Chapter 2
Radio Astronomy Studies in Gorkii

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Abstract Stages in the development and main results of studies of the radio emission of the Sun, Moon, planets, Galactic and extragalactic sources at Gorkii are described. Major achievements are noted, including the discovery of a hot core in the depths of the Moon, the polarised Galactic radio background, etc.

2.1 The First Stage (1946–1957)

The development of radio astronomy studies in Gorkii began at Gorkii State University and the affiliated Physical–Technical Institute (GIFTI) in 1946 under the supervision of Professor M. T. Grekhova, who attracted the Department of Electrodynamics and the associated scientific section of GIFTI to this work.

A large influence on the successful development of these studies was exerted by the organisation at Gorkii State University in 1945 at the initiative of A. A. Andronov, Grekhova and G. S. Gorelik of the first Radio Physics Department in the country, whose Dean was Grekhova herself. The students and lecturers in this new Department actively took part in various radio astronomy investigations. In particular, in 1946, I. L. Bershtein began the development of a radiometer designed to operate at 10 cm. This radiometer, which had a threshold sensitivity of about 3 K, was constructed in the middle of 1948, and was subsequently used to measure the radio emission of the Sun, as well as in experiments on the application of radio astronomy equipments and methods to applied problems (M. M. Kobrin, Bershtein). However, this radiometer was not used further for systematic observations, since a more modern device enabling the same measurements under field conditions was devised.

At the beginning of 1947, radio astronomy studies began to be carried out at GIFTI and the General Physics Department of Gorkii State University under the supervision of Gorelik. Work in radio astronomy was initially (1947–1952) coordinated by the Lebedev Physical Institute (FIAN) under the supervision of S. E. Khaikin. A plan defining the specific themes for radio astronomy work at GIFTI was adopted (with the scientific supervision of this work being given by Grekhova, and then Gorelik, starting from 1948).

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In 1947, V. S. Troitskii, who was then a PhD student at Gorkii State University (supervised by Gorelik), chose radio astronomy as the theme for his dissertation. He began to work on a radiometer operating at metre wavelengths, which was then considered the most promising wavelength range for radio astronomy observations. The signal in the radiometer was modulated by switching the receiver input from the antenna to an equivalent noise load using a polarised relay at a frequency of about 25 Hz. After detection, the signal was separated out using a narrow-band tuning-fork filter. The radiometer was intended for operation at a wavelength of 4 m together with a receiver and antenna of the student radar detection station. At that time, no modulation-type radiometers for metre-wavelength observations had been developed anywhere. In March 1948, this radiometer was used to carry out the first observations of the solar radio emission. The "waveguide-type" antenna was able to rotate in azimuth, and was located on the roof of a building of the Radio Physics Department in the very centre of town, with the radiometer located in the laboratory. Since the antenna could rotate only in azimuth, observations were conducted either at sunrise or sunset.

In spite of the low sensitivity of the radio telescope and the imperfect operation of the radiometer, they represented a first important step that made it possible to contemplate the solution of theoretical and practical problems in radio physics associated with methods for the reception of weak, noisy signals in general, and at metre wavelengths in particular. In contrast to the situation at centimetre wavelengths, where a Dicke radiometer had already been devised, there were no previous analogs to the technical problem of designing a radiometer for metre wavelengths.

The development of a more modern radio telescope suitable for operation under field conditions at a wavelength of 1.5 m began in the middle of 1948. This wavelength was chosen because two beds of co-phased antennas on a turning mount were available from an old radar station. At the suggestion of Gorelik and Grekhova, two new beds of appreciably larger co-phased antennas that could be installed on the same turning mount were constructed under the supervision of A. P. Skibarko. The development of a laboratory model for the radiometer proceeded in parallel with the manufacture of these antennas. New ideas for signal modulation were tested, and parts for the radiometer were assembled. The student from the Radio Department V. A. Zverev (now a Corresponding Member of the USSR Academy of Sciences) actively took part in this work, proposing a number of signal-modulation schemes and ways to modernise the radiometer design.

When the main principles behind the operation of the new radiometer had been tested under laboratory conditions, the engineers V. L. Rakhlin and A. A. Varypaev and the mechanical technician E. A. Lyubimkov were given the task of making an operational version. In this way, the first experimental radio astronomy group was formed in Gorkii.

