28, 1947), these results were noted with a diploma

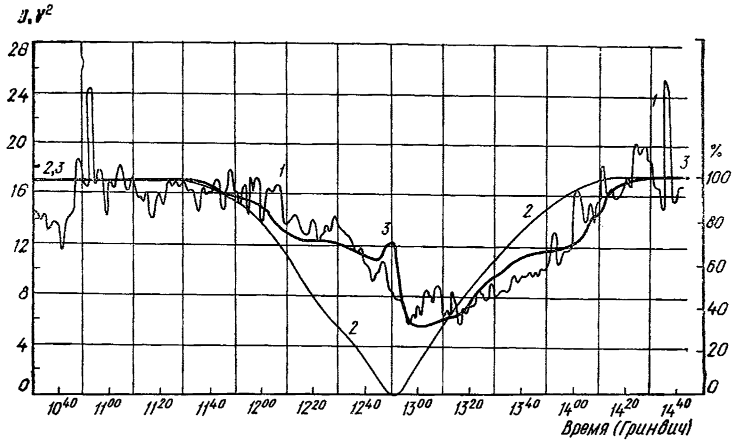

Fig. 1.5 Recording of the radio eclipse of the Sun obtained by Soviet radio astronomers on May 20, 1947: (**1**) variation of the intensity of the solar radio emission at 1.5 m wavelength in arbitrary units; (**2**) variation of the visible area of the solar disk; (**3**) behaviour of the "eclipse" of eruptive prominances and filaments. The horizontal axis denotes GMT

honouring the discovery, in the names of N. D. Papaleksi, S. E. Khaikin and B. M. Chikhachev.

The observations of the solar radio emission during the eclipse so enthralled Khaikin that he decided to "pack up" his earlier work and devote all his energy to radio astronomy. Upon his return from the Brazilian expedition, he composed a broad plan for the development of this area in the Soviet Union—not an easy task. None of the required measurement techniques were available, and the country had no specialists whose work was close to the relevant astrophysical questions or technical problems in statistical radio physics. Without interest in these problems, it would not be possible to make plans for radio astronomy observations or to develop the needed methods.

Khaikin suggested that, although radio astronomy was above all an astronomical science, in that early time, when the required experimental methods were first being developed, the most appropriate workers for this field were radio physicists, and the most appropriate bases for their work were physics institutes. He believed that, as radio astronomy grew toward becoming a true branch of astronomy, these first groups would be supplemented with astrophysicists, and bases for radio astronomy would appear among astrophysical observatories as well as physics institutes.

Khaikin also understood that, although the development of radio astronomy receiver technology—radiometers—was a progressing area, possibilities for increasing the sensitivity of receivers were limited, while there were virtually no limitations on increasing the area or resolution of antennas. Therefore, the development of radio astronomy technology required first and foremost antennas with very large areas—preferably reflectors and not refractors (co-phased antennas).

Khaikin correctly predicted the progressive tendency in radio astronomy to move toward ever shorter wavelengths—decimetre and centimetre wavelengths, where the noise temperatures of the antennas would not be limited by the Galactic noise, and where it was possible to achieve better resolution. Of course, the noise temperatures of centimetre-wavelength receivers were very high at that time, and their sensitivity was lower than that achieved at longer wavelengths; but Khaikin understood that this limitation would be temporary. His decision to place emphasis on the development of equipment and methods for observations at ever shorter wavelengths encountered opposition from some astrophysicists, who wanted to stick to observations using radar equipment operating at metre wavelengths in order to obtain radio astronomy measurements more quickly, without taking into account the fact that the scientific potential of such equipment was already nearly exhausted. It would be an exceedingly difficult task to base this new branch of science—radio astronomy—on the development of complex and unwieldy antennas and high-sensitivity receivers "in a vacuum"—without any technological basis or qualified scientific researchers or service personnel, and without the corresponding financing. Therefore, Khaikin proposed a research programme concerning the propagation of radio waves with wavelengths from 3 m to 3 cm through the entire thickness of the Earth's atmosphere, using the Sun, Moon and discrete radio sources as generators of radio emission beyond the atmosphere.

In addition to the refraction of radio waves arriving at various elevations in the troposphere and ionosphere, the attenuation of the signals due to absorption and scattering were measured. Along the way, the fluxes, angular dimensions and precise coordinates of the various sources of radiation were to be determined. Such studies were carried out under the supervision of Khaikin, as well as by a group of radio astrophysicists at Gorkii State University headed by Prof. G. S. Gorelik. The advantage of such a programme, sitting at the cross-roads of radio physics and astronomy, was that it enabled physicists working in the field to acquire knowledge in astronomy and to develop intuition about radio astronomy, and also enabled refinement of the technological resources available. This made it possible for this work to grow into true experimental radio astronomy, encompassing both astrophysical and astrometric problems.

In 1948, at the suggestion of the Presidium of the USSR Academy of Sciences, a programme of this work was adopted for 1948–1950. This programme foresaw the transfer of a number of radar stations operating at metre, decimetre and centimetre wavelengths to FIAN and Gorkii State University, together with the required funding. Engineering and technical staff and corresponding funding were also allocated for affiliate stations in other locations.

We should emphasise that, from the very beginning, the Director of FIAN and President of the Academy of Sciences Academician S. I. Vavilov solidly supported Khaikin's initiative, consistently supporting radio astronomers in the future as well. The same is true of Academician M. A. Leontovich—the new head of the Oscillation Laboratory.

After this decision to develop radio astronomy methods for studies of radio-wave propagation, the Crimean Station of FIAN was reorganised. A former school on Sevastopol' Road in Alupka became the central base, where the administrative headquarters, a workshop and a small dormitory were located. In addition to this centre,

Fig. 1.6 Viktor Vitol'dovich Vitkevich (1917–1972); photo taken in 1948

the Crimean Station had the Alushta base, which was located on a parcel of seashore in Rabochii Ugolok, where a Finnish house with a basement for a workshop and a stone shed with a diesel generator was built in 1949. (Both locations were initially intended for the continuation of pre-war work by Papaleksi on interferometric distance measurements.) B. N. Gorozhankin of the FIAN Oscillation Laboratory was assigned as the Head of the Crimean Station.

It was clear that the sites in Alupka and Alushta were insufficient for work on a large scale. In agreement with the director of the Crimean Astrophysical Observatory Academician G. A. Shain, the Crimean Station of FIAN was given a site (250 × 150 m) on Koshka Mountain near Simeiz, bordering on the observatory, intended for large antennas, laboratory buildings, a workshop, a storeroom and a dormitory.

Khaikin attracted V. V. Vitkevich (Fig. 1.6) to this new work in 1948. He had finished postgraduate studies at Moscow State University by correspondence in 1944, being at that time an officer in the Navy, and had been working toward his doctorate in the Radio Technology Section of the Academy of Sciences since 1947. An experienced radio specialist and senior scientist, Vitkevich headed a group that soon also included the engineers D. V. Kovalevskii and V. S. Medvedev, and later the radio technicians M. T. Levchenko, L. A. Levchenko, E. K. Kurkina (née Karlova), T. I. Shakhanova (née Gavrilenko) and others. This group set about the work of devising radiometer and radio-interferometer equipment operating at decimetre wavelengths. In the Spring of 1949, successful tests were carried out of an interferometer operating at 50-cm wavelength comprised of 3-m antennas from a radar system and a receiver supplemented by a modulating radiometer, in which Vitkevich used a capacitor switch he had developed. However, the volume of work needed required the application of considerable efforts.

Various co-workers of Khaikin (Ya. I. Likhter, N. L. Kaidanovskii and A. E. Salomonovich) who had returned after demobilisation in 1946 and continued work on their pre-war topics—radio physical studies of solids and liquids—turned their attention to the new research direction that was being developed. In place of B. N.

Gorozhankin, who headed the Group for the Mathematical Processing of Observations (L. N. Borodovskaya, V. M. Antonova), Salomonovich was appointed as the Head of the Crimean Station, Kaidanovskii as his assistant, Vitkevich as the Head of the Alushta operation and the engineer Kovalevskii as the Head of the operation on Koshka Mountain. This reorganisation made it possible to speed up the work being carried out. Fourth-year (R. L. Sorochenko, F. V. Bunkin, B. D. Osipov, N. B. Delone) and third-year (V. V. Kobelev, N. V. Karlov, T. A. Shaonov, V. G. Veselago) students from the recently founded Physical–Technical Institute were also assigned to the Crimean Station, and the graduates of the Moscow Energy Institute N. F. Ryzhkov and T. M. Egorova were taken on in 1950.

The development of measurement methods was carried out under the overall supervision of Khaikin, at metre wavelengths by Chikhachev and Likhter, at decimetre and then metre wavelengths by Vitkevich, at 10 cm by Kovalevskii and Sorochenko and at 3 cm by Kaidanovskii. Measurements of refraction at metre and decimetre wavelengths were conducted using a so-called sea radio interferometer, which used the sea surface to reflect the radio waves—a radio analog of a Lloyd reflector.

The use of the sea interferometer made it possible to measure refraction in a relatively simple way at metre and long decimetre wavelengths, with good accuracy based on the times of passage of the Sun through the lobes of a multi-lobe antenna beam. The roughness of the sea (whose surface served as the Lloyd reflector) could be neglected for observations near the horizon. By that time, a number of powerful discrete sources with small angular sizes were known, enabling measurements using comparatively narrow lobes of the interferometer beam.

An antenna operating at 1.5 m was installed on the site at Koshka Mountain at a fairly high altitude above sea level (∼285 m) in 1948 under the supervision of Gorozhankin. The receiver had an attachment at its output that enabled correction for the noise of the receiver itself.

In the Summer of 1949, Vitkevich and his group set about using the sea interferometer at Alushta to take measurements of the solar radio emission at 50-cm wavelength, which did not require high altitudes above sea level. The antenna was mounted on an angular turret pointed at the Finnish house, at a height of several metres above sea level. Later, in 1950, two-antenna radio interferometers were constructed at the cape of Ai-Todor. The source Taurus A (in the Crab Nebula) was detected for the first time in the Soviet Union using one of these interferometers operating at 1.5 m wavelength (Vitkevich, Rykhkov, Medvedeva). Measurements with interferometers at high altitudes were carried out in 1949–1952, on the mountains Ai-Petri (Osipov, Delone, Kurkina) and Kastel' (Rykhkov and others).

When taking measurements of the Sun at centimetre wavelengths, it was possible to get by without interferometric observations, using parabolic antennas with diameters corresponding to about 100 wavelengths. The angle of refraction could be determined by tracking the Sun in azimuth and noting the times when its centre passed through the axis of the vertical beam of the antenna, which was mounted at specified angles. Thus, radio telescopes suitable for observations at wavelengths of 3 and 10 cm were sufficient for this work.

A radio telescope with a diameter of 7–10 m was needed for observations at 10 cm wavelength. The mount of the 7.5-m diameter parabolic dish from a

Wurzburg–Riese German radar system operating at 50 cm wavelength—a trophy of the war—was used in its construction. Its turning apparatus, found in another place, had to be rebuilt and augmented. In addition, the 10-cm observations required a new, more accurate reflecting surface of solid sheet aluminium. The work on this radio telescope was headed by the highly qualified construction engineer and Doctor of technical sciences P. D. Kalachev, who joined FIAN in 1948, and has done much for Soviet radio astronomy. The assembly of the mechanisms and constructional elements was carried out by N. S. Bulanov and P. I. Maiorov, under the supervision of P. M. Butuzov. The development of the technology for preparing the reflecting surface was done by Kalachev, Kaidanovskii and Salomonovich. This problem was solved using a specialised template and concrete matrix to punch out the reflector elements. In May 1949, all the components of the radio telescope had been sent from Moscow to Koshka Mountain, where the assembly of the telescope began immediately.

The constructional rigging for the large-scale and heavy components of the radio telescope was strung in the most primitive way, using two parallel block-and-tackle setups based on tubular tripods. Fortunately, the entire operation was carried out without incident. S. I. Kharlamov punched out the aluminium sheets on the concrete matrices with an accuracy to within 1 mm. However, it was not possible to attach these sheets to the crude frame, originally intended for observations at 50 cm, since this would degrade the accuracy of the reflecting surface. Therefore, well dried pine lathes were fixed to the ribs of the frame, which were then carefully planed, leaving no gaps, placed beneath a "flag" and painted. The punched-out aluminium sheets were then screwed onto the pine lathes. The shape of the resulting surface was monitored with accuracy to 1 mm using the "flag."

The prepared reflecting surface was carried to the telescope mount by hand using a specialised platform, raised and fixed to the mount. All the assembly and mechanical adjustment for the 7.5-m diameter radio telescope were finished in July 1949, after which the process of outfitting the telescope with the necessary radio and technical equipment began under the supervision of Kovalevskii and Sorochenko. This was how the construction and outfitting of the RT-7.5—the first Soviet reflector radio telescope—was brought about (Fig. 1.7). After it was equipped with a radiometer operating at 10 cm wavelength, this radio telescope was long used for observations of the Sun and Moon. It provided data on the propagation of radio waves at this wavelength through the Earth's atmosphere, and was later used to conduct a series of measurements of the radio emission of the Sun, Moon and other sources.[3]

The 3-m diameter antenna of a "Small Wurzburg" radar system, originally operated at 50 cm wavelength, was used in the construction of a radio telescope for observations at 3 cm wavelength. The surface was aligned by Kharlamov to an accuracy sufficient for such observations. The radio telescope was set up on the Alushta

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[3] Many years later, a researcher in the Crimean station, Yu. I. Alekseev, used this radio telescope for polarisation measurements of the Sun. The reflecting surface was replaced by a co-phased antenna operating at 1.64 m, but the RT-7.5 mount continued to be used for this new purpose.

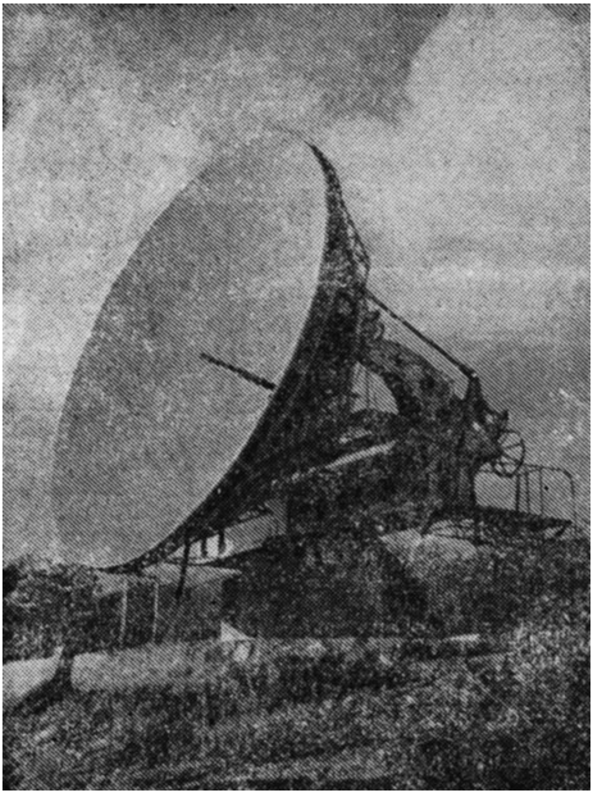

Fig. 1.7 First large reflecting radio telescope of the Crimean station of the FIAN, with a diameter of 7.5 m

site, right by the seashore. The Small Wurzburg radar system was augmented with radio equipment and the required measurement devices.

A Dicke disk modulator and absorbing valve were inserted into the antenna tract, to be used as an attenuator during the calibration of the radiometer when the radio telescope was pointed at the zenith. A high-frequency block with a heterodyne and preliminary cascade of intermediate-frequency amplifiers were mounted in the antenna. The subsequent cascades were installed in the laboratory. The apparatus for the 7.5-m diameter radio telescope operating at 10 cm was implemented in the same way.

The first metre-wavelength radio telescopes, used first for refraction measurements and then also for astronomical observations, were multi-dipole co-phased antennas set to receive at a fixed wavelength and usually outfitted with compensating radiometer receivers. Examples include the radio telescope operating at 1.5 m wavelength described above, later improved by Kalachev to enable variation of the elevation of the electrical axis via mechanical rotation about the horizontal axis. Antennas operating at 2 and 4 m wavelength were likewise constructed or adapted with record speed.

In June–July 1949, all the observational installations were ready, and systematic measurements of the refraction and attenuation of signals as a function of the elevation and observing conditions were begun. These observations continued for about a year. In 1950, the brightness temperature of the Sun was estimated at various wavelengths.

Simultaneous with the observations at the Crimean Station, similar measurements were carried out at the Gorkii Physical–Technical Institute by a large group under the supervision of G. S. Gorelik and V. S. Troitskii. A general report on this work, confirmed by Vavilov, was presented on June 15, 1950, and members of this group were awarded the prize of the Council of Ministers of the USSR.

In this period, experience in solving methodological problems accumulated, experimental measurement techniques were developed and sensitive receivers capable of operating over a wide wavelength range were devised. In addition, the physicists and engineers involved acquired some experience with astronomical observations and interest in astrophysical problems. Technological possibilities for improving the methods used to measure various physical characteristics of cosmic radio sources appeared. Beginning in 1949, at the initiative of Khaikin, Vitkevich and Chikhachev, a group of constructors headed by Kalachev began to plan and then construct new radio telescopes intended primarily for radio astronomy observations. These second-generation radio telescopes are described below.

Chikhachev carried out broad and interesting studies of active regions on the Sun at metre wavelengths, which became the basis for his PhD thesis—the first dissertation on radio astronomy at FIAN and only the second in the Soviet Union[4] Vitkevich was also undertaking fruitful activity in radio astronomy at that time, and put forth in 1951 the idea of studying the solar corona by analysing the radiation from a background source (the Crab Nebula) that had passed through the coronal material.