The new radio telescope operating at 1.5 m wavelength differed from previous telescopes in a number of interesting features of its design. It incorporated two types of modulation: switching the receiver input from the antenna to an equivalent noise load, and nodding the direction of the antenna beam. As is indicated above, the antenna consisted of two co-phased beds of antennas supported on a common turning

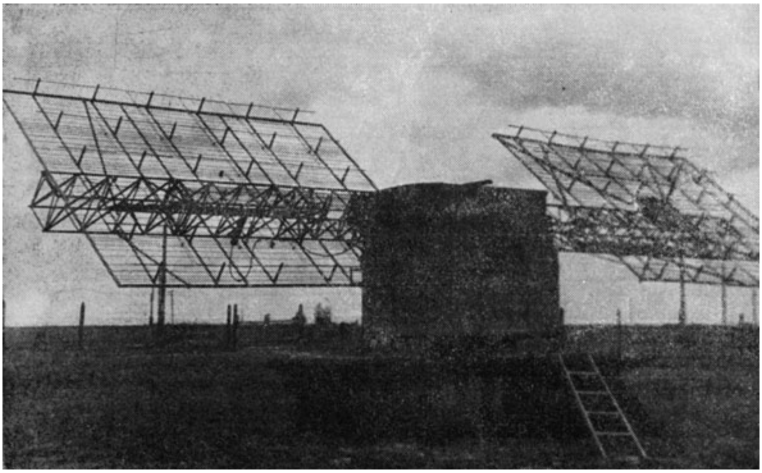

Fig. 2.1 Radio telescope constructed to operate at 1.5 m (Zimenki station)

mount (Fig. 2.1). A high-resistance regulatable segment of terminated co-axial cable in a trombone-like shape taken from the radar equipment was used as an equivalent noise load. This “trombone” made it possible to change the length of the terminated cable from a quarter to half a wavelength, thereby changing the impedance of the input amplifier, and thus the noise level of the load. By setting the noise level in the equivalent load equal to the mean noise level of the antenna, which was determined by the distribution of radio emission received from the sky and the Earth’s surface, it was possible to exclude the background signal. In this way, a quasi-null receiver method was realised.

The nodding of the beam was realised by varying the phase difference fed to the antenna beds by alternately attaching the receiver input to two specially adjusted feeder points (joining both antenna beds) using a relay contact or volume switch operated by a synchronised motor. The nodding angle was chosen to be half the antenna-beam width. The low-frequency part of the radiometer had a heterodyne filter analogous to a Dicke radiometer.

The beam-nodding method proved to be very effective, enabling reliable operation in the presence of undirected interference in Gorkii, where the radio telescope was used to conduct test observations of the Sun in Spring 1949. The telescope was then moved to the Zimenki Station on a high bank of the Volga 30 km from Gorkii, where regular observations of the solar radio emission at 1.5 m began in August 1949. During this same time, measurements of the refraction of metre-wavelength radio waves in the Earth’s atmosphere were also carried out using observations made during the radio sunrise and radio sunset.

Various researchers and PhD and other students at the university took part in studies using this first Gorkii radio telescope—S. A. Zhevakin, G. G. Getmantsev, A. I. Malakhov, A. V. Zolotov, V. M. Plechkov, Z. I. Kameneva and others. Starting at this time, Zimenki began to be developed as a radio astronomy laboratory outside the city. A two-hectar plot of land was given to this laboratory in 1949, two prefabricated buildings were put up in 1952, and a laboratory building, apartment building, dormitory and helium cryogenic station were constructed and brought into use in 1960–1962.

The metre-wavelength radio telescope was used right up until 1956. Radio refraction studies were carried out until 1952. Later, Razin used the telescope to search for polarised cosmic radio emission. Using the existing radiometer together with new, specialised radiometers that were better suited for detecting polarised signals, Razin demonstrated the presence of linear polarisation of the extended cosmic radio emission in 1956. Getmantsev used this same radio telescope to measure the radio emission of the most powerful discrete sources in order to accurately determine their intensities. For this purpose, he developed a means for thermal calibration of the radiometer to replace the previously used noise-diode calibration.

The successful operation of the radiometer in the beam-nodding mode stimulated the use of this method with a new radio telescope operating at 10 cm wavelength, also based on a radar station. In this latter case, there was a device to nod the beam using mechanical rotation of the feed (dipole) about the main focus of a paraboloid. In essence, this was a nearly complete radio telescope, which provided an important function of a radiometer—modulation of the signal. It was only required to connect a heterdyne filter. Rakhlin began the development of this instrumentation, completing this work in March 1950.

Systematic measurements of the radio emission of the Sun from sunrise to sunset were carried out on this radio telescope in the Spring and Summer of 1950, in order to determine the refraction and absorption of radio waves in the Earth's atmosphere and study seasonal variations in these phenomena. The radio emission of the Earth's atmosphere was first detected at such a long wavelength (10 cm) using this telescope.

The circular rotation of the beam of the radio telescope enabled very accurate determination of the direction toward the Sun. This was a prototype radio sextant, which subsequently found wide application thanks to theoretical and experimental development of this idea with the participation of Kobrin, I. F. Belov, Rakhlin and B. N. Ivanov.

At the end of 1948 and the beginning of 1949, the development of a radiometer designed to operate at 3 cm was begun at the initiative of Grekhova. This work was carried out in the Electrodynamics Department by the group of S. I. Averkov. The receiver part of an on-board aviation radar station was used. A Dicke scheme with a rotating absorbing disk was used to modulate the signal. In April–June 1950, measurements of the radio emission of the Sun and of the Earth's atmosphere were carried out on the 3-cm radio telescope under a protective cap; the telescope's sensitivity was about 5 K and its reflecting surface had a diameter of 0.6 m.

The development of radio telescopes and methods for measuring weak continuum signals were accompanied by theoretical studies by Troitskii. The creation of the first metre-wavelength radio telescope and accompanying studies formed the basis for Troitskii's PhD dissertation, which was the first dissertation on radio astronomy in the Soviet Union, defended in Spring 1950 at FIAN.

Fig. 2.2 Samuil Aronovich Kaplan (1921–1978)

From the very first, the development of radio astronomy in Gorkii was closely tied to the solution of topical practical problems, first and foremost with studies of the conditions for the propagation of radio waves in the Earth's atmosphere. Radio astronomy presented unique possibilities for studies of the refraction and absorption of radio waves in the atmosphere. These phenomena were first studied based on the attenuation of the radio emission of the Sun, and then also the Moon, as a function of the hour angle of the Sun or Moon during the course of the day. Later, it became possible to determine the atmospheric absorption based on the thermal radio emission of the atmosphere itself, which was reliably measured at centimetre and decimetre wavelengths using the radio telescopes that had been built. The need to develop the theory of radio emission of the atmosphere and methods for measuring absorption arose. Work in these directions was carried out by Troitskii, Zhevakin and others. Later, wide-ranging theoretical, methodological and experimental studies of the absorption of radio waves in the atmosphere and of the radio emission of the atmosphere itself from submillimetre to decimetre wavelengths were conducted by Zhevakin, N. M. Tseitlin, A. G. Kislyakov, Razin, K. S. Stankevich, L. I. Fedoseev, V. V. Khrulev, D. A. Dmitrenko and others.

Thus, in 1946–1950, Gorkii State University, together with the Gorkii Physical–Technical Research Institute and FIAN, became a leading centre for radio astronomy studies in the Soviet Union. At that same time, studies in theoretical radio astronomy began to develop in Gorkii under the supervision of V. L. Ginzburg, with whom Getmantsev, N. G. Denisov, Razin, Zheleznyakov and others collaborated. The well known Soviet astrophysicist S. A. Kaplan (Fig. 2.2) also worked in Gorkii from 1960 until his tragic death in 1978.

2.1.1 Radio Telescopes and Radiometers

After the first results of radio astronomy and applied studies, it became evident that further development of radio astronomy would require new, more powerful radio telescopes. This was especially true for work at centimetre and decimetre wavelengths, where the first telescopes used had diameters of less than one metre. The director of the GIFTI Grekhova and the division head Gorelik ordered 4-m-diameter antennas to be built in accordance with plans provided by FIAN (P. D. Kalachev) from one of the Gorkii factories. The antennas were manufactured by 1952, but without a means to turn them. Turning mounts from decommissioned zenith cannons were adopted for this purpose. In this way, this wartime technology was turned toward peaceful, scientific goals.

The development of new, more modern and sensitive radiometers operating at centimetre and decimetre wavelengths was begun in the radio astronomy laboratory that formed in Gorelik's division. Experience working on new radio telescopes operating at 3 and 10 cm showed a number of important problems with the radiometers used, which had a fundamental character. This was especially true of the Dikke-type radiometer working at 3 cm. First and foremost, the large background signal, equal to the difference between the temperatures of the antenna (usually 50 K) and the disk (300 K) hindered measurements of weak signals due to fluctuations in the amplification. In addition, a strong false signal usually arose due to interference between the input noise signals reflected from the antenna and the disk, which were not perfectly matched with the waveguide. There were also cruder technical problems, such as the modulation of the mixer noise at the input, etc.