Studies of the propagation of radio waves through the Earth's atmosphere using radio astronomy methods were continued in 1951–1953, with the Radio Physical Research Institute in Gorkii also taking part. The scientific supervisor for this new series of studies was Khaikin, while the supervisors of individual areas of research were Kaidanovskii, M. A. Kolosov, Troitskii and Chikhachev. In addition to the observations in the Crimea and Gorkii, systematic measurements of the Sun and Moon were carried out at the newly organised station in the Kaluga region.

The radio emission of the Sun was used earlier for propagation measurements at centimetre wavelengths, with the measurements carried out when the Sun was rising or setting. It was also important to know the run of the measured quantitites throughout the day, which could be derived from observations of the Moon, which was the second most powerful source of centimetre-wavelength radiation after the Sun. Work in this area was led by the group of Kaidanovskii. The sensitivity of the radio telescope operating at 3 cm was substantially enhanced, and the diameter of the parabolic antenna was increased to 4 m.

The upgrade of this antenna by increasing the diameter to 4 m and the radiation angle to 120° was carried out under the supervision of Kalachev. The sensitivity

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[4] The first was the thesis of V. S. Troitskii. We do not indicate here all subsequent dissertations in this field, and explicitly make note only of these two theses.

of the radio telescope was 1–2 K, with a time constant of one second. The radio technicians N. A. Amenitskii, A. A. Gromadin and S. K. Palamarchuk and the technical assistants V. P. Izvarina and E. P. Morozova participated in the construction and exploitation of this equipment.

To investigate the influence of climatic and meteorological conditions, one of the new 3-cm wavelength radio telescopes was installed in the Crimea at Koshka Mountain and another in the Kaluga region. Joint measurements with these telescopes were fully completed in December 1952.

In parallel with the radio-physical measurements at the Kaluga and Crimean Stations, measurements of the brightness temperature of the Moon at wavelengths of 3 and 10 cm as a function of the lunar phase were initiated. Measurements of the brightness temperature of the Moon during eclipse were also carried out, which did not show any changes.

During the course of these investigations, M. T. Turusbekov first looked for inhomogeneity in the brightness temperature across the lunar surface by looking for shifts of the “centre of gravity” of the emission. No such shifts were detected over the duration of the series of observations with an accuracy to within 0.5 min, in agreement with calculations based on the theory of Troitskii, which indicated that possible variations in the mean temperature of the Moon should be no larger than 7–10 K.

At the Kaluga Station, the 3-cm receiver was fully rebuilt in preparation for measurements of the polarisation of the solar radio emission in 1953–1954.

The original methods and equipment developed by E. G. Mirzabekyan (1912–1979) under the supervision of Khaikin and Kaidanovskii subsequently led to interesting astrophysical results (see Essay 4). In October–December 1954, using this same radiometer in a mode in which unpolarised radiation was received, Kaidanovskii and N. S. Kardashev (then a Master’s student at Moscow State University) conducted successful observations of three supernova remnants and, for the first time at this wavelength, the diffuse Omega and Orion nebulae. These observations confirmed the theoretical conclusions of Shklovskii. By the end of 1954, all the FIAN radio telescopes were freed of their applied tasks and were fully turned toward astrophysical observations.

In this way, the plan of Khaikin was gradually realised: from applied tasks that could be solved using rebuilt radar equipment that was already available, to radio astronomy observations using radio telescopes constructed especially for this purpose.

Back in 1952, in contrast to Khaikin and Kaidanovskii, most prominent coworkers in the Radio Astronomy Section of FIAN thought it would be expedient to move to astronomical observatories. However, it proved to be more efficient to carry out this work within the walls of a multi-department physics institute. Unfortunately, there was also a certain attitude of “we don’t need astronomers, except perhaps to calculate coordinates.” This led to the loss from FIAN of a number of talented graduates of Moscow State University, including the astrophysicists Yu. N. Pariiskii and N. S. Soboleva, who carried out their Master’s work in the Radio Astronomy Section of FIAN (under the supervision of Salomonovich).

Before 1954, in contrast to the Byurakan and Crimean Observatories (see Essays 6 and 7), the Pulkovo Observatory, which was the largest in the Soviet Union, did not yet have a radio astronomy department, and Khaikin took on the organisation of such a department. The subsequent development of radio astronomy at FIAN was associated with work at the Crimean Station under the supervision of Vitkevich, and with preparations for and then the construction of the new Radio Astronomy Station in Pushchino. After Khaikin stepped down as head of the Radio Astronomy Section of FIAN in 1955 in connection with his final move to the Pulkovo Observatory, this position was occupied by Vitkevich, assisted by Salomonovich.

1.2 The Crimean Station of the Lebedev Physical Institute (1952–1962)

Using the existing experimental base of the Crimean Station and throughout its continuous upgrades, radio astronomy investigations of the Sun, Crab Nebula, Galaxy (at 21 cm) and ionosphere were widely expanded. Possibilities for the further development of radio astronomy studies at the Crimean Station were essentially exhausted in this stage.

The head of the Crimean station in 1952 was Vitkevich and then, beginning in 1958, Yu. L. Kokurin. The assistant head for scientific and technical matters was Kovalevskii from 1950–1954, followed by V. A. Udal'tsov from 1954–1958.

In 1952, the station was located at three separate bases: in Alupka, Simeiz (Koshka Mountain) and Alushta. The main experimental base was located at Koshka Mountain, next to the Crimean Astrophysical Observatory. The radio telescope operating at 1.5 m wavelength was located there; during observations of the Sun in winter months, it could be used as a sea interferometer during the rising and setting of the Sun. The 7.5-m and 4-m radio telescopes were also located there, although the 4-m telescope was moved to Alushta in 1953.

Later, the B-1 radio telescope, operating at a wavelength of 3.5 m and based on an adaption of a radar station, was also constructed. Two such antennas formed an interferometer with a baseline of 160 m oriented East–West. Radiometers operating at 1, 2 and 2.6 m were mounted on the Ch-1 antenna (a parabolic dish without a means of steering). In addition, the facilities on Koshka Mountain included a small mechanical workshop, diesel and storage buildings, a cafeteria and an administrative building with accommodation, to which the heads of the station were moved from Alupka in 1953 and which also housed the construction group starting from that same year.

Two 3-m antennas operating as an interferometer at a wavelength of 50 cm were located at Alushta (but were moved to Koshka Mountain together with their radiometer in 1953), as well as a 4-m radio telescope operating at 23 cm wavelength.

First Investigations of the Supercorona of the Sun At the beginning of 1952, Vitkevich organised the Ashkhabad station for observations of the solar eclipse of

February 25, 1952. Chikhachev, G. G. Stolpovskii (assistant head of the station), the engineers T. M. Egorova, Rykhkov, Kalachev, and Medvedeva and others took part in this work. The observations were carried out using the Ch-1 antenna with four dipole systems placed at its focus, adjusted to receive at wavelengths of 1.1, 2.6 and 5.2 m. An original turning device supported by two tripods enabled tracking of the Sun during the eclipse.

The observations of this eclipse allowed Vitkevich and Chikhachev to obtain data on the distribution of the solar radio emission at metre wavelengths, and to determine the effective parameters of this emission together with their wavelength dependences.

After the successful completion of the eclipse observations, this antenna and its radiometer were moved to the Crimea (the village of Karabakh), where it was subsequently used for a series of observations carried out under the supervision of Chikhachev aimed at studying the radio emission of the active Sun.

Two new members of the Oscillation Laboratory joined the station in 1952—R. L. Sorochenko and V. A. Udal'tsov. Sorochenko modernised the 7.5-m antenna to enable observations of the Moon as well as the Sun at 10 cm. These measurements provided data about the daytime and nighttime refraction in the atmosphere, and also about the radio emission of the Moon itself.

As early as 1951, Vitkevich proposed the idea of investigating the solar corona by analysing radiation of the Crab Nebula source that had passed through the coronal material, when this source was located at various angular distances from the centre of the Sun.

Each year, the Crab Nebula approaches to within about 4.5° of the Sun on June 14–15. It is possible to estimate the parameters of the medium making up the corona by analysing the influence of the solar corona on the radiation passing through it from a background source. This could take the form of refraction, absorption or scattering of the radio waves due to inhomogeneities in the electron density in the corona. All these effects (except for the effects of small-scale structure) should be manifest more strongly with increasing wavelength. This made observations at metre wavelengths most suitable for such studies.

However, the Sun is a brighter source of radio emission than the Crab Nebula. The flux density of the radio emission of the quiescent Sun at a wavelength of 3 m exceeds 2×10^4 Jy[5], while the flux density of the Crab Nebula is about 2×10^3 Jy. Therefore, it would not be possible to distinguish the Crab Nebula's radiation from the stronger solar radiation as the nebula approached the Sun. An elegant method was proposed to attenuate the signal from the quiescent Sun, using the difference in the angular sizes of the Sun and the Crab Nebula source (30 and $6'$, respectively). The interferometer baseline was chosen so that the angular width of the interferometer's resolution was smaller than the angular size of the Sun, but larger than the angular size of the Crab Nebula source.

Vitkevich conducted the first such measurements in 1951 at 4 m wavelength using a sea interferometer with a baseline of 420 m (the interferometer resolution was $16'$).

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[5] The unit of flux density used in radio astronomy is the Jy, 1 Jy = 10^{-26} W/(m^2 Hz).

The Crab Nebula was observed as it was rising. However, the Sun was active in the period of approach (from June 9 to June 22): local sources of radio emission strongly distorted the interference pattern due to the Crab Nebula.

A second set of observations was undertaken in 1952. An expedition under the supervision of Udal'tsov was organised to Ai-Petri, where it was possible to lay out long interferometer baselines. Two East–West interferometers operating at 6 m and 12 m wavelength and with baselines of 700 and 1200 m were set up. The 6-m observations were successful (the amplitude of the interferometer signal decreased), but it was not possible to carry out the 12-m observations due to a high level of interference. When analysing the results of these 1952 observations at Ai-Petri, Vitkevich concluded that the solar corona influenced the passage of radiation from the background source at distances of more than 4.5 solar radii from the centre of the Sun.

These observations of the Crab Nebula through the solar corona showed the effectiveness of this method. However, since it rained during the observations, the parameters of the radio telescope could have changed during the session. This raised the necessity of improving the observational methods. It was decided to conduct simultaneous observations at a single wavelength but with different interferometer baselines. In the case of scattering, the apparent angular size of a source should increase as it approaches the Sun, while this size should remain constant in the case of absorption. Therefore, in the case of absorption, as the source approaches the Sun, the variations in the interference pattern should be correlated on different interferometer baselines; in the case of scattering, the variations should be visible earlier on long baselines than on short ones. To study the form of the scattering region, it would also be desirable to have baselines at the same wavelengths but with different orientations.

At this time, Vitkevich had already introduced the term *supercorona* in his publications, referring to the outer region of the corona that was discovered due to its effect on other background radio sources.

Further Development of the Work It followed from the first observations of the supercorona that further studies of the solar corona based on analysing signals passing through the corona required the construction of a large number of interferometers operating at various wavelengths and with baselines that differed in both length and orientation.

In 1951, none of the bases of the Crimean Station had areas that were suitable for such new interferometers. Therefore, a new experimental base was founded in 1953 near Katsiveli at the initiative of Vitkevich, and subsequently became the main base of the station. It is located to the west of Simeiz beyond Goluboi Bay, near the Black Sea Division of the Moscow Hydrophysical Institute of the Academy of Sciences.

In the period from 1952 to 1955, the number of workers at the station steadily increased from 20 to 90. Yu. A. Alekseev, A. N. Sukhanovskii, Yu. L. Kokurin, A. D. Kuz'min, M. A. Ovsyankin and Z. I. Kamenova began their work at the station in 1953–1955, and L. I. Matveenko in 1956.

To better organise the work being done at the station in this period, several scientific groups were founded, which carried out various observations and investigations

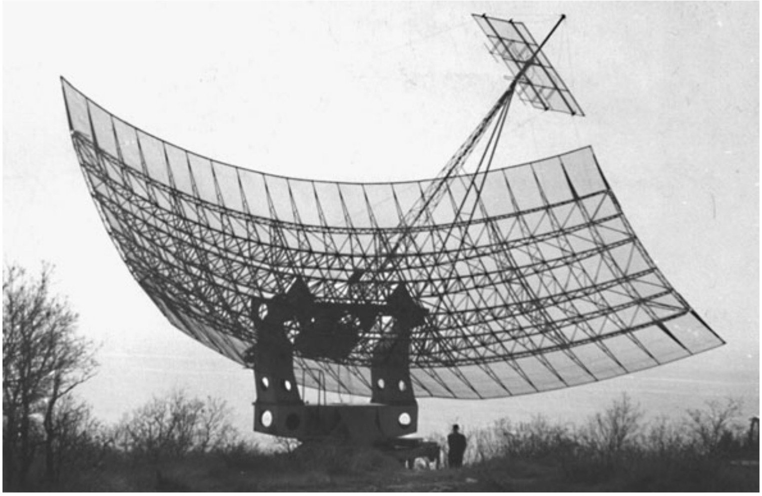

Fig. 1.8 Reflecting radio telescope used to conduct spectral observations at 21 cm starting in 1954

under the overall supervision of Vitkevich. The group of Udal'tsov performed experimental studies of the solar corona based on analyses of signals that had passed through the corona, and independently developed radio astronomy studies of the Crab Nebula; the group of Kokurin (to an appreciable extent independently) carried out experimental investigations of the ionosphere. The group of Chikhachev built instruments and carried out spectral studies of hydrogen lines. The construction of a spectral radiometer in this group was supervised by Sorochenko (Fig. 1.8). The group of Alekseev worked on experimental studies of the Sun at 1.5 m wavelength, including regular observations of the Sun during the International Geophysical Year. The group of Kamenova and Ovsyankin performed experimental investigations at wavelengths of 50 cm and 1 m of the sporadic radio emission of the Sun at frequencies of 80–120 MHz. A number of researchers also worked under the direct supervision of Vitkevich. In addition to the scientific and administrative groups, the Crimean station included a construction group (M. M. Tyaptin and others) and a group of mechanics.

Development of Methods and the Experimental Base In 1952–1956, a number of new methodological and constructional ideas were put forward by researchers at the station. Vitkevich proposed and developed a method for realising a wide-band radio interferometer, which was essentially a new means of creating an antenna system with a single beam providing high spatial resolution; a multi-channel radio interferometry system with two outputs, intended for determining the coordinates of a rapidly moving source whose intensity was changing; and an interferometer with a double modulation system (Fig. 1.9). Vitkevich and Udal'tsov also proposed a radio interferometer with a scanning antenna beam, which was realised by Udal'tsov in 1955–1956. Vitkevich and Sorochenko put forth the idea of creating a multi-element radio interferometer in the form of an equivalent diffraction grating, versions of

Fig. 1.9 Interferometer formed of two radio telescopes. The diameters of these parabolic dishes are 4 m. Observations at decimetre and centimetre wavelengths were carried out on this interferometer

which were put into operation by Udal'tsov in 1953 and by Matveenko in 1956. Udal'tsov developed a correlational method for polarisation measurements in 1957, bringing it into operation in 1960. Kuz'min proposed a method for changing the direction of an interference beam by changing the frequency of the heterodyne used. In 1954–1955, he developed noise generators and introduced them into use in measurements of the radio emission of the Sun and cosmic sources. In 1957, Matveenko devised a polarisation device in which the analysis of the received signals was carried out at an intermediate frequency, and brought into operation an interference triangle operating at 5 m wavelength in 1959.

A large antenna complex was constructed in the Crimea from 1952–1960, for radio astronomy observations under the supervision of Vitkevich. Old instruments were modernised as well, and a number of interferometers and receiving devices constructed.

Let us consider in more detail the construction at the initiative of Udal'tsov of a precise, transit, parabolic radio telescope with a diameter of 31 m (the RT-31), based on the earlier "eastern" RT-30 radio telescope. A special feature of this instrument (Fig. 1.10), which was unique for its time, was that it provided a large effective area suitable for use at wavelengths right down to 3 cm in a relatively simple way. The precise parabolic surface was obtained using a knife template, which was used to monitor the concrete and metal surfaces. The reflecting surface was sprayed with zinc. A platform supporting a movable cassette with feeds and receivers was installed on a vertical mast, above the focus of the paraboloid. This cassette could be moved either by hand or automatically, according to a specified programme, in a plane parallel to the aperture, within 4° of the axis in two orthogonal directions.

In 1958, Udal'tsov and Sukhanovskii devised an original system for the automatisation of radio astronomy observations, making it possible to carry out the entire

Fig. 1.10 Large fixed centimetre-wavelength radio telescope, with a diameter of 31 m

observing process in accordance with a specified programme (including the calibration of the radio telescope) without the participation of an operator.

Continuation of Studies of the Solar Supercorona Multi-faceted studies of the solar supercorona were carried out in 1953–1955 at metre wavelengths using the Crab Nebula as a source of radio radiation passing through the coronal material and the methods and resources described above. These investigations established the presence of an inhomogeneous scattering medium at large distances from the Sun, which increases the apparent angular size of the Crab Nebula source as it approaches the line of sight toward the Sun. The supercorona extends to several tens of solar radii, nearly to the orbit of Mercury.

Subsequent observations in 1956–1958 elucidated the role of the 11-year solar activity cycle in variations in the size of the supercorona. It turned out that the size of the supercorona increases as the solar activity grows. This correlation was revealed for both the inner and outer supercorona. The electron densities in inhomogeneities nearly doubles during periods of maximum solar activity. These observations showed that electrons concentrated in inhomogeneities in the solar supercorona are always present, in years of both minimum and maximum solar activity.