To eliminate the background signal and expand the capabilities of the radiometer, it was decided to devise a new radiometer designed to operate at 3 cm in which the receiver input would be switched between two equivalent inputs—one connected to the antenna feed and the other to an adjustable noise source or to a second antenna feed located next to the first, in order to implement nodding of the beam, which in fact turned out to be very effective. This required a rapidly acting switch. At that time, there were only spark switches, which were not suitable for this purpose due to their high noise. Therefore, a mechanical, rapidly acting, waveguide T-joint switch operating with a frequency of 20–80 Hz was created. Through the action of a polarised relay, the switch was alternately closed first one, then the other arm of the T-joint. The closure of the circuit was brought about by closing a gap between pins in the clearance of the inductive diaphragms. The gap was closed in antiphase by a rod moved by a relay inside the tube-like pins.

A switch amplifier with two equivalent inputs was also used in the 10-cm radiometer. Another innovation that appreciably improved the real sensitivity of the radiometer was the implementation of a "snail shell"—a long waveguide curled up like a snail's shell that eliminated the interference of the input noise signals of the receiver. When the length of the waveguide used is such that the time for the noise signal to travel to the antenna and back is longer than the noise-correlation time in the receiver bandwidth, there will be no interference. In another method used to suppress the interference signal, the frequency of the heterodyne was modulated over a small range determined by the length of the antenna tract; when the frequency was rapidly changed periodically with a period that was shorter than the time constant of the output, the interference pattern was averaged. All these techniques made it possible to exclude false signals and various "parasitic" effects, enabling the obtained sensitivity to approach its theoretical value. The properties of interference noise were studied by Khrulev and A. M. Starodubtsev, whose theory and the associated influence on the measurement accuracy were considered in one of the papers of Troitskii.

The desire to understand all sources of errors in measurements of the noise signals led further to studies of the noise in the heterdynes used in all radiometer applications at that time. Questions having to do with generator noise had already been studied before the war by I. L. Bershtein, who developed the theory of natural line widths and a method for measuring this width in radio generators. In 1954, Troitskii devised an apparatus for this purpose and measured the natural line widths of a klystron generator operating at 3.2 cm. The results of this work provided a basis for choosing an intermediate frequency for the radiometer receiver and an optimum heterodyning scheme.

Together with such experimental studies of noise in systems with self-excited oscillations, a number of theoretical investigations were carried out. In particular, a more adequate mathematical approach to studying fluctuations of the self-excited oscillations was developed in Gorkii and Moscow (S. M. Rytov). Instead of applying the Einstein–Fokker equations to solve the fluctuation equation, a more usual spectral approach was used. This enabled Troitskii to resolve questions having to do with the influence of flicker noise and taking into account periodic non-stationarity of interacting shot noise signals.

When striving to make accurate measurements of noise signals, the sensitivity threshold was not as important as excluding systematic errors in the measurements. This required accurate calibration, which could be provided only by standard sources of thermal radio emission. Therefore, as part of the development of the new radiometers (for 3 and 10 cm), precise standard sources of thermal radio emission with fairly high temperatures of 200°C or higher were devised. Such a standard source was made by Rakhlin for the waveguide used at 3 cm, based on a matched blackbody wedge that was heated in the waveguide. This long served as the primary standard for calibrating radiometers at this wavelength. Simultaneously, Plechkov developed a standard source for a temperature of 1500°C in the form of a tungsten-filament lamp with a special construction, which was placed in the waveguide. This was used as a secondary standard, and required calibration using a primary standard source.

At the same time, primarily through the efforts of students, work was begun on a radiometer designed to operate at 1.63 cm wavelength, which was brought into use by Kislyakov and L. I. Turabovaya in 1954, and was used for observations of a solar eclipse in Novomoskovsk (Fig. 2.3).

During the course of this work on various radiometers, the idea arose of using them as devices to accurately measure the power of weak signals and the noise signals of various instruments, and also to calibrate attenuators. The first industrial radiometers operating at 3 and 10 cm were devised, based on studies and developmental work carried out by Rakhlin and Starodubtsev in 1954–1960 under the supervision of N. A. Serebrov. In subsequent years, serially produced, broadband radiometers adjustable to wavelengths from 2 to 60 cm were developed at this same institute, under the supervision of N. N. Kholodilov.