All the available data were used to construct models for the times of minimum and maximum solar activity. In the course of this work, asymmetry of the supercorona was discovered: the sizes of the inner and outer supercoronae are 1.5 and 2.5 times larger in the equatorial plane than they are perpendicular to this plane.

In 1956 and the following years, cases of the refraction of radio waves on large-scale inhomogeneities near the Sun were discovered, and used to estimate the parameters of these inhomogeneities. Focusing by these inhomogeneities was invoked to explain the growth in the intensity of a background radio source when its radiation passed through the corona, first observed in 1953. Matveenko detected flows of material moving with speeds in excess of 1000 km/s in 1960.

This series of studies was completed in 1962 with the construction of a two-component model for the solar supercorona, based in part on optical data on the mean electron density in the corona. In 1962, Vitkevich was awarded a diploma commemorating the discovery of the supercorona (granted on October 6, 1961, with the discovery date given as November 11, 1954).

Vitkevich and B. N. Panovkin (1931–1983) detected anisotropy in the scattering by analysing measurements of the scattering angle for the Crab Nebula at different orientations of the line connecting the source and the Sun relative to the interferometer baselines used, for observations at wavelengths of 3.5 m (1957), 5.8 m (1958) and 3.5 m (1958). A. G. Sukhova and M. A. Ovsyankin also measured the scattering angle for the Crab Nebula in various directions. Observations obtained in the following years both in the Soviet Union and abroad confirmed these results, which led to the discovery by Vitkevich and Panovkin of radial magnetic fields in the supercorona (the discovery diploma was issued on July 14, 1970, with the discovery date given as June 1957).

Studies of the Crab Nebula In these studies of the solar supercorona, the Crab Nebula was essentially used as a source of background radio emission. Therefore, nearly all the fixed radio telescopes of the Crimean Station were pointed at the Crab Nebula at some time, making it possible also to carry out specialised investigations of the nature of the radio emission of this interesting astronomical object.

The importance of polarisation observations came to the fore in the first half of the 1950s. The new hypothesis that the emission of various astronomical objects was synchrotron radiation, put forth and developed by the Soviet scientists V. L. Ginzburg, I. S. Shklovskii and G. G. Germantsev, as well as by many scientists abroad, shattered the then still predominant view from optical astronomy that essentially all electromagnetic radiation was thermal in nature.

A determining test in verifying whether observed emission is synchrotron radiation is the detection of linear polarisation in the optical and radio (see Essay 3). The most suitable object for such studies was the Crab Nebula, classified by R. Minkowski as a supernova remnant. This object had also been accessible to observations with medium-size antennas at the Crimean Station.

The first polarisation study of the Crab was undertaken in 1954, in both the optical (V. A. Dombrovskii and M. A. Vashakidze at the Byurakan Astronomical Observatory) and the radio, at wavelengths of 3.5, 5.8 and 7.5 m (V. A. Udal'tsov). A high degree of linear polarisation was detected in the optical ($\sim$15%), but no polarisation was detected in the radio, with an upper limit of 3%.

One possible reason for the absence of polarisation at metre wavelengths could be depolarisation of the signal due to Faraday rotation in the interstellar medium, as well as in the medium of the nebula itself. Testing this hypothesis required linear-polarisation measurements at shorter radio wavelengths, where Faraday rotation is manifest more weakly. It was desirable to carry out these measurements with a large radio telescope, in order to measure the degree of polarisation with an accuracy of a fraction of a percent. It was with these goals in mind that the 31-m parabolic telescope, suitable for observations at wavelengths down to 3 cm, was constructed (the RT-31).

A radiometer operating at 9.6 cm was used in the polarisation measurements carried out with the RT-31. In 1957, Kuz'min and Udal'tsov detected linear polarisation of the radiation from the Crab Nebula, equal to $(3 \pm 0.5)\%$. Polarisation was independently detected in that same year by radio astronomers in the USA at 3.15 cm. The detection of linear polarisation in both the optical and the radio represented convincing proof of the presence in the Universe of sources of non-thermal (synchrotron) radiation, demonstrated the non-thermal nature of the radiation of supernova remnants and illustrated that the radiation of the Crab Nebula had the same nature across its entire spectrum.

Udal'tsov carried out polarisation measurements of the Crab Nebula at 21 cm in 1959, using the RT-31 radio telescope and a specially constructed correlation polarimeter. These accurate measurements revealed linear polarisation at this wavelength as well, equal to $(11 \pm 0.5)\%$. It turned out that the polarisation position angles at 21, 9.6 and 3.15 cm displayed a linear dependence on the square of the wavelength. Thus, the effect of Faraday rotation was first detected, and used to measure the rotation measure in the interstellar medium and to demonstrate the depolarisation of the radiation of the Crab Nebula. This result also provided direct experimental evidence of the presence of regular interstellar magnetic fields.

A unique phenomenon occurred in 1955—an occultation of the Crab Nebula by the Moon. A special detachment was sent to the Pakhra Station of FIAN (see below), where radio astronomy studies at millimetre wavelengths were carried out near Krasnaya Pakhra (now the city of Troitsk), in order to observe this event. The complete phase of the occultation was observed on November 30, 1955 and January 24, 1956. Measurements were carried out using interferometers operating at 6 and 3.5 cm. As a result of these studies, Vitkevich and Udal'tsov detected an increase in the brightness toward the centre of the nebula and non-radial symmetry of the emission region—similar to that observed in the optical.[6]

Studies of the Radio Emission of the Sun Studies of the distribution of the radio brightness of the Sun in polar and equatorial regions carried out by Ovsyankin and Panovkin in 1955–1958 at wavelengths of 50 cm and 1 m showed that the shape of the Sun at 50 cm resembles an ellipse whose minor axis joins the two polar regions. In contrast to the situation at 1 m, an enhancement in the brightness was observed at this wavelength at a distance of 0.65 solar radii from the centre of the Sun, which is more weakly expressed in the polar regions. Vitkevich and Panovkin had discovered the "radio limb" of the Sun at 50 cm.

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[6] The conclusion drawn previously that the Crab had different sizes in the optical and in the radio was erroneous, and due to insufficient accuracy in the measurements used. In subsequent observations, using the large telescopes of FIAN (the 22-m and DKR-1000 telescopes in Pushchino) and the antennas of the Deep Space Communications Centre, Matveenko, Sorochenko, V. S. Artyukh and others (1964 and 1974) demonstrated that the sizes of the Crab Nebula in the optical and radio were the same.

Based on an analysis of all the new solar radio data obtained by Ovsyankin and his collaborators, Panovkin proposed a new model with a temperature gradient in the inner corona of the Sun. He showed that it was not possible to explain the shift of the brightness maximum inside the optical disk and the growth of this shift with increasing wavelength using a simple, isotropic model for the Sun.

In 1957, Vitkevich, Kuz'min, Salomonovich and Udal'tsov made the first radio survey of the Sun at centimetre wavelengths, using the RT-31 telescope and scanning in declination with the antenna beam, together with radiometers operating at 3.2 and 9.6 cm. This revealed the presence of regions of enhanced radio brightness. A correlation was established between these regions and manifestations of solar activity in the optical (coronal condensations). Investigations continued by Vitkevich and Matveenko at wavelengths of 1.5 and 3 cm with polarisation sensitivity showed that some active regions were circularly polarised.

Vitkevich and M. I. Sigal established the presence of a correlation between the slowly varying component of the solar radio emission at 50 cm and coronal condensations in 1956. Vitkevich and his coworkers obtained new results in 1955–1960, including the discovery of a new type of solar radio flare, quasi-monochromatic phenomena on the Sun and small "peaks" of radio emission of various classes.

In 1959, after generalising the data on the total radio emission of the Sun obtained at 1.45 m during the International Geophysical Year (from August 1957 through August 1958), Alekseev came to an important conclusion—the sporadic radio emission of the Sun was due to local, primarily polarised, sources on the solar disk, with sizes, as a rule, less than $9'$.

Vitkevich and Alekseev obtained various important results based on polarisation measurements of the active Sun at 1.45 m, including results concerning the polarisation of the "peaks" mentioned above.

Development of Radio Astronomy Spectroscopy In 1951, American, Australian and Dutch radio astronomers detected nearly simultaneously the radio line of neutral hydrogen at 21 cm, which had been predicted earlier by the theoreticians van de Hulst and Shklovskii (see Essay 3). At the end of 1952, Chikhachev carried out a series of monochromatic investigations, aimed at developing a radio spectrometer operating near 21 cm, for studies of this hydrogen line. During 1953–1954, this radio spectrometer was developed by Sorochenko in Moscow, and brought to Katsiveli in Autumn 1954, where it was placed in the laboratory near the "western" V-3 radio telescope.

The first recording of the 21-cm hydrogen line at the Crimean Station was obtained on December 28, 1955; these were the first successful radio astronomy spectroscopic observations carried out in the Soviet Union. More than three years went by before regular observations were established, however. During this period, the specific requirements of spectral radio astronomy observations were studied, instruments prepared and the radio telescope outfitted; in particular, an automated tracking system incorporating electro-mechanical coordinate translation, originally developed for the 22-m radio telescope in Pushchino (see below), was installed.

In 1954, Sorochenko, Vitkevich and Chikhachev attempted to detect line radio emission from the CH radical, which, according to the calculations of Shklovskii (which subsequently were shown to be too optimistic), should have been emitted at a frequency of 3180 MHz. For this purpose, they used their accumulated experience to develop a spectrometer operating at 10 cm wavelength, which was then installed on the 7.5 m radio telescope. The results of spectral observations toward the centre of the Galaxy were negative: the sought-for CH line was not detected in the frequency range (3190 ± 12) MHz (with the antenna temperature of the line being <30 K).

Sorochenko began a large series of studies in a complex region of the Galaxy—Cygnus X, including measurements of the distribution of neutral hydrogen. It turned out that Cygnus X is located inside the nearest spiral arm, and consists of two main condensations of ionised hydrogen located at distances of 1.5 and 3 kpc. Analysis of both radio and optical studies were used to find the distances to four regions of ionised hydrogen near the Galactic plane, between Galactic longitudes of 75 and 89°. It was shown that an observed cluster of optical emission nebulae in Cygnus X coincided with a region of enhanced radio emission, and was due to the projection of several HII regions located at various distances.

This group of spectral studies at the Crimean Station formed a centre and a school for spectral radio astronomy in the USSR. Many specialists from other institutions came to carry out spectral investigations and to obtain experience in instrumental development, including the now widely known radio astronomers N. S. Kardashev (Space Research Institute), T. A. Lozinskaya and M. I. Pashchenko (Sternberg Astronomical Institute), T. M. Egorova (Main Astronomical Observatory) and G. T. Tovmasian (Byurakan Astronomical Observatory). Sorochenko became the scientific supervisor of spectral studies in the Radio Astronomy Laboratory in 1960 (after the departure of Chikhachev).

Ionospheric Studies Using Radio Astronomy Methods Observations of the inhomogeneous structure of the ionosphere based on the analysis of radio emission from the most intense cosmic radio sources (Cassiopeia A, Cygnus A, Virgo A and the Crab Nebula) after its passage through the ionosphere begun earlier were continued starting in 1951. Beginning in 1954, these studies were carried out by the group of Yu. L. Kokurin.

A series of studies of small-scale inhomogeneities in the ionosphere were conducted as part of the programmes of the International Geophysical Year and the International Year of the Quiet Sun. The dimensions, shapes and motions of inhomogeneities with characteristic sizes of about several kilometres were studied in detail, as well as their daily and seasonal behaviour and their connection with the state of the Sun. This work was carried out using observations of Cassiopeia A, Cygnus A and Virgo A made with spatially separated receivers operating at a wavelength of 6 m.

Small-scale ionospheric inhomogeneities were also studied using sounding measurements made with a triangle formed of three rhombic antennas operating at 7–8 MHz. This yielded the interference patterns of magneto-ionic components of the radio signal reflected from the ionosphere. On this basis, it was proposed that fading of the signal was observed, and the fluctuations in the electron density due to small-scale ionospheric inhomogeneities were estimated (from a joint analysis of the results of transmission and ionosphere-sounding measurements).

Another large series of studies continuing until 1969 was devoted to studies of the large-scale structure of the ionosphere. This work was a direct continuation of investigations begun in 1949. On their basis, Vitkevich and Kokurin showed that the regular component of the vertical refraction in the ionosphere is due to inhomogeneities with sizes of about 200 km in the F layer. The speeds of the motions of these inhomogeneities in the ionosphere were measured (50–100 km/s). Vitkevich estimated the ratio of the total number of electrons contained in inhomogeneities to the total number in a column with unit cross section for the unperturbed ionosphere with inhomogeneities with sizes of 5 km, based on the results of interference observations obtained in 1951–1956.

Based on calculations of the dependences of the vertical and horizontal refractions on the zenith angle at 4 m wavelength carried out in 1958, Kokurin identified an appreciable difference between these dependences for two models for the non-uniform structure of the ionosphere (wavy and cloudy). He pointed out that this difference could serve as a basis for discriminating between ionospheric models.

A series of simultaneous refraction measurements at zenith angles of 0–30 and 77–90° carried out in 1955–1959 enabled Kokurin, Sukhanovskii and Alekseev to obtain new data on large-scale ionospheric inhomogeneities, in particular on their scales, structure and behaviour throughout the day. Ovsyankin also actively took part in all the ionospheric studies carried out after 1957.

Radio interference methods have found applications in a wide range of radio astronomy and applied problems.

Observations of the First Soviet Space Rockets In 1958, the Crimean Station of FIAN faced an important and extremely complex task—determining the flight trajectory of a rocket heading towards the Moon. The construction of the measurement complex was supposed to be completed over several months. The head of the Oscillation Laboratory of the FIAN, A. M. Prokhorov, defined the task at hand. It was necessary to construct a high-sensitivity, precision interferometer operating at a wavelength of 1.76 m. The work was monitored directly by M. V. Keldysh and S. P. Korolev, who arrived and acquainted themselves with the work at the site. An operative headquarters was established, headed by Vitkevich.

The antennas of the radio spectrometer, which seemed huge and, in any case, immovable, were shifted over several hours and mounted with an accuracy of several millimetres. New feeds (Yu. P. Ilyasov) and low-noise amplifiers (Matveenko) were developed and constructed, the cable system was laid and the necessary equipment assembled. The radio interferometer was ready in Autumn; it was aligned using radio astronomy methods—observations of cosmic radio sources.

On January 2, September 12 and October 4, 1959, this radio interferometer was used to determine the flight trajectory of the rocket with very high accuracy for that time—about a minute of arc (absolute error). The time when *Luna-2* would land on the Moon was determined, and the automated radio measurement complex was used to determine the landing site, near the crater Archimedes. The results of this unique experiment were published (Vitkevich, Kuz'min, Matveenko, Sorochenko and Udal'tsov).

Together with this work of the Crimean Station of FIAN, radio astronomy investigations were carried out on the eight-antenna radio telescope of the Deep Space Communications Centre (see Essay 9). The preparation of the equipment complex and organisation of the observations was supervised by Matveenko. In 1960–1961, equipment operating at 32 and 8 cm was developed with the direct participation of G. Ya. Gus'kov. The first observations of cosmic radio sources at 32 cm were carried out in the Summer of 1962, and the first observations at 8 cm in the Summer of 1963. These observations were the first to use a quantum paramagnetic amplifier (Matveenko, V. B. Shteinshleiger).

At the stage of bringing the equipment into operation, a number of PhD students at the Sternberg Astronomical Institute joined the effort (see Essay 3). The ability to join the forces of these two organisations with the friendly participation and help of V. A. Kotel'nikov and his group at the Institute of Radio Physics and Electronics made it possible to accelerate the work. Detailed measurements of the radio telescope's beam were conducted, and the presence of absorption by thermal electrons in the spectrum of the Seyfert galaxy NGC 1275 was established (Matveenko).

In November 1958, the Crimean Station of FIAN was reorganised into the Crimean Scientific Station, and work in radio astronomy began to be taken over by the newly constructed Radio Astronomy Station in Pushchino. In 1962, the Crimean Station became part of the laboratory of N. G. Basov, and the topic of the work there changed; the leading radio astronomers who had worked there moved to Pushchino.

1.3 The Radio Astronomy Station in Pushchino. Founding and Development

The Moscow Division of the Radio Astronomy Section As early as November 1951, at the initiative of Khaikin in the framework of a programme to organise a solar service in the Soviet Union, the USSR Academy of Sciences and two ministries were given the task of preparing proposals for the planning and construction of large reflecting telescopes for radio observations of the Sun and other cosmic radio sources at centimetre and millimetre wavelengths. For the first time, the construction of a radio telescope with the participation of industry was discussed. The possibility arose of forming an experimental basis for developing radio astronomy at millimetre wavelengths. Khaikin offerred the development of this direction to Salomonovich, and the development of a radio telescope operating at millimetre wavelengths to Kalachev. In 1952, the group of Salomonovich included the radio technicians E. K. Karlova and N. A. Amenitskii and the mechanic S. K. Palamarchuk, with U. V. Khangil'din joining slightly later.

In 1952–1954, a radiometer designed to operate at 8 mm with a balance mixer based on silicon diodes and an electrodynamic modulator was devised. At the same time, Kalachev developed a turning device with an equatorial mount for a glass parabolic surface (2-m diameter) taken from a searchlight. This radio telescope, the RT-2, was apparently the first Soviet radio telescope to have an equatorial mount.

Adjustments in declination were carried out by hand using a theodolite. The radio telescope was manufactured entirely at FIAN by workers in the corresponding shops in the Radio Astronomy Section (A. A. Levin, I. G. Evtyukhov, P. D. Lebedev and A. V. Rybakov).

By the Summer of 1954, the RT-2 radio telescope together with a cooled radiometer was ready to be sent to Novomoskovsk (in the Dnepropetrovsk region), where it was proposed to observe a solar eclipse on June 30 (a large group of researchers from the Crimean Station also took part in these observations, using radio telescopes operating at metre and decimetre wavelengths). Several days before it was to be shipped, the two-metre surface cracked as it was being mounted into the frame of the radio telescope. The situation was saved by Ya. N. Fel'd, who kindly loaned a similar but slightly smaller parabolic surface. Yu. N. Pariiskii actively took part in the adjustment of the radio telescope and the observations that were conducted during the eclipse. These first observations of a solar eclipse at millimetre wavelengths in the USSR revealed an enhancement in the radio brightness of the solar limb.

In 1953, two Masters' students of Salomonovich, and then two PhD students of Khaikin, N. V. Karlov and T. A. Shmaonov, began their work in the Moscow Division of the Radio Astronomy Section. At that time, in connection with the move toward observing at shorter wavelengths and the need to observe relatively weak sources, the question of the limiting sensitivities of radio astronomy equipment became quite critical. This question had been examined from a theoretical point of view by F. V. Bunkin (a PhD student of S. M. Rytov) and by Karlov; the results of their studies subsequently became classic.

With the aim of selecting an optimal modulation frequency, Salomonovich and Smaonov experimentally studied the spectrum of the low-frequency noise of a radiometer. For the first time, a non-mechanical means of modulation was applied at centimetre wavelengths, based on the Faraday effect in a ferrite rod, and the first model of an automated zero radiometer was developed (Salomonovich and Karlov).

In 1955, the RT-2 radio telescope operating at a wavelength of 8 mm was installed at the site of the Solar Radio Laboratory in Krasnaya Pakhra (Institute for Terrestrial Magnetism, the Ionosphere, and Radio-wave Propagation of the Academy of Sciences). In 1955–1958, Salomonovich carried out a series of solar observations, including observations of the partial eclipse of 1956. These observations made it possible to determine the brightness temperature of the Sun and the dependence of the slowly varying component on the activity index. The phase dependence of the brightness temperature of the lunar radio emission was detected for the first time. In connection with this last result, the presence of a second harmonic of the periodic dependence of the varying component on the phase was detected, and was consistent with the theory worked out at that time by V. S. Troitskii. Radio astronomy methods were also used to study the absorption of 8 mm radiation in the atmosphere as a function of the meteorological conditions (O. M. Ataev, Salomonovich).

In the beginning of 1953, a new group focusing on studies of monochromatic radio emission was formed in Moscow under the leadership of Chikhachev. This group included Sorochenko, Yu. L. Sverdlov, S. A. Zaitsev and V. I. Kruchinenko.

In a comparatively short time, they had built a complex and, in many ways, quite unusual spectrometer designed for studies of 21 cm radio emission.

Kuz'min joined the Radio Astronomy Section in 1954; earlier, he had specialised in measurements of electrical noise signals and the construction of high-sensitivity receiver-amplifier schemes, being the author of the book *Measurements of the Noise Coefficients of Receiving and Amplifying Devices* (Moscow/Leningrad, Gosenergoizdat, 1955). A group working on the development of methods for measuring the intensities of cosmic radio sources and the construction of radiometers with low noise levels was formed under his supervision (L. A. Levchenko, M. T. Levchenko, V. S. Borodacheva and A. N. Khvoshchev). The first noise generators in the Soviet Union were built. In 1957, the group finished the development and construction of a high-sensitivity polarisation-sensitive radiometer designed to operate at 9.6 cm, which had the high fluctuation sensitivity for that time of about 0.15 K.

Salomonovich, Karlov and Amenitskii devised a new generation of radiometers operating at 3 cm, which were subsequently installed on the radio telescope in Pushchino, and then on the RT-31 radio telescope in the Crimea in 1957 (see above). This same group began the development of a polarisation-sensitive radiometer for observations at 8 mm, based on the use of ferrites, designed to measure all four Stokes parameters. This work, carried out by U. V. Khangil'din, led to the establishment of an installation for studies of solar active regions.

The first polarisation radiometer indicated above was tested during observations of the solar eclipse of April 24, 1958 on a radio telescope equipped with a parabolic surface with a diameter of 90 cm and an equatorial mount located on Hainan Island (People's Republic of China), where collaborative observations were carried out by the Academy of Sciences of the USSR and scientists of the PRC. Salomonovich, Khangil'din and Amenitskii participated in these observations.

N. A. Lotova joined the Radio Astronomy Section in 1955, working on the theory of the scattering of radio waves in the interplanetary medium under the supervision of Vitkevich. In connection with this, the work of the construction group of Kalachev was very productive.

Thus, the Moscow Division of the Radio Astronomy Section, and further the Radio Astronomy Laboratory, played a very important role in the development of radio astronomy techniques and equipment and the construction of radio telescopes.

Construction of the RT-22 Telescope. First Observations in Pushchino The large amount of experience with radio astronomy investigations obtained in the 1950s led to the determination of the main requirements for radio telescopes. The question of expanding into the range of millimetre and short centimetre wavelengths became pressing. Observations at precisely these wavelengths could more easily be used to compare the results of radio and optical studies. This required a radio telescope with a large effective area to enhance its sensitivity and angular resolution. The construction of such an instrument was not a simple task, however. There was no experience in constructing large, steerable, precision surfaces either in the Soviet Union or abroad.

None of the industrial organisations at that time was willing to take on the construction of such an instrument, citing lack of experience. Therefore, the development of a draft design for a steerable radio telescope with a parabolic surface and a diameter of 16 m was entrusted to FIAN in 1955, together with a number of other organisations, each of which would be responsible for the development of various individual systems of the radio telescope.

The work on the draft design of this 16 m radio telescope, in which Kaidanovskii participated, in addition to Salomonovich and Kalachev, was completed in 1952. Starting in February 1954, workers at FIAN and a number of organisations and ministry industries carried out the technical and operational design of an experimental model of the radio telescope. Based on the results of the draft design, after analysing the possibilities for constructing a supported, steerable device and the framework for the reflecting surface, it was decided to increase the diameter to 22 m and construct the radio telescope that is now known as the RT-22 of FIAN.

A division concerned with the development and exploitation of radio telescopes was formed in the Radio Astronomy Section of the Oscillation Laboratory of FIAN. The scientific supervisor of this division was the main construction engineer in the section—Kalachev. G. G. Stolpovskii was the assistant head of the section for some time. Attentive interest in this work was expressed by the assistant director of FIAN, M. G. Krivonosov, as well as the head of the Oscillation Laboratory, Prokhorov.

There were many difficulties in constructing the RT-22 radio telescope. On the scientific and technical side, it was necessary to solve the fundamentally new problem of constructing a reflecting surface for an antenna that was 22 m in size with an accuracy of a fraction of a millimetre. In addition, when the dish, which had a mass of more than 50 tons, was tilted, the deformations of the shape must likewise not exceed a fraction of a millimetre.

Kalachev and Salomonovich and their teams solved the problem of how to build a precise, large reflecting surface using a new and original type of construction—attaching an accurate reflecting surface to a rigid but crude frame using studs. The accuracy of the surface was achieved by adjusting the length of the studs, and its rigidity by an optimal choice of construction.

The development and construction of an instrument such as the RT-22 did not present a complex problem in those years only from a mechanical and surface-accuracy point of view. It was necessary to determine how to receive and channelise the radio signal on scales that had never been used before; high-sensitivity receiver/recorder equipment operational at a wavelength of 1 cm was required; the pointing and tracking system was supposed to steer an instrument with a mass of more than 700 tons with an angular accuracy of no worse than 10–20″ with an altitude–azimuth mount, which required translation from equatorial coordinates. Specialists from a number of industrial organisations also took part in the development of the radio telescope (A. A. Pistol'kors, L. D. Bakhrakh, K. I. Mogil'nikova, M. I. Grigor'eva, I. V. Vavilova, G. Yu. Pogozhev, N. M. Yakimenko, Yu. N. Semenov, V. A. Vvedenskii, P. V. Dobychin, A. N. Kondrat'ev, N. Ya Bulkin and others).

When the designs for the supporting and turning structure arrived at the construction division of the manufacturing plant, the constructional engineers there pointed out the strong similarity of the support and turning system for rotation in azimuth with the design for the main gauge of a linear ship that had been manufactured earlier and never used, and suggested that this prepared structure be used, which saved time and resources. A team of constructional engineers from FIAN headed by Kalachev went to the plant, reworking over several weeks the adjacent nodes for the support and turning system for rotation in hour angle.

The construction of the RT-22 radio telescope played an important role in the beginnings of the Radio Astronomy Station of FIAN in Pushchino, which now carries out primarily radio astronomy studies.

In 1954, the question arose of finding a suitable location for the RT-22, together with a complex of scientific and technical buildings, living quarters and buildings housing the equipment necessary for its use.

It was first proposed to place the new radio telescope on a small area located on the territory of the Institute of Terrestrial Magnetism, the Ionosphere and Radio-wave Propagation near Moscow. However, in 1955, Vitkevich and Chikhachev suggested that another new cross radio telescope operating at metre wavelengths be built. This radio telescope (see below for more details) needed an area 1 km by 1 km in size, and a much larger area was required for both radio telescopes. Therefore, FIAN made the decision at the beginning of 1955 to built a radio astronomy station where both radio telescopes would be located somewhere near Moscow.

Special groups under the leadership of Stolpovskii and M. M. Tyaptin were formed to search for a suitable site, and investigated a number of places in the southern part of the Moscow region, as well as in the Kaluga, Ryazan and Tula regions.

As a result, a site on the banks of the Oka River was chosen, where it was proposed in the future to house a scientific centre of the USSR Academy of Sciences (now the city of Pushchino).

The construction of the Radio Astronomy Station of FIAN helped prepare the production–construction base for the future scientific city, which also simplified the solution of a number of day-to-day and social questions concerning the lives and work of the workers at the station.

It is traditional to take the birthday of the Radio Astronomy Station to be April 11, 1956, when the permission to construct the RT-22 radio telescope was granted. Thus, FIAN became the first scientific institution to begin the creation of a scientific base at the site of the future scientific city of Pushchino.

The new location began to take shape under the general supervision of Vitkevich, who was at that time the head of the Radio Astronomy Section of the FIAN, and his assistants Salomonovich and Kovalevskii. The Oka Station was organised to monitor the construction and assembly of the equipment, and also the preparation of the first scientific studies using the cross and RT-22 radio telescopes (subsequently the continuously operating Oka Radio Astronomy Station of FIAN).

In February 1960, the Radio Astronomy Section of the Oscillation Laboratory was separated off to form the independent Radio Astronomy Laboratory of FIAN, consisting of the Oka and Crimea Radio Astronomy Stations, as well as the Moscow group. Vitkevich became the head of this laboratory, simultaneously being named the head of the Oka Radio Astronomy Station, with Kovalevskii as his assistant.

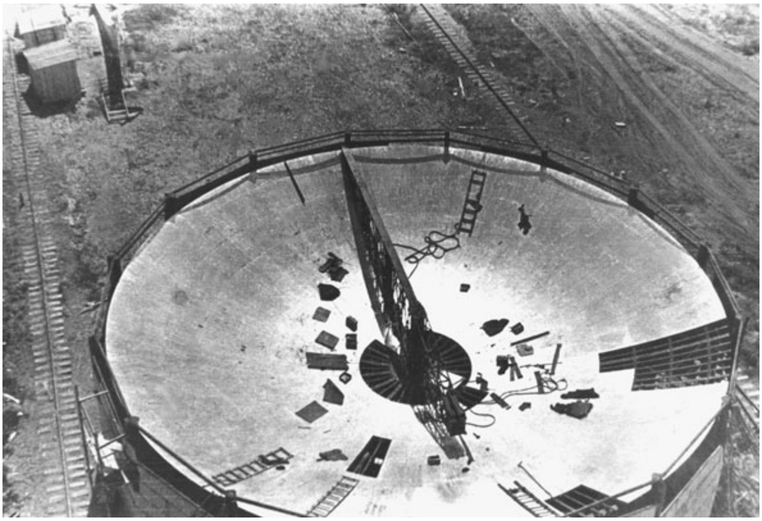

Fig. 1.11 Assembly of the reflecting surface of the FIAN 22-m radio telescope using a knife template at Pushchino (1957–1958)

While the development and manufacture of the two large radio telescopes was underway, Vitkevich continued his investigations of the solar supercorona in Pushchino.

Using several small antennas from obsolete radar stations, Vitkevich and Panovkin conducted observations that established that the solar supercorona has a radial filamentary structure. Since the motion of charged particles is "frozen" to the magnetic-field lines, they concluded that the Sun had a radial magnetic-field structure. This was the first discovery made in Pushchino, which was issued a discovery diploma in 1970, with the discovery date given as June 1957.

The foundation of the RT-22 was laid at the end of 1956. The construction of the laboratory buildings and living accommodation together with the complex of technical buildings was begun (G. V. Sovkov, A. B. Ulanovskii, Tyaptin).

The work was greatly expanded in 1957–1958. Teams under the supervision of V. I. Emelin and I. D. Krongauz assembled the metal elements and mechanisms arriving from the plants, and assembled and adjusted the control system (the groups of M. A. Vestfal' and V. A. Vvedenskii). The young specialist of the Radio Astronomy Station G. G. Basistov also participated in the adjustment of the control system.

Considerable help in the creation of the Radio Astronomy Station was given by the director of FIAN D. V. Skobel'tsyn, his assistants M. G. Krivonosov and I. F. Kalakin, the head of the Oscillation Laboratory and Corresponding Member of the Academy of Sciences A. M. Prokhorov and the secretary of the Party organisation of the laboratory N. G. Basov.

The construction of an accurate surface proved to be technically extremely complex. This work was brilliantly carried out in an original way by the team of V. N. Kondrashov under the supervision of Kalachev (Fig. 1.11). In November 1958, the surface achieved a record accuracy for that time—0.3 mm (rms error), which was provided by manufacturing the reflecting surface of the radio telescope using a precision template. This painstaking work, conducted under the dome of a specially constructed technical shop with a removable roof, occupied about half a year. On the morning of November 18, 1958, the multi-ton 22-m reflector was lifted from the assembly building using a travelling gantry crane, transported to the already constructed support–turning structure, placed onto this structure and fixed in place. The entire operation lasted two hours.

When the assembly of the RT-22 was completed and the telescope was making its first tests and observations, Kuz'min joined the group of Salomonovich, which had been entrusted with becoming acquainted with this new instrument, actively participating in the adjustment and measurement of the parameters of the RT-22.

By the end of 1958, the reflector axis was installed in the calculated position using a theodolite, the surface had been additionally adjusted, all the cable lines had been assembled and all the drive mechanisms aligned and adjusted. The feed supports were installed at the beginning of 1959, and the first version of the radiometer block, with receivers and feeds operating at 3 cm and 8 mm, mounted at the focus of the RT-22. Various methods for illuminating the main surface were considered during the designing of the RT-22. Salomonovich and N. S. Soboleva (1955) looked into various aspects of the electrodynamics of a two-mirror Cassegrain system. The draft design also considered a modern (operating at several wavelengths) waveguide–horn feed system. However, as a first version, a simple microwave block operational at wavelengths of 3.2 and 0.8 cm with waveguide feeds was developed and used (Fig. 1.12).

The radio telescope became operational at the beginning of May 1959. At the meeting of the A. S. Popov Scientific Society on May 7, 1959, which was dedicated to radio studies, the first recording of the solar radio emission at 8 mm was demonstrated. The recording of the passage of an arched active region across the solar disk was used to estimate the width of the antenna beam, which was $2'$, close to the calculated value.

The experience accumulated during the construction of the FIAN RT-22 was later used to build and equip the analogous RT-22 radio telescope of the Crimean Astrophysical Observatory. In a resolution made on April 21, 1977, the Presidium of the USSR Academy of Sciences awarded Salomonovich and Kalachev (Fig. 1.13) the A. S. Popov Prize for outstanding achievements in the construction and study of millimetre-wave radio telescopes. This new instrument opened wide opportunities for radio astronomy investigations at centimetre and millimetre wavelengths.

In the first systematic observations on the RT-22, carried out in 1959–1960, the two-dimensional radio brightness distribution over the solar disk was measured at 3 cm and 8 mm. This provided the first information about the dynamics of radio-emitting active regions, and also made it possible to identify flares of the millimetre-wavelength radio emission (Salomonovich). Khangil'din detected a region of reduced 8 mm radio brightness on the solar disk associated with protuberances.