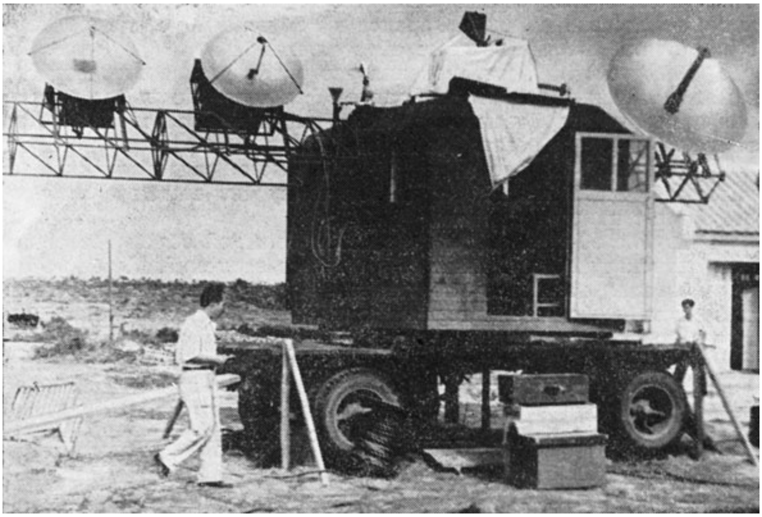

Fig. 2.3 Centimetre-wavelength (1.6, 3, and 10 cm) radio telescopes at the solar-eclipse expedition of 1954 at Novomoskovsk

2.1.2 Radio Astronomy Observations

Intensive radio astronomy studies began in 1952. Razin performed the first measurements in the world of the radio emission of Cassiopeia A and the Crab Nebula at 3 and 10 cm using the new 4-m parabolic radio telescopes. In 1954, these measurements were again carried out by Razin and Plechkov, and Razin who began investigations aimed at searching for polarisation of the extended cosmic radio emission. With the development of the theory of the synchrotron radiation of the Galaxy, it because obvious that the extended cosmic radio emission might be significantly polarised. However, the degree of polarisation of the radio emission received at the Earth should be small (a few percent or less) due to the inhomogeneity of the magnetic fields in the interstellar medium. Razin first pointed out the importance when attempting to detect this polarisation of taking into account the rotation of the plane of polarisation due to Faraday effects in the interstellar medium and the ionosphere of the Earth. He proposed a means to use this effect, consisting of modulating the bandwidth of a radiometer in order to reliably distinguish the polarised component of the radiation. This drastic improvement in the radiometer enabled the detection of linear polarisation of the extended cosmic radio emission at 1.45 m in Summer 1956. On May 10, 1964, Razin was awarded a diploma for this discovery, with the discovery date indicated as June 1956.

In the beginning of the 1950s, a large number of studies of the solar radio emission during eclipses were conducted. Observing during eclipse made it possible to observe local sources on the Sun with resolutions of arcminutes. In addition, such observations provided information about the radio diameter of the Sun. The data obtained at various wavelengths were used to construct a model for the solar corona, that is, the dependence of the kinetic temperature and electron density on height above the solar photosphere. It was also of interest to measure the radio brightness distribution across the solar disk. These questions were investigated in a number of expeditions. The first such expedition using Gorkii radio telescopes was in 1952 to the settlement of Archman, near Ashkhabad, which fell within the total-eclipse strip. Radio telescopes operating at 3 and 10 cm wavelength were used.

In 1954, there was another expedition to the Novomoskovsk region, where likewise, it was possible to observe during a total solar eclipse. Three radio telescopes, operating at 1.6, 3 and 10 cm were used.

Finally, a Radio Physical Institute expedition observed a solar eclipse in China in 1958, on the Hainan Island, using radio telescopes operating at 1.6, 3 and 10 cm. A. N. Malakhov, Razin, Rakhlin, K. S. Stankevich, K. M. Strezhneva, Khrulev, N. M. Tseitling and other participated in this expedition, which was supervised by Troitskii.

Careful measurements of the absorption of radio radiation in the Earth's atmosphere from its own radio radiation were conducted in 1952, in various seasons. Numerous data on the total absorption of radio radiation for various absolute humidities at the Earth's surface were obtained. Gorelik pointed out to Tseitlin, who was conducting these studies, that the dependence of the absorption on the absolute humidity seemed to be linear. In this way, a method was devised to separately determine the absorption by oxygen (extrapolating the linear relation between the total absorption and the humidity to zero humidity) and by water vapour (from the slope of the linear relation). This method led to the beginning of further investigations of absorption in the atmosphere over a wide range of wavelengths, from millimetres to several tens of centimetres.

In 1952–1955, radio astronomy methods for measuring the parameters of antennas began to be developed. As a rule, the antenna beam was usually measured using the radio emission of the Sun. It was at that time that Razin and Troitskii proposed and developed a method for measuring the losses in the antenna tract and in the antenna itself using measurements of the antenna noise.