Soon after these first observations, measurements of the 8 mm radio brightness distribution across the disk of the Moon began, as well as systematic measure-

Fig. 1.12 The 22-m radio telescope of FIAN. The first complex of radiometers (0.8 and 3.2 cm) is at the focus of the parabolic surface

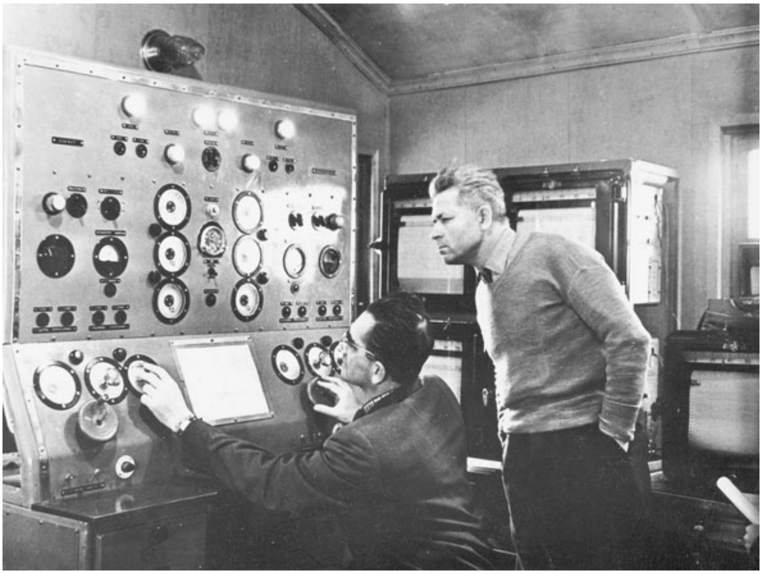

Fig. 1.13 A. E. Salomonovich and P. D. Kalachev in the control room of the 22-m radio telescope (1959)

ments of the phase dependence of the lunar brightness temperature at various wavelengths. These measurements, in which Salomonovich, Amenitsii, Khangil'din, A. M. Karuchun, V. N. Koshchenko, R. I. Noskova and B. Ya. Losovskii participated, yielded results about the degree of constancy (in the case of the Sun) and the magnitude of the regular behaviour (in the case of the Moon) of the shifts of the centres of gravity of the radio emission over the disks of these objects.

After this first series of measurements, Salomonovich, Kuz'min and Karachun electrically adjusted the position of the RT-22 feeds and carried out the first studies of the telescope's parameters. The adjustment and measurement of the parameters of the RT-22 required the solution of a number of scientific and technical problems, which led to the development of new methods based on the use of cosmic radio sources. The considerable experience acquired in this work led Kuz'min and Salomonovich to write the monograph *Radio Astronomy Methods for the Measurement of Antenna Parameters* (Moscow: Soviet Radio), which was published in 1964 and translated into English in the USA in 1964. These methods were subsequently widely used in practise to measure the parameters of the large antennas used for radar and space communications.

An original method for measurements in the near zone—the defocussing method (Salomonovich, B. V. Braude, N. A. Esepkina)—was also used to adjust the telescope and estimate its effective area.

In January–April 1960, Kuz'min, Salomonovich and others carried out a survey of discrete radio sources at 9.6 cm on the RT-22 radio telescope, compiling the first radio catalogue in the Soviet Union, which contained 56 discrete sources, 34 of them observed for the first time at centimetre wavelengths. In June 1960, Karachun, Kuz'min and Salomonovich conducted observations of several radio sources at the shorter wavelength of 3.2 cm. It was discovered that the spectrum of the source Cygnus A becomes steeper at centimetre wavelengths. Based on this break in the spectrum, Kardashev, Kuz'min and S. I. Syrovatskii derived one of the first estimates of the age of this radio source—about 0.5 million years.

A group of Soviet radio astronomers participated in a Soviet–American symposium dedicated to problems in radio astronomy in 1962. Well known scientists from both the USSR and USA actively took part in this symposium (Fig. 1.14).

Construction of the DKR-1000 Radio Telescope In 1959, the construction of another large-scale instrument began at FIAN—the DKR-1000 metre-wavelength radio telescope. This was proposed by Vitkevich as a way to further develop studies of the solar supercorona and cosmological studies.

The discovery of the solar supercorona made detailed investigations of the structure and nature of circumsolar space of considerable interest. This required an increase in the number of radio sources that could be observed as they passed behind the supercorona, which motivated the need for a radio telescope with a large collecting area and high resolution.

At the same time, the problem arose of "counting the radio stars," as the cosmological problem of investigating the distribution of galaxies in the Universe was called at that time. The development of this line of research, which was extremely

Fig. 1.14 Participants of the Soviet–American radio astronomy symposium (USA, 1962). *Lower row* (*from left to right*): G. G. Getmantsev, F. T. Haddock, two unidentified women, R. Minkowski, V. V. Vitkevich, O. Struve, R. L. Sorochenko, J. Fisher, G. Keller, A. D. Kuz'min, R. N. Bracewell, F. D. Drake; *middle row*: C. M. Wade, E. F. McClain, V. A. Sanamyan, P. D. Kalachev, G. Stanley, A. Barrett, H. Weaver, G. Swenson, C. Mayer, D. S. Heeschen, J. Kraus; *upper row*: G. Field, T. Menon, R. Seeger, L. Woltjer, A. Sandage, A. Lilly, A. Blaauw, F. Kahn, B. Burke

important for studies of the evolution of the Universe, required observations of a large number of sources. Meter wavelengths were most suitable for this purpose, since it was possible to achieve high sensitivity using comparatively simple technical methods, and high resolution could be provided by constructing the telescope in the form of an extended cross. It was also possible to match the sensitivity of the instrument for source counts with the telescope's resolution.

The mechanisms generating the gigantic energies of extragalactic sources already deeply interested scientists at that time. In this connection, as well, it was important to study the structures and spectra of as many radio sources as possible.

In 1956, Vitkevich aided by Chikhachev proposed to construct a Mills-cross-type radio telescope, but with reflectors in the form of parabolic cylinders, each 1000 × 40 m in size. Estimates indicated that such an instrument could detect several thousand discrete sources. The high angular resolution required for studies of the structure of radio sources could be obtained by adding comparatively small movable antennas to the main radio telescope, thus forming an interferometric system. This proposal was approved by the head of the Oscillation Laboratory of FIAN, Prokhorov, who also subsequently supported the construction of the metre-wavelength cross telescope.

Kalachev rapidly came up with a draft scheme for the project, according to which the east–west arm of the antenna would be rotated in hour angle using a synchronised electrical shaft containing 37 motors, one for each of the parabolic 40-metre trusses. It was planned to use an electrical phasing method to change the direction of reception for the north–south arm of the antenna to be consistent with that for the east–west arm.

During the construction of the radio telescope, Kalachev, V. P. Nazarov and Tyaptin spent an appreciable amount of time at the construction site, supervising the assembly process. The construction of such a gigantic structure was a complex technical task that was being tackled by the constructor engineers of the Radio Astronomy Laboratory for the first time: nobody in either the Soviet Union or abroad had previous practical experience with such a project.

The financing for the construction of the radio telescope was rather limited. The available resources were sufficient only to carry out the most important aspects of the work. The further development of the radio telescope system, in particular, of the receivers and control computer, had to be carried out later.

Essentially simultaneously with the mechanical construction, the electrical wiring for the east–west antenna was strung up, and the necessary electrical and radio frequency cables laid. At the suggestion of Alekseev and A. M. Veselov, the drive motors were used in an asynchronous regime, and equipped with protection against discrepancies between the positions of the trusses.

The development of the microwave system of the cross radio telescope began in 1957 with the construction at the Oka Station of a section of a feed with an operating wavelength of 3.5 m under the supervision of Kuz'min. This work was carried out by Ilyasov, aided by Kruchinenko and L. A. Levchenko.

During the analysis of the perspective use of the telescope, it became clear that narrow-band feeds would limit the observational capabilities of the future instrument; in addition, the use of such feeds would create complex problems associated with the movement or reassembly of the feeds in order to change the observing wavelength. Based on the broadband oscillators that had been designed by G. Z. Aizenberg and V. D. Kuznetsov, in 1957, Kuz'min and Ilyasov proposed the use of a broadband feed that could operate at 30–120 MHz.

A model of the V-3 section of the antenna was constructed in 1958, and was used to study the parameters of this section of the feed and work out the best means for its construction.

The broadband oscillators and a co-phased, parallel-storey design for the addition of the signals provided unique opportunities to carry out observations simultaneously within a range of two octaves. The instrument was accordingly named the *Diapozonnii krestoobraznii radioteleskop* ("Broadband Cross Radio Telescope", DKR-1000).

The design work for the radio telescope proceeded in parallel with the assembly and adjustment work. Much was done to organise this work by Kovalevskii, who was the assistant head of the station at that time, as well as by N. P. Vladimirov, N. F. Kotov and K. I. Stepnov.

The construction of the V-3 antenna reflector was carried out on schedule. The first of a series of feed sections consisting of eight oscillators was installed in the first span of the antenna, and the first observation of the passage of a discrete source was conducted on October 15, 1961.

The installation of the remaining feed sections all along the antenna began in Spring 1963. The alignment and adjustment of the electrical lengths of the trunk cables (500 m) to an accuracy of better than 1 cm—carried out by Ilyasov, aided by A. V. Afon'kin, V. T. Solodkov, A. N. Ivanov, N. N. Lapushinskii and others—was finished by the middle of 1964. By the same time, V. I. Vlasov, V. S. Medvedeva and T. I. Gavrilenko had manufactured a two-frequency radiometer that could operate at 30–120 MHz.

Fig. 1.15 DKR-1000 cross radio telescope of FIAN: North–South arm

Fig. 1.16 DKR-1000 cross radio telescope of FIAN: East–West arm

By the end of 1964, the V-3 section of the antenna was ready for scientific observations, which were initiated by V. S. Artyukh and R. D. Dagkesamanskii under the supervision of Vitkevich. The adjustment of the north–south antenna was finished and the antenna ready for observations at the end of 1965 (Figs. 1.15, 1.16).

Development of Studies Using the RT-22 in the 1960s and 1970s The RT-22 was actively used for research on the Sun, Moon, planets and other cosmic radio sources at millimetre and centimetre wavelengths.

Losovskii obtained images of the Sun at 2 cm before and after the solar eclipse of February 15, 1961.

As is noted above, the construction of a radio telescope with high resolution enabled investigations of the two-dimensional radio brightness distribution over the lunar disk at 8 mm, as well as at some centimetre wavelengths. These studies reliably established the presence of a latitude distribution of the brightness temperature, indicating a decrease in the surface temperature toward the poles. Lunar radio maps were used to estimate the mean dielectric constant ($\epsilon \simeq 2$). Estimates provided evidence that the material making up the lunar surface had a low density and thermal conductivity, and also a small loss angle (Salomonovich, Koshchenko, Losovskii).

In 1961, A. G. Kislyakov, Losovskii and Solomonovich detected a modest enhancement of the brightness temperatures at 4 and 8 mm in the region of the lunar "seas" compared to the region of the "continents." In 1963–1965, Losovskii and Salomonovich conducted a prolonged series of measurements at 0.8 and 1.35 cm. The results showed that the surfaces of the lunar seas and continents have slightly different physical characteristics, and Losovskii later concluded that, indeed, they have different chemical and mineral compositions. These conclusions reached on the basis of radio astronomy measurements were later confirmed in direct studies of the Moon using spacecraft.

By the completion of the construction of the RT-22 in 1958, a group of American radio astronomers had published a paper reporting that the brightness temperature of Venus was unexpectedly high—around 600 K. This contradicted the generally accepted view at that time that the planet Venus had physical conditions that were roughly the same as on the Earth. Kuz'min and Salomonovich developed a broad programme of studies of Venus and other planets, which was also very timely in connection with the flights of various spacecraft to Venus. FIAN proposed to study the possible usefulness of carrying out parallel terrestrial measurements of the radio emission of Venus at all accessible wavelengths, and this was viewed favourably by the President of the USSR Academy of Sciences, Academician M. V. Keldysh. Thanks to the support of the chairman of the Scientific Council on Radio Astronomy, Academician V. A. Kotel'nikov, it was possible to bring the laboratory of I. V. Shavkovskii and I. S. Rabinovich into the project in connection with building sensitive radiometers at centimetre wavelengths. By 1961, with their help and under the supervision of Salomonovich and Kuz'min, the groups of V. P. Bibinova and V. V. Ermolaeva had devised radiometers with parametric amplifiers operating at wavelengths of 1.6, 3.3 and 10 cm, which yielded an increase in sensitivity by about an order of magnitude. An apparatus designed to operate at 8 mm was developed at the Institute of Radio Physics and Electronics (V. A. Ablyazov, B. G. Kutuza), while a radiometer operating at 4 mm was devised at the Radio Physical Research Institute in Gorkii (Kislyakov).

In connection with the desire to conduct observations simultaneously (or nearly simultaneously) at several different frequencies, for example, to investigate the radio spectrum of Venus, a composite feed with electrical axes intended for simultaneous observations at 8 mm (in both polarisations) and at 1.6, 3.3, 10 and 21 cm was designed, manufactured and installed on the RT-22 (L. D. Bakhrakh, I. V. Vavilova, G. K. Galimov, Kalachev, A. M. Karachun, Kuz'min, Losovskii, Salomonovich).

As a result of a series of measurements by Yu. N. Vetukhnovskaya, Kislyakov, Kuz'min, Kutuza, Losovskii and Salomonovich, it was possible to obtain the spectrum of the brightness temperature of Venus from 4 mm to 10 cm for the first time.

The very high brightness temperatures that were measured at centimetre wavelengths did not necessarily imply that the surface and lower atmosphere of the planet had such high temperatures—a question that very much worried the engineers designing the equipment intended to land on the Venusian surface. Hoping to distinguish between the various models for Venus, two groups of researchers measured the radio brightness distribution over the disk of the planet in 1962. The Pulkovo group found a modest limb darkening toward the edge of the disk, consistent with the planetary surface being hot. However, a group of American radio astronomers obtained the opposite result.

In connection with the ambiguity of these interpretations of the spectrum and the associated radio brightness distribution, which led to very different conclusions about the physical conditions on Venus, Kuz'min proposed an experiment designed to identify the radiating medium, choose the appropriate model and thereby determine the temperature of the planetary surface. The idea behind the experiment was that, due to the differences in the Fresnel reflection coefficients for the vertical and horizontal polarisations, the radio emission of Venus should be polarised at the limb of the visible disk if this emission was radiated by the surface, but unpolarised if the emission was generated in the ionosphere, a cloudy layer or some other diffuse formation. This experiment, which was carried out in 1964 by Kuz'min and B. Clark on the radio interferometer of the California Institute of Technology, showed that the radio emission was polarised, thus demonstrating that the source of this emission was the surface of Venus, which had a temperature of about 650 K. The radius of the planet was also determined for the first time. These data were used in the development of the *Venera* landers, whose design incorporated thermal protection and a parachute of thermally stable fabric. In turn, the direct measurements of the temperature of the surface of Venus carried out in 1970–1972 by the *Venera-7* and *Venera-8* spacecraft confirmed that Venus is, indeed, a hot planet.

The equipping of the RT-22 with a very sensitive set of radiometers in the early 1960s, apart from various planetary measurements carried out by Kuz'min, Kutuza, Losovskii and Salomonovich (including the first observations of the 8 mm radio emission of Jupiter, Mars, Saturn and Mercury in the USSR), made it possible to conduct important studies of other cosmic radio sources. For example, in early 1963, V. A. Udal'tsov conducted polarisation studies of the Crab Nebula at 3.3 and 1.6 cm using the RT-22. These observations yielded the first measurement of the rotation measure in the direction of the Crab Nebula ($a = 0.28 \times 10^{-2}$ rad/cm^2). Udal'tsov obtained data indicating that there were different spatial distributions for the relativistic electrons giving rise to the optical and radio emission of the Crab Nebula.

The first international radio astronomy programme on the territory of the Soviet Union was carried out on the RT-22 telescope using the 8 mm radiometer in 1964. Kutuza, Matveenko, Salomonovich and the American radio astronomer A. Barret obtained the two-dimensional radio brightness distribution of the Crab Nebula at 3.3 and 0.8 cm. This same equipment was used for the detection of high-frequency excesses in the spectra of a number of quasars.

In the 1960s and 1970s, the development of work on the RT-22 was associated primarily with spectral studies of interstellar, monochromatic radiation and the installation of quantum paramagnetic amplifiers (QPAs) on the radio telescope.

At the beginning of 1963, Sorochenko, who had completed a series of investigations of the 21-cm hydrogen line at the Crimean Station, proposed to carry out a search for and study of radio lines of excited hydrogen on the RT-22. According to his calculations, searches for these lines, which had been predicted earlier by Kardashev, would be most effective at wavelengths near 3 cm, where the capabilities of the RT-22 matched the requirements of this task very well.

In order to realise this programme, Sorochenko and E. V. Borodzich, aided by M. T. and L. A. Levchenko, devised a new zero radiospectrometer intended for the search for radio lines, based on the 3-cm radiometer referred to above. This radiospectrometer was installed on the RT-22 telescope in early 1964. On the first day of observations, April 27, 1964, Sorochenko and Borodzich were able to detect a radio line of excited hydrogen in the direction of the Omega Nebula. This line, which was clearly visible even in individual recordings, corresponded to transitions between the 91st and 90th levels of the energetic states of the hydrogen atom. Subsequent measurements confirmed the results of these first observations.

The State Committee for Inventions and Discoveries registered the radiation of radio lines by excited hydrogen as a discovery made by FIAN researchers R. L. Sorochenko, E. V. Borodzich and N. S. Kardashev (who had first predicted this phenomenon), together with the husband and wife radio astronomers of the Pulkovo Observatory A. F. and Z. V. Dravskikh, who had carried out analogous measurements of radio lines at 5 cm. The date of the discovery was indicated as August 31, 1964, when a report on the detected lines was given at the XII IAU General Assembly.

In 1963, at the Oscillation Laboratory, under the supervision of Prokhorov, his PhD student R. M. Martirosyan built a QPA operating at a wavelength of 21 cm, which was successfully used on the RT-22 as part of a radiospectrometer complex (Martirosyan, Prokhorov, Sorochenko). This was the first such amplifier in the USSR constructed for radio astronomy studies. Its appearance proved to be very timely in other connections as well.