Radio astronomy methods for studying antennas subsequently developed in the independent direction of applied radio astronomy due primarily to work by radio astronomers and radio physicists in Gorkii (Troitskii, Tseitlin, Dmitrenko and others).

Investigations of the radio emission of the Moon were begun in 1951–1952 under the supervision of Troitskii. The new 4-m radio telescopes enabled the reliable detection of the thermal radio emission of the Moon. By that time, Piddington and Minnet in Australia had detected a phase dependence for the radio emission at 1.25 cm, and established that the amplitude of the Moon's temperature fluctuations was much lower than at infrared wavelengths. They explained this by suggesting that the radiation at 1.25 cm was not emitted at the surface, where the temperature fluctuations from the lunar day to night were 300 K, but instead from some depth where these fluctuations were damped by a factor of five.

The first observations of the Moon were carried out at 3 cm, but only when the Moon was rising or setting, in order to determine the refraction and absorption of the radio emission in the atmosphere. These measurements were used to estimate an upper limit for possible temperature fluctuations of the Moon, which turned out to be much lower than at 1.25 cm. It became obvious that this wavelength was emitted from a still thicker layer of material, at a depth where the temperature fluctuations were essentially completely damped. Troitskii studied the properties of the surface-layer material and devised a very complete theory for the lunar radio emission for the case of a homogeneous composition of its surface layer. Specialised, more accurate studies of the lunar radio emission were then begun. Much attention was paid to accurate calibration of the fluxes measured by the radio telescope. The intensity of the solar radio emission was measured using a reference horn antenna, and this intensity was then used to calibrate the 4-m radio telescope.

These studies led in 1955 to the detection and measurement of the phase behaviour of the lunar radio emission at 3 cm. These measurements, in turn, represented the beginning of a more than ten-year series of investigations of the Moon from millimetre to decimetre wavelengths, which served as the basis for the development of new methods for accurate absolute intensity measurements and the calibration of radio telescopes by Troitskii and Tseitlin, and later V. D. Krotikov and V. A. Porfir'ev as well. Kislyakov began the work on the creation of radiometers for millimetre wavelengths. It was necessary to overcome enormous difficulties, since neither measuring devices nor the necessary microwave elements (in particular, crystal mixers) existed for this wavelength range.

In 1954, work on radar studies of the Moon began at Gorkii, whose importance had been pointed out earlier by Academician N. D. Papaleksi. Radar measurements of the Moon at centimetre wavelengths (3 and 10 cm) were first realised in 1954–1957 by a group of researchers under the supervision of Kobrin. This work encountered great difficulties, since, in contrast to the situation at metre and decimetre wavelengths, there were not yet at that time transmitters operating at centimetre wavelengths that could provide the necessary radio power for this purpose. Researchers at the Physical–Technical Institute had to carry out special studies to learn how to design and construct the necessary transmitting and receiving equipment. They developed the method of bistatic radar measurements using comparatively low power and a modest antenna area, foreseeing the use of radiometer devices to receive the reflected signal, and proposed a phase method for the measurement of the distance to the Moon.

To obtain high power, a method for adding the powers of several (two to four) centimetre-wavelength generators in series using bridge connectors was proposed and realised. These systems were able to yield continuum radio powers of several kilowatts and a frequency stability that was higher than that of the individual generators making up the system (D. I. Grigorash, V. S. Ergakov). At the same time, methods for the parametric stabilisation of the transmitter and monitoring of this stabilisation using a quartz heterdyne, as well as methods for amplitude manipulation, were developed in parallel. Specialised radiometer receivers with a travelling wave tube at the input and a narrow receiver bandwidth of from 1.5 to 3.0 MHz were devised to increase the sensitivity of the receivers (V. I. Anikin, I. M. Puzyrev). The heterodyne of the 3-cm receiver was stabilised with a quartz self-tuning phase system. I. V. Mosalov and V. I. Morozov designed and built antenna systems with accurate 4–5-m diameter surfaces and semi-automated tracking (an equatorial mount).

The transmitter was in an institute building in Gorkii, while the receiver was located 30 km away at the Zimenki site. The frequencies of the transmitters and receiver heterodynes were matched using a special communication channel. The transmitter and receiver were turned on alternately for 3 s in order to exclude the direct reception of the transmitted signal.