On April 16, 1964, it was possible to observe an occultation of the Crab Nebula by the Moon from Pushchino. It proved to be convenient to observe this very rare event at 21 cm: the signals from the Crab Nebula and the Moon were nearly identical for observations on the RT-22. Pushchino observations at 3, 10 and 21 cm yielded unique data on the brightness distribution of the Crab Nebula radio emission (Matveenko, Martirosyan, Sorochenko). Analogous observations were carried out at 8 and 32 cm on the antennas of the Deep Space Communications Centre in the Crimea, and also at metre wavelengths at Pushchino.

Work with the QPAs operating at 21 cm demonstrated that these amplifiers provided fundamentally new possibilities for radio astronomy studies, especially for observations of spectral lines.

In 1964, at the initiative of Salomonovich, radio astronomers of FIAN established close contact with the group of V. B. Shteinshleiger, who worked on the development of industrial models of the QPAs. Due to their joint efforts, a number of high-sensitivity radiometers with QPAs were devised for the RT-22 telescope. The development of the QPA radiometers was conducted under the supervision of Sorochenko.

A new group focusing on studies of the recently discovered radio lines of excited hydrogen and work on the development of new instruments for the RT-22 was formed, with its members being V. I. Ariskin, E. B. Borodzich, I. I. Berulis, V. M. Gudnov, L. M. Nagornykh, Yu. G. Chugunov and others. In their work, this group relied on the experience of N. F. Il'in, S. K. Palamarchuk and V. I. Pushkarev.

A radiospectrometer with a parametric amplifier was devised in 1966 for studies of the 21-cm neutral-hydrogen line on the RT-22 radio telescope (Berulis, B. Z. Kanevskii, A. A. Spangenberg, I. A. Strukov). A new zero radiospectrometer with a QPA operating at 5.2 cm was introduced into action in the same year. The system noise temperature was 130 K. The use of symmetric beam modulation with switching of the receiver input between two identical horn feeds made it possible to substantially reduce the influence of atmospheric fluctuations, which was important when using the high-sensitivity QPA radiometer. This radiospectrometer was used to carry out a survey of HII regions in the H 104 line of excited hydrogen, with detections being obtained in eight sources.

In 1964, anomalous high-frequency excesses were detected in the radio spectra of several extragalactic radio sources, due, as it was later elucidated, to the presence of components with very small angular sizes (10^{-2}–10^{-3} arcmin) in the nuclear regions of these galaxies and quasars. One of the earliest studies dedicated to the spectra and then the variability of the core components of active galaxies at centimetre and millimetre wavelengths was carried out on the RT-22 telescope under the supervision of Matveenko. V. I. Kostenko also actively participated in these studies.

Since the capabilities of the RT-22 telescope could best be applied in millimetre observations, it was always considered important to equip the telescope with sensitive equipment at these wavelengths. In 1964, nearly simultaneous with the development of the radiometer and 5.2 cm QPA, a similar radiometer for 8 mm observations was built. Since it was not possible to place the QPA at the prime focus of the telescope due to the operating conditions, and the losses in the millimetre waveguides were very high, Bakhrakh and Grigor'eva together with Kuz'min and Matveenko developed a two-mirror Cassegrain system at the initiative of Salomonovich, essentially simultaneous with its construction. This system made it possible to lower the antenna noise and fully realise the high sensitivity of the QPA. The Institute of Radio Physics and Electronics (V. A. Puzanov) also became involved in this work carried out under the supervision of Sorochenko and Kuz'min, who collaborated on the construction of a spectral radiometer operating at 8 mm wavelength that was used to study a QPA devised under the supervision of Shteinshleiger. All these developments brought about a sharp increase in the efficiency of the RT-22 telescope at 8 mm, by more than an order of magnitude.

A new system operating at 36,466 MHz was used to detect the H 56α radio line of excited hydrogen in 1968 (Sorochenko, Puzanov, Salomonovich, Shteinshleiger). This was the first radio line detected in the millimetre range, which later proved to be so fruitful for spectral investigations. Puzanov, K. S. Stankevich and Salomonovich measured the cosmic background radiation with this same radiometer (without the QPA) in 1967.

8 mm became the main operational wavelength for the RT-22 telescope. It was at this wavelength that Berulis and Sorochenko carried out a survey of thermal radio sources, while Kuz'min, Losovskii and Vetukhnovskaya conducted studies of planets, including the first detection of the radio emission of Uranus in the USSR. Measurements of the brightness temperature of Venus over its full phase cycle showed that day-to-night variations of the atmospheric temperature of Venus do not exceed 1%. The electrical parameters of the Martian surface were determined. In addition, the first detection in the USSR of radio emission from a planetary companion—Jupiter's moon Callisto—was made.

In subsequent years, a spectral radiometer with a 13.5 mm QPA was built. The importance of observing at this wavelength was determined by the discovery of maser emission by H_2O molecules, which opened the possibility of observations using interferometers with very long baselines.

The RT-22 telescopes of FIAN in Pushchino and of the Crimean Astrophysical Observatory in Simeiz were used together with an equipment complex developed at the Space Research Institute (IKI) to realise a Very Long Baseline Interferometry (VLBI) experiment (Matveenko, L. R. Kogan, Kostenko, I. G. Moiseev, Sorochenko, L. S. Chesalin). The possibility of devising a radio interferometer with independent recording of signals at the telescopes was first demonstrated by FIAN researcher L. I. Matveenko, who reported on this technique at a seminar at the Radio Astronomy Station in Pushchino in Autumn 1962. The first publication in connection with this question was somewhat delayed, and appeared only in 1965.

In 1969, the director of FIAN D. V. Skobel'tsin and the director of IKI G. I. Petrov decided to collaborate on studies of VLBI methods, which Matveenko was assigned to supervise.

As part of attempts to enhance the sensitivity of VLBI observations, a radiometer operating at 8 mm based on a travelling waveguide with a transmission bandwidth of 2000 MHz was tested. This radiometer was used in August 1971 to measure the radio emission of Mars during a grand opposition. The simplicity of its use gave preference to the travelling waveguide radiometer over the QPA radiometer for observations that did not require spectral resolution.

Investigations Using the DKR-1000 Telescope and Radio-Relay-Linked Interferometer Scientific observations on the DKR-1000 radio telescope began in 1964. The main focus of these first studies was constructing the spectra of a large number of radio galaxies and quasars in the relatively poorly studied metre-wavelength range. Artyukh, Vitkevich and Dagkesamanskii obtained the first measurements of the flux densities of radio sources at 38 and 86 MHz, using two correlation radiometers constructed in 1963 by Vlasov, Gavrilenko and Medvedeva.

Analogous measurements at 60 MHz were acquired in 1966, with the participation of colleagues from the Byurakan Astronomical Observatory. The extensive new observational material obtained made it possible to carry out a statistical analysis of the spectral characteristic of several hundred extragalactic objects, and to estimate the magnetic-field strengths and electron densities in individual radio sources. Dagkesamanskii detected a variation in the mean spectral indices of quasars with redshift (or equivalently, with the age of the quasars).

In 1965, T. D. Antonova (Shishova), Vitkevich and Vlasov carried out scintillation observations of the quasars 3C48, 3C144, 3C147 and 3C196 at 36 and 86 MHz on the V-3 antenna. Two correlation-type receiver complexes with orthogonal outputs were constructed in 1967, for use with the cross radio telescope at frequencies of 86–110 MHz (I. A. Alekseev, V. V. Gudnova, Yu. F. Sigaev). These receivers proved to be long-lived, and were subsequently used for a large number of scientific programmes.

Transistor-based antenna pre-amplifiers were constructed in 1965–1967 to enhance the sensitivity of the V-3 antennas of the DKR-1000 radio telescope (A. N. Cheremisin, Yu. P. Shitov, P. P. Nikolaev, S. T. Nuzhdin). A system of 18 amplifiers phased over a wide bandwidth (60–120 MHz) was installed on the V-3 antenna, increasing the sensitivity of the radio telescope by approximately an order of magnitude.

In 1968, Ilyasov and S. N. Ivanov carried out observations of the eclipse of the Crab Nebula by the solar supercorona under the supervision of Vitkevich, using the T-shaped DKR-1000 radio telescope with the 2PR receiver. The first such observations of the Crab Nebula at metre wavelengths were obtained with a pencil beam $10 \times 13'$ in size.

In 1970, Udal'tsov, V. N. Brezgunov, A. N. Tolstov and I. I. Galyamova devised an eight-channel receiver with a frequency range of 60–115 MHz (with the width of each channel being 120 kHz), designed for studies of variations of pulsar spectra.

It was already clear in the 1960s that studies of the structure of discrete sources required high angular resolution, better than $1'$. At the initiative of Vitkevich, work began on the creation of a radio interferometer based on the DKR-1000 telescope and a number of comparatively small antennas forming baselines of several tens of kilometres, with the received signals to be conveyed to a central processing point along a radio-relay line.

Work on this interferometer moved forward after 1965, when G. I. Dobysh and a group of researchers in the Radio Technical Department at the Tula Polytechnic Institute began to manufacture the required radio apparatus. Toward the Summer of 1968, Dobysh and the young FIAN engineers working with him B. I. Ivanov, M. T. Rezepin and V. A. Frolov, devised a radio interferometer designed to operate at 35 MHz, and carried out the first interferometric observations of several of the most powerful radio sources using the V-3 antenna and a simple movable antenna forming a baseline of 13 km.

In October 1971, under the supervision of Vitkevich and Dobysh, researchers of the Radio Astronomy Station (B. K. Izvekov, S. A. Sukhodol'skii, V. A. Frolov) completed work on the construction of a new radio interferometer with a variable baseline designed to operate at 85 MHz. The parameters of the radio-relay line enabled operation with baselines up to 40 km in length. The V-3 antenna of the DKR-1000 telescope was used as the main element in this interferometer. The antenna used for the movable site was an easily transportable array made up of 64 waveguide elements with an effective area of about 200 m^2. This array was developed and constructed by Ilyasov, Solodkov, Tyaptin and V. Ya. Shcherbinin. Dagkesamanskii and a group of his co-workers used this interferometer to study the structures of about 150 radio sources with an angular resolution of about $30''$.

In 1964, Vitkevich proposed to study the solar wind using the DKR-1000 telescope and two new antennas to be placed at distances of 150–250 km from Pushchino. It was proposed to measure the time shifts between the scintillation patterns obtained at each site, and thereby to measure the speed of plasma inhomogeneities in the solar supercorona. Under the general supervision of Vitkevich, two movable antennas were constructed near Staritsa in the Kalinin Region and in Pereslavl'–Zalesskii in the Yaroslav Region in 1965–1966 (Afon'kin, V. A. Egorov, Ilyasov, S. M. Kutuzov, Tyaptin).

The equipment for these sites was devised by Alekseev, Gudnova, M. V. Sil'yanov and Sigaev. The most outstanding feature of these antennas was their ability to operate simultaneously at two wavelengths (3.5 and 7.0 m). The parabolic cylindrical antennas were 280×20 m in size, and were placed low above the ground. The first measurements of the speed of the solar wind using radio astronomy methods in the USSR were carried out using this system in 1966.

The results of all these studies laid the basis for a report on investigations of near-solar space using radio astronomy methods carried out by radio astronomers of FIAN made by Vitkevich in 1966 at a session of the Presidium of the USSR Academy of Sciences, which was met with considerable interest by M. V. Keldysh and members of the Presidium. Vitkevich's series of investigations of the supercorona, including observations of the solar wind, was awarded a State Prize of the USSR in 1969—the first State Prize received by a scientist working in the area of radio astronomy.

In 1969, the movable antenna at Pereslavl'–Zalesskii was used together with the V-3 antenna of the DKR-1000 telescope in the first Soviet VLBI experiment carried out by the Radio Physical Research Institute in Gorkii and the Radio Astronomy Station of FIAN (Alekseev, Vitkevich, E. D. Gatelyuk, Troitskii and others).

In early 1968, English radio astronomers announced the discovery of a new class of object—pulsars. Studies of pulsars began at the Radio Astronomy Station immediately after this report, at the initiative of Vitkevich. Appropriate receiver–detection equipment was devised in short order. A two-channel radiometer based on R-313 receivers and operating at two adjustable frequencies in the range 60–120 MHz was constructed in 1968. This apparatus was used to carry out the first studies of the pulsars SR 1919 and SR 0809 (Alekseev, V. F. Zhuravlev and Shitov).

A 12-channel spectral analyser operating at 60–120 MHz was developed in 1969, intended to enable studies of the fine structure of pulsar spectra due to scintillations in the interstellar plasma. This analyser was used to measure the polarisation and strength of the Galactic magnetic field in the interstellar medium in the directions of a number of pulsars.

In 1968, Vitkevich and Shitov discovered that the pulses of the pulsar PSR 0809+74 consisting of two or three individual subpulses (components) regularly drift relative to the main mean period of the pulsar, appearing at an earlier phase in each new period and disappearing before the leading edge of the "window" for the pulsar's radio emission.

In that same year, Vitkevich, Yu. I. Alekseev, Zhuravlev and Shitov discovered one of the first new pulsars, named PP 0943: Pushchino pulsar with right ascension 09 hr 43 min. Vitkevich made a presentation about the results of these pulsar studies at a session of the Presidium of the USSR Academy of Sciences on June 11, 1970. In discussions with scientists promoting various pulsar models, Vitkevich defended the "rotating lighthouse" model proposed by himself earlier, which indeed proved to be physically correct. A large group of workers in the Radio Astronomy Laboratory were awarded a prize of the Presidium of the USSR Academy of Sciences for their investigations of pulsars.

In connection with the high degree of polarisation of the radio emission of pulsars, which provided additional information about the mechanism generating this radio emission, it was of interest to obtain measurements in two orthogonal polarisations.

In 1968, Ilyasov, Kutuzov and Tyaptin developed a simple antenna array that received radiation polarised orthogonal to the polarisation of the DKR-1000 telescope at 3.5 m. Simultaneously, Yu. I. Alekseev designed a polarimeter and developed a method for calibrating the polarisation of an interferometer consisting of the V-3 antenna of the DKR-1000 telescope and the new "polarisation" antenna. A small additional antenna that could receive radiation polarised at an angle of 45° to the polarisation of this antenna was built for the purposes of this calibration. Most of the observations on the polarisation antenna were carried out by Alekseev and S. A. Suleimanova.

In 1969, Matveenko and Lotova showed that the observed angular size of the pulsar in the Crab Nebula is determined by scattering, and should increase in proportion to the square of the wavelength, while the duration of the pulses should increase in proportion to the fourth power of the wavelength.

The Large Scanning Antenna of FIAN These pulsar studies led to the creation of a third large-scale radio telescope—the Large Scanning Antenna (BSA) of FIAN. Vitkevich was the first to point out that radio telescopes intended for pulsar studies can be constructed according to a filled-aperture scheme, but being aware to within known limits of restrictions on their sensitivity due to the effect of confusion. Together with Ilyasov, he started the construction of a large metre-wavelength radio telescope in the form of a large phased array. A team working under the direction of Vitkevich (Udal'tsov, Alekseev, Shitov, Grezgunov, Kutuzov, Tyaptin, K. K. Darkov) took on the task of planning the corresponding antenna–equipment complex for pulsar investigations.

The manufacture and construction of the new radio telescope began in the beginning of 1969, and the elements were assembled in 1970–1972. The main constructional and technical directors were Kutuzov and Tyaptin. This was the main work of the laboratory (the assistant heads of the laboratory at that time were Udal'tsov and N. P. Vladimirov). Nearly all the engineers in the laboratory were employed to carry out this work.

The combination of the proposed temporal methods for phasing (a discrete phase rotator) and phase methods (a beam-forming matrix) appreciably simplified the microwave system, and turned the BSA radio telescope into an instrument that was able to realise operative changes in the direction of signal reception and a multibeam antenna beam (Ilyasov, A. A. Glushaev, S. N. Ivanov, Kutuzov, Sodolkov and others).

The efficiency of the new single-frequency radio telescope depended on its stability against interference. A two-stage system for distributing the amplification was employed to protect the antenna amplifiers from cross interference (television and ultra-short-wave FM stations), and narrow-band filters were installed at the amplifier inputs (G. F. Novozhenov, I. A. Alekseev and others).

V. V. Vitkevich died in the prime of life in January 1972. His passing represented a heavy loss for Soviet radio astronomy.

The general direction of the work was taken on by Kuz'min, who was the new head of the laboratory and director of the Radio Astronomy Station. The scientific supervision for the antenna–equipment complex for the BSABSA was entrusted to Ilyasov, who was named assistant head of the laboratory. A large amount of help in the final stage of the work was given by the assistant director of FIAN S. I. Nikol'skii. The construction of the Large Scanning Antenna of FIAN was completed in 1974 (Fig. 1.17).

In 1976, at the initiative of Udal'tsov and under his supervision, the BSA was linked with the V-3 antenna of the DKR-1000 telescope in some observations, in order to enhance the resulting spatial resolution of the system. This interferometer was used to conduct observations of several discrete radio sources with high resolution and sensitivity.

The BSA was used for studies of pulsars (Kuz'min, Shitov, Izvekova, I. F. Malov, V. M. Malofeev, T. V. Smirnova, Suleimanova, T. V. Shabanova), the interplanetary plasma (V. I. Shishov, Vlasov, T. D. Shishova), supernova remnants (Udal'tsov, A. P. Glushak, A. V. Pynzar'), clusters of galaxies (Dagkesamanskii) and other objects.

A survey of northern pulsars was carried out in 1974, and the first low-frequency catalogue of the fluxes and profiles of pulsar pulses, which included about 100 objects, was compiled. As a result of studies of pulsar spectra, a number of which were conducted in collaboration with the Institute of Radio Physics and Electronics and Jodrell Bank Observatory (England), it was established that a low-frequency "cutoff" is characteristic of the radio emission of pulsars, with the maximum emission usually being concentrated, on average, near a frequency of 100 MHz. It was discovered that, during the evolution of a pulsar, as its rotation slows down (its period increases), the radio spectrum and its maximum shift toward lower frequencies, and the magnetic axis approaches the rotational axis.

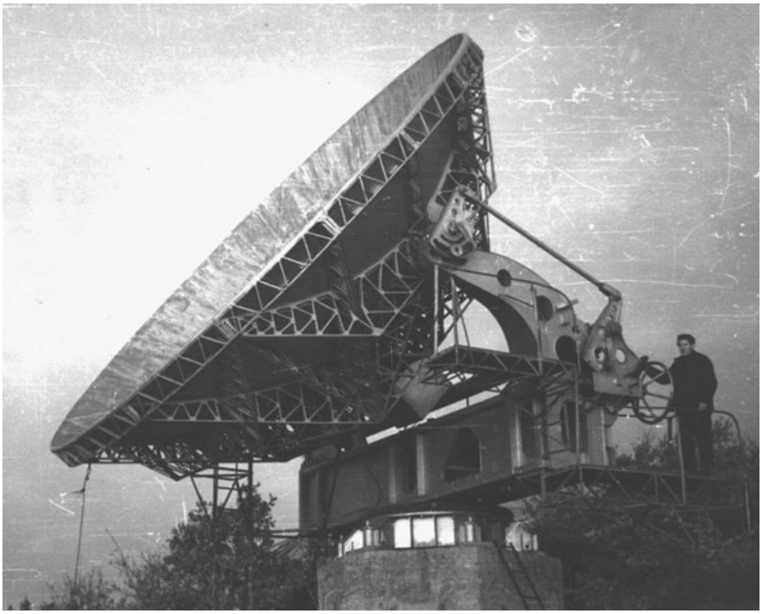

Fig. 1.17 BSA radio telescope. Antenna-feeder system

Investigations of the linear polarisation of pulsars were carried out using an original technique developed in the laboratory and based on the use of Faraday rotation in the interstellar medium. It was discovered that the variations of the degree and position angle of the polarisation along the mean pulsar profile at metre wavelengths differ substantially from the pattern observed at shorter wavelengths.

Four new pulsars in the solar neighbourhood were discovered, one of them (PSR 0320+39) displaying an anomalous (opposite to the usual direction), regular, highly organised subpulse drift.

Thanks to the high sensitivity of the BSA radio telescope and the application of specialised methods for processing of the observations, it was possible to achieve a time resolution of 10 μs. These studies, which were conducted jointly with the Space Research Institute, showed that the individual pulses of pulsars at metre wavelengths are made up of numerous micropulses. The simultaneous existence of two fine temporal structures with different periodicity time scales in pulsar pulses was discovered.

Udal'tsov, Glushak and Pynzar' detected radio halos around two pulsars, which apparently arose as a result of the interaction of relativistic particles ejected by the pulsar with the interstellar medium.

Observations of pulsars on radio telescopes and long-baseline interferometers required the installation of a high-accuracy local time standard at the Radio Astronomy Station, which would provide a time signal synchronised with the USSR state reference time. The realisation of this system was carried out by A. S. Vdovin under the supervision of Ilyasov, with active methodical help from the All-Union Scientific Research Institute for Physical and Radio Technical Standard Measurements (V. G. Il'in, A. R. Oksentyuk, G. N. Palii, S. B. Pushkin).

The ability to rapidly redirect the BSA beam made it possible to observe up to 500 scintillating sources in the course of a day. Such measurements, proposed and carried out by Vlasov in 1975–1980, were used to determine the time variations of the large-scale structure of the interplanetary plasma, and to investigate their relationship to solar activity and geomagnetic phenomena. It was shown that, at the period of maximum solar activity (1979), the interplanetary plasma was distributed nearly spherically symmetrically, while it was appreciably elongated along the plane of the solar equator in the period of minimum solar activity (1976).

The structures of extragalactic radio sources were studied using the BSA and the scintillation method. The results were interpreted to indicate that quasars are not a special class of object, and instead are radio galaxies that are located in a stage of very high core activity. Artyukh and Vetukhnovskaya used scintillation observations to study the structures of more than a hundred peculiar extragalactic objects: BL Lac objects, quasars, Seyfert galaxies, Markarian galaxies, etc. (More recently, colleagues at the Byurakan Astronomical Observatory have also taken part in this programme.)

In addition to experimental work at the Radio Astronomy Station, a series of theoretical studies related to the passage of radio waves through the interplanetary plasma was conducted. V. I. Shishov developed a correlation theory for strong scintillations, introduced the main equation of this theory and analysed solutions to this equation.

In 1967–1969, N. A. Lotova and A. A. Rukhadze (Plasma Physics Laboratory of FIAN) laid out the basis for the theory of turbulence in the solar wind. They introduced concepts relating inhomogeneities in the electron density giving rise to scintillations with wave processes, and considered the development of instability in the interplanetary medium.

In 1973–1981, Lotova, I. V. Shachei, D. F. Blums and other researchers at the Radio Astronomy Station carried out a series of studies dedicated to the theory of the formation of a non-stationary scintillation pattern.

In 1981–1982, Lotova, Sorochenko and Blums proposed and successfully applied a new method for studies of the solar wind—scintillation observations of water maser sources. M. V. Konyukov solved the very important problem of reconstructing the phase front of a wave that is distorted during propagation through an inhomogeneous medium (such as the ionosphere). This opened possibilities for creating large aperture-synthesis systems operating at metre and decimetre wavelengths.

Modernisation and Automation of the Radio Astronomy Station The development of the experimental base at the Radio Astronomy Station was facilitated by the continuous modernisation of its unique radio telescopes. As early as January 1965, in response to a proposal from FIAN, a special commission of the Presidium of the USSR Academy of Sciences made a decision on the main directions for modernisation of the FIAN radio telescopes.

The development and realisation of projects to modernise the DKR-1000 and RT-22 radio telescopes were carried out by the Radio Telescope Department (P. D.

Kalachev, V. P. Nazarov, I. A. Emel'yanov, V. L. Shubeko, G. A. Pavlov and others), the Spectral Radio Astronomy Department (R. L. Sorochenko, I. I. Berulis, V. A. Gusev, G. T. Sirnov, A. M. Tolmachev and others), the Antenna Group (Yu. P. Ilyasov, S. N. Ivanov, V. T. Solodkov and others), the Equipment Group (G. N. Novozhenov, Yu. I. Alekseev, G. I. Dobysh, I. A. Alekseev and others), the Electronic–Computational Device Group (Yu. V. Volodin, A. A. Sal'nikov and others), and the Groups for Exploitation of the DKR-1000 (P. D. Tsyganov, V. M. Karlov, V. V. Ivanova and others) and the RT-22 (L. M. Nagornykh and others).

Major work on the modernisation of the control system for the north–south antenna beam of the DKR-1000 cross radio telescope was completed in 1978. An antenna-beam control system capable of tracking a source in a 4° sector was developed in order to enable a tracking regime for the V-3 antenna of the DKR-1000 telescope. This system could be implemented at 30–120 MHz without changing the electrical length of the antenna system, which is especially important when using the V-3 antenna in interferometric observations or joint observations with the north–south antenna of the DKR-1000.

The receiver apparatus for the radio telescope was devised at the Radio Electronics Department of the Tula Polytechnic Institute under the supervision of V. V. Davydov. A large contribution was made by Dobysh, who later transferred from the Tula Polytechnic Institute to the Radio Astronomy Station of FIAN, and was named assistant head of the laboratory in 1979. A three-channel receiver was brought into use in 1981.

Automation of the DKR-1000 was based on the use of an M-6000 computer, and was initially developed at the Automation Department of the Tula Polytechnic Institute, with the participation of Udal'tsov and Artyukh (Fig. 1.18). In the initial stages, a large role in the automation of the data reduction was played by the installation of multi-channel recording, realised in 1972 at the Institute of Radio Physics and Electronics for use at the Radio Astronomy Station. Filter spectral analysers for pulsar studies were devised at the end of the 1970s. A 16-channel analyser with a frequency bandwidth of 160 kHz per channel was introduced into use in 1977 (Alekseev and others). A 128-channel with a channel bandwidth of 20 kHz was manufactured in 1979 (Dobysh and others).

The programme for modernisation of the RT-22 radio telescope foresaw the creation of an automated system for the control of the radio telescope and the collection, accumulation and initial processing of the observational data.

In 1970, Sorochenko and Udal'tsov suggested the use of a series of industrially produced computers in the automation systems for radio astronomy observations on the RT-22 and DKR-1000 radio telescopes. In 1971, at the initiative of Sorochenko, the Division of Computational Devices of FIAN (headed by A. V. Kutsenko) worked on a system for the automation of the RT-22 based on an M-6000 computer. One fundamental property of this project developed jointly with this division was its comprehensive nature. The computer controlled the entire operation of the radio astronomy experiment: the pointing of the telescope, control of the receiver, and the collection and reduction of the observational data. The realisation of this project in its entirety required more than five years.

Fig. 1.18 Members of the Scientific Council of the USSR Academy of Sciences on Radio Astronomy (Pushchino, December 1981) get acquainted with the control system of the DKR-1000. *Right to left*: Yu. N. Pariiskii, K. s. Shcheglov, V. A. Kotel'nikov, A. D. Kuz'min, R. D. Dagkesamanskii, S. Ya. Braude. V. M. Malofeev is at the controls

The first system with a TPA/I mini-computer was introduced on the RT-22 in January 1974, when it was used during observations of Comet Kohoutek.

A large contribution to the development of the automation of the RT-22 drive system was made by Kuz'min, who attracted the group who prepared the first analog system for the driving and control of the RT-22 to this work (G. N. Posokhin, B. K. Chemodanov, V. A. Vvedenskii, Yu. N. Semenov).

Kalachev and his co-workers developed a special design for sensor equipment designed to eliminate the influence of backlashes in the radio telescope drive and perpendicular shifts of the rotating platform. The final accuracy of the pointing was verified using a specially developed programme that enabled the computer to use selected guide sources to find corrections to the pointing and take them into account; in other words, the programme implemented a certain "self-teaching" of the computer. A project pointing accuracy of $10''$ was realised by the RT-22 pointing system. Researchers in the division of Kutsenko (E. A. Zubova, B. A. Polos'yants, S. A. Terekhin, V. A. Shirochenkov) actively took part in the automation of the RT-22 together with their colleagues at the Radio Astronomy Station. The scientific and technical supervision of the construction of the automation complex for the RT-22 was carried out by Sorochenko and Kutsenko.

This system was introduced into use on October 5, 1978. The efficiency of using the radio telescope was increased by an appreciable factor, making it possible to substantially broaden the programme of observations conducted on the RT-22 telescope. The now traditional studies of radio lines of excited hydrogen at 8 and 13 mm were joined by observations of molecular radio lines. Radiation corresponding to the $J = 4 \rightarrow 3$ rotational transition of the cyanacetylene molecule was detected, and these measurements used to derive the physical conditions in a number of molecular clouds in which star-forming processes were occurring (Sorochenko, Tolmachev).

A programme of systematic observations of a large number (more than 60) of H_2O maser sources was conducted in collaboration with colleagues at the Sternberg Astronomical Institute, with the aim of elucidating the regularities in their variability (Sorochenko, Berulis, E. E. Lekht, G. M. Rudnitskii, M. I. Pashchenko).

The current Radio Astronomy Station of FIAN is a major radio astronomy centre that is well known for its scientific and technical work both in the USSR and abroad. Two large-scale metre-wavelength radio telescopes (the DKR-1000 and LSA) operate at the Radio Astronomy Station, as well as one of the largest millimetre-wavelength radio telescopes (the RT-22). The scientific topics covered by the research carried out at the station include radio astronomy investigations of the Sun, planets, the interstellar and interplanetary media, pulsars, supernova remnants, and quasars, radio galaxies and other galaxies in both their continuum and spectral lines.

Researchers at the Radio Astronomy Station have carried out a large amount of work on the creation and implementation of various methods for the reception of weak signals from cosmic radio sources, original and unique receiver equipment, automation systems and a whole series of specialised radio technical schemes and systems that have found employment in both radio astronomy and in various other technical areas.

Radio astronomers of FIAN conduct collaborative investigations with scientists at the Space Research Institute, Radio Physical Research Institute, Institute of Radio Physics and Electronics, Byurakan Astronomical Observatory, Leningrad State University and the Sternberg Astronomical Institute. Long-term scientific collaborations have been established between the Radio Astronomy Station and the Jodrell Bank Observatory (England), the Max Planck Institute for Radio Astronomy (Federal Republic of Germany) and the University of Tasmania (Australia). Many foreign scientists have come to the Radio Astronomy Station of FIAN to conduct observations using its radio telescopes.

1.4 Radio Astronomy Studies in the Theoretical Physics Division

The beginning of work on radio astronomy carried out in the Theoretical Physics Division of FIAN can be taken to be the calculations published by V. L. Ginzburg in his paper *On the Radiation of the Sun at Radio Frequencies* (1946), which played a determining role in our understanding of the nature of solar radio emission. Theoretical radio astronomy studies gradually developed in subsequent years, with a central position being occupied by theoretical analyses of radiation mechanisms, the propagation of waves and relativistic particles and a number of problems in Galactic, extragalactic and solar radio astronomy.

S. I. Syrovatskii (Fig. 1.19), who came to the Theoretical Physics Division in 1951, actively took part in these studies. The death of Syrovatskii on September 26, 1979 broke off his scientific activity when he was at a high peak in his abilities.

Fig. 1.19 Sergei Ivanovich Syrovatskii (1925–1979)

Theory of Cosmic Synchrotron Radiation At the end of the 1940s and the beginning of the 1950s, the concept that non-solar radio emission, which was predominantly non-thermal, was associated with some class of cosmic radio source—"radio stars"—was widespread. The alternative hypothesis that non-thermal cosmic radio emission was synchrotron radiation, which had appeared in the scientific literature outside the Soviet Union in 1950, long remained in shadow. In 1951, Ginzburg showed that synchrotron radiation by relativistic electrons in Galactic magnetic fields "is very natural and attractive as an explanation for the general radio emission of the Galaxy." Ginzburg analysed the relation between the flux of the electron component of the cosmic rays and the intensity of this component's synchrotron radiation. In their subsequent papers, Ginzburg and Syrovatskii showed how it was possible to study various characteristics of Galactic relativistic electrons based on radio astronomy observations of non-thermal Galactic radio emission, and, in some cases, the characteristics of cosmic-ray protons and nuclei in our own and other galaxies. The radio astronomy theory of the origin of cosmic rays that was developed on the basis of these studies now occupies an important place in modern astrophysics. Moreover, the establishment of the relationship between radio astronomy and the physics of cosmic rays led to the birth of a new direction in astronomy—the astrophysics of cosmic rays, and then high-energy astrophysics.

During the development of these areas, fundamental questions in the theory of synchrotron radiation were posed and solved, having to do with the spectral and polarisation characteristics of the radiation in the case of non-circular motion of the radiating electrons, the influence of reabsorption with a power-law spectrum, etc. (Ginzburg, Syrovatskii, V. N. Sazonov). The monograph of Ginzburg and Syrovatskii *The Origin of Cosmic Rays* (Moscow, Leningrad; USSR Academy of Sciences; 1963) is still widely used today as a scientific textbook. This monograph was again published in 1964 after having been supplemented and translated into English.

Theory of Radio Galaxies, Quasars and Their Variable Radio Emission With the discovery of radio galaxies, and then quasars and activity in the nuclei of various types of galaxies, the nature of the energy release in these objects became a burning question, which has remained one of the central problems in astrophysics right to the present day. Ginzburg related this energy with the release of gravitational energy (for example, associated with gravitational instability of the galaxy or its central regions). A number of fundamental studies were carried out in this direction, which retain their importance to this day.

In 1964–1966, Ginzburg and L. M. Ozernoi showed that the compression of a magnetised gaseous cloud is accompanied by a huge amplification of the magnetic-field strength. The compression of a massive, rotating cloud with a magnetic field leads to the formation of a magnetised plasma body—a magnetoid, which could serve as a source of activity in a quasar or galactic nucleus over a long time. Depending on its entropy, a magnetoid could be hot (quasi-spherical) or cool (in the form of a disk). Its structure, evolution and electrodynamical properties and the character of its radiation were studied in detail by Ozernoi and V. V. Usov (1971–1973). In particular, powerful non-thermal radiation with its maximum at submillimetre wavelengths or the far infrared, as is the case for many quasars and active galaxies, can be explained by the magnetoid theory. Instability accompanied by twisting of the magnetic-field lines connecting the magnetoid and the surrounding plasma can lead to repeating magnetorotational outbursts and the ejection of beams and jets of relativistic electrons from the magnetoid. In 1970, Ozernoi and B. M. Somov calculated the parameters of such magnetorotational outbursts, which could explain the energetics and a number of properties of the radio variability of quasars.

At the end of the 1960s and the beginning of the 1970s, observational data indicating the presence of relativistic effects in the radio variability of quasars became available. In 1968, Ozernoi and Sazonov developed the theory of synchrotron radiation for a relativistically moving jet and relativistically expanding spherical sources. In 1969, they calculated in detail the spectrum, polarisation and time variations of a radio source having the form of two components moving from each other in opposite directions. This model or modified versions of it are still referenced today in connection with the interpretation of apparent superluminal motions in compact radio sources. In 1974, Ozernoi and L. E. Ulanovskii proposed a theory of radio variability in the case of motion of relativistic electrons in an external spatially inhomogeneous magnetic field, and used this theory to interpret a number of effects observed in the radio variability of quasars.