During the lunar-radar experiments at 10 cm in July 1954 and at 3 cm in June 1957, it was found that the effective area of the Moon for reverse scattering[1] was 0.07 of the area corresponding to its transverse cross section, in agreement with later measurements at centimetre wavelengths obtained outside the Soviet Union. It was found that the Moon's reflection of centimetre waves was very different from its reflection of optical waves. Based on the dependence of the signal on the accuracy with which the antenna was pointed at the centre of the Moon, it was concluded that the reflection occurs primarily from the central part of the visible lunar disk.

In this period and also in subsequent years, theoretical studies of radio astronomy and astrophysics were also widely developed in Gorkii. Important results in the theory of the extended cosmic radio emission and the radio emission of discrete sources were obtained by Ginzburg, Getmantsev and Razin, in studies of plasma mechanisms for the generation of various types of solar radio emission by Zheleznyakov, and in connection with various problems in astrophysics by Kaplan.

At that same time, Ginzburg and Getmantsev developed the theory of occultation observations of the Crab Nebula, when the Moon passes in front of the source for some period of time. This method, which was also put forth by Gorelik, is still used today, and provides an effective resolution of fractions of an arcsecond.

2.2 Development of Radio Astronomy at the Radio Physical Research Institute

The number of radio astronomy studies being undertaken was appreciably expanded with the formation in 1956 of the Radio Physical Research Institute (NIRFI), on the basis of several departments of the Physical–Technical Institute and research groups at the Polytechnic Institute.

Three radio astronomy departments were created in the institute: the Department of Microwave Radio Astronomy, headed by Troitskii, the Department of Long-wavelength Radio Astronomy and Ionospheric Physics, headed by Germantsev and the Department of Solar Radio Emission, headed by Kobrin. In subsequent years, three new divisions were created from the Department of Microwave Radio Astronomy: the Laboratory of Galactic and Extragalactic Radio Astronomy in 1963 (headed by Razin), which became a department in 1967, the Department of Applied Radio Astronomy (headed by Tseitlin) and the Laboratory of Millimeter-wave Radio Astronomy (headed by Kislyakov), which became a department in 1975. A new

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[1] The ratio of the power of an isotropic source of radiation located at the same place as the observed object that would give rise at the receiver to the same power flux density as the observed object, to the power flux density of the incident radiation from the object.

department headed by E. A. Benediktov became distinct from the department of Germantsev in 1965, and another new department headed by V. O. Rapoport was separated off in 1976. In addition to studies of radio-wave propagation and plasma physics, these departments are concerned with the decametre radio emission of the Sun and powerful discrete radio sources.

The radio astronomy instruments at the Zimenki station (which became the Zimenki Laboratory in 1971) were expanded and outfitted. New radio astronomy stations of NIRFI were founded in Karadag (Crimea) and Staraya Pustyn' (Gorkii region) in 1964, and a radio astronomy base near Vasil'sursk (Gorkii region) in 1965, which later became the Vasil'sursk Laboratory.

Systematic radio astronomy studies in a number of directions began in the newly founded institute: investigations of the radio emission of the Sun, Moon and atmosphere, the polarisation of cosmic radio emission and the intensities and spectra of discrete radio sources, as well as work in applied radio astronomy. These studies were carried out on the basis of corresponding theoretical, methodological, instrumental and antenna developments.

Close and fruitful collaboration with radio astronomers at FIAN under the supervision of S. E. Khaikin and then V. V. Vitkevich was important for the development of radio astronomy studies at NIRFI.

2.2.1 The Zimenki Laboratory

A fully steerable 5-m millimetre-wavelength radio telescope was installed at Zimenki in 1957 (Kalachev, Mosalov, Morozov and others). In 1958, work began on the creation of instrument complexes for studies of cosmic radio emission at decametre wavelengths and studies of the ionosphere using radio astronomy techniques (Benediktov, V. V. Velikovich, Getmantsev, L. M. Erukhimov, Yu. S. Korobkov, A. I. Tarasov and others), the construction of two 15-m fully steerable radio telescopes, which were completed in 1962 and a complex of laboratory buildings and living quarters (Kobrin, A. A. Petrovskii, Zhuravlev, L. V. Grishkevich, I. S. Motin and others; Fig. 2.4).

In 1967, the unique RT-25 millimetre-wave radio telescope was constructed and brought into use. This is a transit-type telescope with a 2×25 m^2 surface, and has until recently provided the highest angular resolution at millimetre wavelengths in the world—$13''$ in azimuth and approximately $2'$ in elevation at 1.35 mm (Kislyakov, Mosalov, V. P. Gorbachev, V. N. Glazman, K. M. Kornev, V. I. Chernyshev and others).