In the early 1980s, it became clear that a large fraction of the power emitted by many quasars and active galactic nuclei is radiated not only in the far infrared, but also in hard X-rays and gamma-rays. A number of studies have interpreted this high-energy radiation of quasars as a result of inverse Compton scattering on the relativistic electrons. The important role of this effect in quasars and the possibility of obtaining powerful gamma-ray radiation via this mechanism was noted in 1963 by Ginzburg, Ozernoi and Syrovatskii, using 3C273 as an example.

Radio Emission and the Nature of the Galactic Centre The centre of our Galaxy contains a pointlike radio source that also radiates in other energy bands, and in this sense qualitatively resembles the centres of active galaxies and quasars, although the level of its activity represents a negligibly small fraction of the activity of these more powerful objects. For example, the power of its radio emission is a factor of 10^{10}–10^{11} weaker than the radio emission of a typical quasar. Many theoreticians have proposed that there is a massive black hole at the Galactic centre, which represents a "dead" quasar, that is, a quasar with an extremely low accretion rate. However, a series of studies carried out in the Theoretical Physics Division have shown that the inevitable tidal disruption of stars surrounding the galactic nucleus by the black hole should give rise to a flow of gas onto the black hole, with an associated emission of radiation. This contradicts available X-ray observations if the mass of the black hole exceeds 1000 times the mass of the Sun (Ozernoi, V. I. Dokuchaev, V. G. Gurzadyan).

Radio interferometric measurements of the size and structure of the point-like radio source in the Galactic centre have demonstrated the important role of scattering of its radiation on inhomogeneities of the electron density. In 1977, Ozernoi and Shishov showed that the scattering region is located in the vicinity of the radio source itself. Later, they presented arguments suggesting that the scattering inhomogeneities are located in compact clouds of ionised gas surrounding the radio source. These clouds were subsequently discovered in 1979. Ozernoi and Shishov have proposed that the 0.511 MeV annihilation line observed in the direction toward the Galactic centre originates precisely in these clouds. The energy of an electron–positron wind from the central source is sharply decreased in these clouds due first to adiabatic and then to ionisational losses, after which annihilation becomes possible. Observations of scintillation of the radio flux from the pointlike source were used to estimate its intrinsic size, which suggests it is either a young pulsar or a moderate-mass black hole.

Models for the Propagation of Cosmic Rays and the Background Radio Emission of the Galaxy In 1953, Ginzburg, following S. V. Pikel'ner, used the concept of a halo of cosmic rays, having in mind an extensive region around the Galactic disk where cosmic rays, including relativistic electrons, could be confined over long times before escaping into intergalactic space. This work essentially predicted that the size of the radio halo should depend on the frequency, since the relativistic electrons occupy only part of the halo due to energy losses, and occupy a smaller volume the higher their energy. This frequency dependence of the size of the halo was subsequently detected in studies of the radio emission of other galaxies.

In 1972–1976, S. V. Bulanov, V. A. Dogel' and Syrovatskii carried out careful calculations of the propagation of relativistic electrons in the Galaxy, taking into account synchrotron and Compton losses, and analysed the spatial distribution of the Galactic radio background. Based on an analysis of observational data on the intensity of the radio background at various frequencies and on the energy dependence of the electron component of cosmic rays, they likewise concluded that the Galaxy has an extended halo.

Observations of galaxies using radio telescopes with high spatial resolution began to be made approximately in the middle of the 1970s. These observations revealed extended radio halos with thicknesses of several kiloparsecs[7] around the optical disks of several galaxies. Observations at several frequencies were used to investigate the motion of cosmic rays in the halos of these galaxies. The most popular models for the propagation of cosmic rays at that time were the diffusion model of Ginzburg and Syrovatskii and a convection model, in which cosmic rays are carried from the Galaxy by a Galactic wind. Analysis of the spectra of the various components of cosmic rays observed at the Earth did not enable unambiguous identification of either of these models as being preferable; the characteristic properties of the spectra could be explained using either model with an appropriate choice of parameters.

Ginzburg then noted that more definite conclusions could be drawn using data on the radio emission of galactic halos. Since the size of the radio halo at some frequency is determined by the mean-free path of an electron with the corresponding energy, and the energy dependences of this mean-free path are different in the diffusion and convection models, the observed variation in the size of the radio halo with frequency should also be different in the models. Studies of the halo radio emission of galaxies showed that the propagation of electrons in the halos can be better described using the diffusion model, with the effective diffusion coefficient $D \simeq 10^{29}$ cm^2/s (Dogel', Kovalenko, Prishchep).

The diffusion of charged particles in galactic space is determined by the spectrum of inhomogeneities of the magnetic field. An expression for the relative fluctuations of the halo radio intensity was obtained with the aim of determining this spectrum. In 1981, V. S. Ptuskin and G. V. Chibisov showed that the anisotropic part of the correlation function for the radio intensity could be used to obtain the magnitude of the regular magnetic field. Experimental studies of these concepts require observations of the radio background at frequencies no higher than a hundred Megahertz and with an angular resolution of better than $1'$.

The question of where and how cosmic rays are accelerated is among the most important astrophysical problems. Acceleration processes can also be studied using radio observations, since the acceleration of charged particles is often accompanied by the emission of radiation (including radio radiation) as a consequence of various types of energy loss.

Ginzburg showed that the acceleration of particles in shock fronts entering the halo could be detected from the synchrotron radiation of the accelerated relativistic electrons. A model for the propagation of a shock front through the Galactic halo was developed, in which the distribution of the electrons depended only on the electron energy, as a consequence of energy losses. It turned out that the electrons could be accelerated under certain conditions. The presence of such acceleration could be detected by comparing the spectra of the radio emission from the vicinity of the shock front and the radio emission from regions without acceleration. It was shown that variations in the spectral index of the radio emission are associated with two effects: the acceleration of particles at the shock front and adiabatic losses in the region behind the front. For acceleration to occur, the efficiency of the scattering

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[7] A parsec is approximately 3.08×10^{16} m—Translator.

in the vicinity of the front must be higher than the average efficiency of scattering in the Galaxy (Bulanov, Dogel', Kovalenko). Specific data on primary cosmic rays near the Earth suggest that acceleration in interstellar space is, in all likelihood, inefficient (Ginzburg, Ptuskin).

Active Processes. Radio Emission of the Sun, Neutron Stars and Pulsars In 1946, the existence of strong thermal radio emission from the outer regions of the solar corona was hypothesised, which subsequently found full experimental confirmation (see Sect. 1.1). Following this, Ginzburg and G. G. Getmantsev proposed in 1952 that the sources of enhanced radiation above sunspots had a synchrotron nature. This hypothesis proved to be very fruitful in connection with explaining the various components of the solar radio emission (Type IV bursts, microwave bursts, etc.).

In 1958, Ginzburg and V. V. Zheleznyakov proposed a theory for the generation of rapidly drifting Type III bursts, and also studied in detail the propagation in and emergence from the coronal plasma of electromagnetic waves. An analysis of the combined scattering of plasma waves laid the basis for a broad series of investigations of decay interactions of electromagnetic waves in a plasma. In 1968, immediately after the discovery of pulsars, Ginzburg, in collaboration with researchers at the Radio Physical Research Institute in Gorkii, considered a number of questions in the theory of the radio emission of pulsars, as well certain properties of neutron stars.

A new push was given to studies of active processes on the Sun by theoretical work of Syrovatskii begun in 1966, concerned with the behaviour of plasma in a strong magnetic field. He showed that a current sheet with a width much larger than its thickness could form with time in the vicinity of a zero point of the magnetic field in such a plasma. One of the frequent applications of this work was modelling the behaviour of plasma in the solar corona, where the energy density of the magnetic field is much larger than the energy density of the plasma. The formation of current sheets in the atmosphere of the Sun is associated with the appearance of active regions on the photosphere (regions whose magnetic fields are strong compared to the background fields), as a result of which there arises an electrical field along the force lines of the magnetic field.

Over many years of investigations carried out under the supervision of Syrovatskii at a number of institutions (FIAN, the Institute for Terrestrial Magnetism, the Ionosphere, and Radio-wave Propagation, the Institute of Applied Mathematics, the Institute of Applied Geophysics), various processes having to do with the formation, stability and decay of current sheets were studied. Under the conditions in the solar corona, the lifetimes of these structures are several hours. This leads to the accumulation in the solar atmosphere of colossal energies in the form of the magnetic energy of current sheets. In the model of Syrovatskii, the disruption of current sheets accompanied by the release of this accumulated energy in various forms is observed as a solar flare.

The parameters of a pre-flare current sheet should differ appreciably from those of the surrounding coronal plasma, and its spectrum should differ from the spectrum of the unperturbed solar atmosphere. In 1977, Syrovatskii suggested the possibility of predicting solar flares using radio astronomy methods. These and later studies carried out by Syrovatskii together with V. S. Kuznetsov showed that the radiation of the current sheet leads to an increase in the flux from the Sun in some range of radio wavelengths, while the current sheet simultaneously blocks the radiation of the lower solar atmosphere, leading to a decrease in the flux at certain other radio wavelengths. It was concluded that it should be possible to detect a pre-flare situation on the Sun using already existing radio telescopes with high resolution operating at centimetre and millimetre wavelengths.

New Methods for Radio Astronomy Investigations In 1947, Ginzburg suggested making observations of the diffraction of the radio emission from discrete sources at the limb of the Moon as a means of studying their structure (the method was developed jointly with Getmantsev in 1950). An opportunity to apply this high-resolution method arose when the recently discovered quasar 3C273 passed behind the Moon in 1963, making it possible to reveal the presence of complex structure.

In 1960, Ginzburg proposed a new method for determining the magnetic-field strength in the outer solar corona by observing the polarised radio emission from a background source that had passed through the coronal material. This was based on observations of the rotation of the plane of polarisation, as well as any depolarisation of the radio emission.

In 1956–1963, Ginzburg and V. V. Pisareva worked out a method for studying the inhomogeneous structure of the circumsolar plasma using observations of the diffractive scintillation of compact background radio sources due to inhomogeneities in the plasma. Such scintillations were detected in 1964, and were used to obtain valuable information about the physical properties of both the solar wind and the discrete radio sources. Developing this idea, Ozernoi and Shishov (1980) showed that interstellar scintillation observations could be used to study fine structure (scales of the order of 10^{-5} arcseconds) in quasars and galactic nuclei at centimetre wavelengths. Scintillation observations can appreciably supplement results obtained with Very Long Baseline Interferometery.

1.5 Radio Astronomy Space Studies in the Spectroscopy Laboratory

The first suggestion to place radiometers operating at centimetre and millimetre wavelengths on board spacecraft for radio astronomy studies was put forth jointly by M. A. Kolosov, A. E. Basharinov (Institute of Radio Physics and Electronics) and Salomonovich (FIAN) as early as 1962. The basis for such an experiment was laid and the required equipment developed and tested in collaboration with the groups of S. T. Egorov and L. D. Bakhrakh over the following years. The successful results obtained using a multi-channel radiometer (devised later) to study the surfaces and atmospheres of Mars and the Earth are now well known (see, for example, Essay 2).

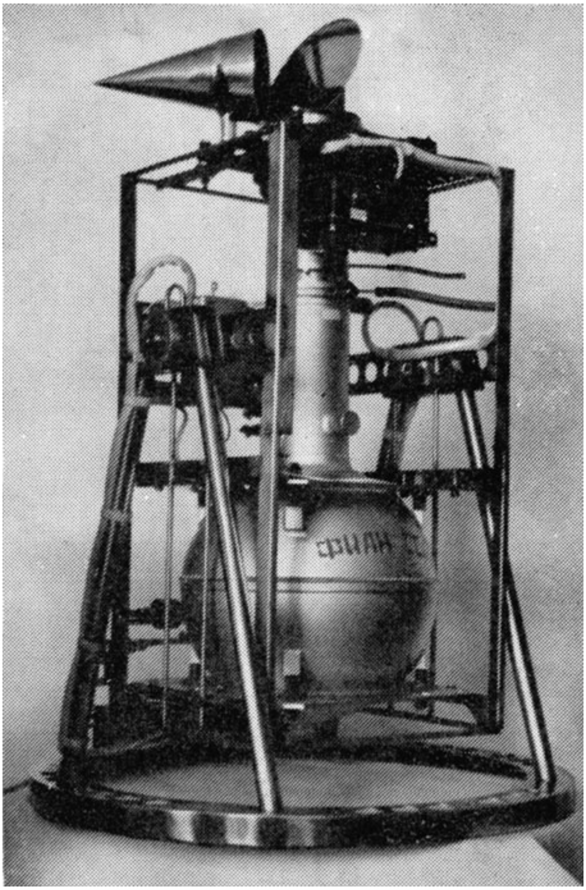

Fig. 1.20 "Obzor" submillimetre cryogenic radiometer of FIAN. It was used to obtain maps of the Earth as a planet at wavelengths of 0.1 and 0.5 mm from the "Cosmos-669" spacecraft during five days in 1974

Beginning in 1965, a new direction was developed at FIAN, associated with the expansion of studies at still shorter wavelengths, in the submillimetre range (1–0.1 mm). To exclude the influence of the Earth's atmosphere, which severely hindered the passage of this radiation, it was necessary to develop a submillimetre receiver suitable for use on board balloons, satellites and orbiting piloted stations. This problem was tackled in the Spectroscopy Laboratory, which had experience with space studies, under the supervision of Corresponding Member of the Academy of Sciences S. L. Mandel'shtam. It was worked on by the Group, and then the Section, of Space Submillimetre Studies headed by Salomonovich.

Spectral radiometers and telescopes with liquid-helium-cooled photoresistor-type receivers designed for observations at submillimetre wavelengths were also developed and tested under natural conditions. These were tested on high-flying balloons, *Vertikal'* geophysical rockets, automated satellites and, finally, on board the *Salyut-8* orbiting piloted station. The specialists in infrared studies V. I. Lapshin and A. S. Khaikin (1937–1977), the radio physicists and radio engineers S. V.

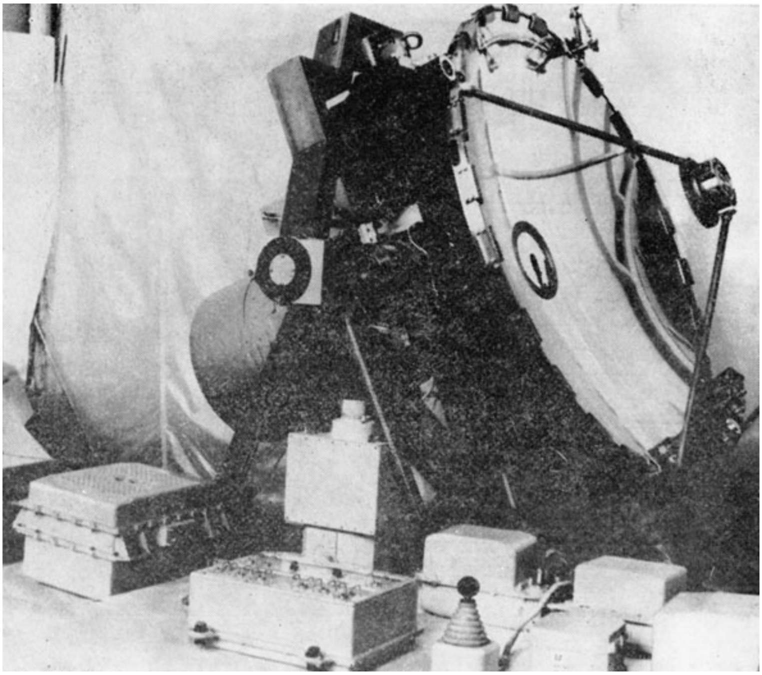

Fig. 1.21 Laboratory testing of the BST-1M submillimetre telescope of FIAN, with its parabolic surface and receivers cooled to about 4.5 K. In 1977–1982, several expedition teams carried out experiments with the BST-1M on the "Salyut-6" orbiting manned station

Solomonov, V. S. Kovalev, V. N. Bakun and G. B. Semin, and the specialist in low-temperature physics T. M. Sidyakina and others all actively participated in this work. The setting up of the experimental base for the section was facilitated by P. D. Kalachev.

Original interference filters, Fourier interferometers (Lapshin) and other equipment were developed in 1965–1983. The construction of instruments was carried out by B. N. Leonov and V. N. Gusev. Since the receivers required cooling to low temperatures, the Cryogenics Department of FIAN (A. B. Fradkov, V. F. Troitskii) created unique on-board cryostats for telescopes operating at submillimetre wavelengths under weightless conditions. The first systematic data on the radiation of the Earth as a planet were obtained in this period at 0.1 and 0.3–0.8 mm, which were of interest for studies of the atmosphere. The *Obzor* radiometer (Fig. 1.20) on board the *Kosmos-669* spacecraft was used to make the first maps of the Earth at these wavelengths, which established the relationship between the distribution of the submillimetre brightness temperature and the dynamics of active regions in the troposphere and atmosphere of the Earth. The long (from 1977 through 1981) use of the 1-m BST-1M telescope (Fig. 1.21) on board the *Salyut-6* station made it possible to accumulate valuable information on the functioning of large-scale radio astronomy telescopes on piloted orbiting stations. The work of FIAN on the creation of space radiometers and telescopes for submillimetre observations and studies of the submillimetre radiation of the Earth was highly valued. At the *Vystavka Dostizhenii Narodnogo Khozyaistva* ("Exhibition of National Economic Achievement") of the USSR, the construction of the *Obzor* radiometer was awarded medals (Khaikin, Solomonov, Troitskii and others) and the BST-1M telescope a diploma and medals (Bakun, Salomonovich, Solomonov, Semin and others).