In 1976, a “Solar Service” complex was established at Zimenki, consisting of centimetre- and decimetre-wavelength radio telescopes and standard “black” disks, which provide high-accuracy monitoring observations of the solar radio flux (O. I. Yudin, M. S. Durasova, T. S. Podstrigach, Yu. B. Bedeneev, I. M. Prytkov, G. I. Lupekhin, G. A. Lavrinov, V. S. Petrukhin and others).

Fig. 2.4 15-m radio telescope, the system of smaller radio telescopes, and the black disk for the solar service at Zimenki

2.2.2 The Karadag Radio Astronomy Station

The Karadag Radio Astronomy Station of NIRFI was established as a base for making very accurate absolute measurements of the intensity of the radio emission of the Moon and of powerful discrete sources at centimetre wavelengths. In 1957, Troitskii and Tseitlin proposed the method of comparing the received radio emission from a source with the radio emission of a standard black area. Such an area can be realised by observing the radiation from a hill slope below the Brewster angle. A metallic disk that reflects the "cool" radio emission from the region of the zenith toward the antenna is also placed on the hill side. The difference of the intensities of the "black" hill side and the metallic disk served as the calibration signal.

The landscape along the shore of the Black Sea between Planerskii and Sudak, where measurements were carried out under expedition conditions in 1957–1959, turned out to be a convenient location to realise this method (Troitskii, Tseitlin, Porfir'ev, Rakhlin and others). However, these measurements did not provide sufficient accuracy due to diffractional "heating" of the metallic sheet (radio emission from the Earth fell into the diffractional beam of the sheet and was reflected toward the antenna). Therefore, it was decided in 1960 to use black disks observed at fairly large angles to the horizon as standards, in order to shield them from "cool" regions of atmospheric radio emission. The first experiment of this kind was carried out in 1960 at Yalta, where a half-metre disk was mounted on the roof the *Oreanda* hotel, and radio telescopes operating at wavelengths of 3 cm (with a diameter of 1.5 m) and 10 cm placed 200 m from this location. Since the angular diameter of the disk was equal to the angular diameter of the Moon (which facilitated more accurate measurements of the lunar radio flux), it was called an "artificial Moon." To take into account radio emission from the Earth (the so-called diffraction correction), the radio emission of a screen with an opening equal in size to the disk was used in addition to the radio emission of the standard black disk itself (Troitskii, Porfir'ev, Krotikov). After the corresponding calculations of the diffraction correction carried out by Tseitlin, it was possible to avoid using the screen with an opening, and

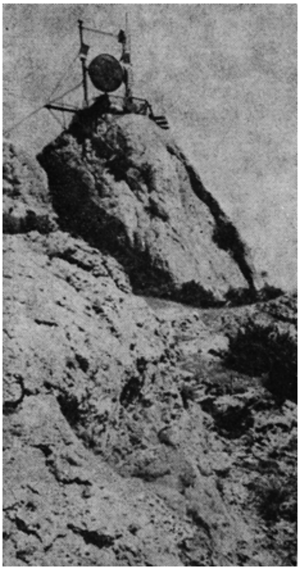

Fig. 2.5 Five-metre artificial Moon at the peak of a cliff (Karadag station, Crimea)

measurements began to be conducted by comparing the source radio emission and the radio emission from the standard black disk on its own. In this way, the "black disk" (or "artificial Moon") method arose—one of the most accurate methods for obtaining absolute measurements of the intensities of radio signals.

Since the placement of the black disk required a high pole or hill, for economic reasons, it was most convenient to conduct accurate measurements of the intensities of the Moon and discrete radio sources at sites in the mountains. After extensive study, it was determined that the most suitable mountainous site to carry out measurements was a region in the Eastern part of the Crimea. A large expedition to Sudak took place in 1961 (Troitskii, Tseitlin, Stankevich, Krotikov, Porfir'ev, L. N. Bondar', K. M. Strezhneva and others), where an artificial Moon with a diameter of 4 m was place on a cliff near Genuez Fortress (Fig. 2.5). The radio telescopes were placed on the sea shore at a distance of about 400 m from the disk. The main task of the expedition was to study the Moon at 3 and 10 cm with the aim of determining a possible temperature gradient with depth.

As a result of this work, the increase in the temperature of the Moon with depth was reliably established for the first time—a discovery for which Troitskii and Krotikov were awarded a diploma with the discovery date indicated as November 19, 1962.

At the beginning of 1961, Razin and Tseitlin proposed to carry out precision measurements of the fluxes of the most powerful discrete sources using the "black" disk method, at decimetre wavelengths as well as 3 cm. In other words, they wished to compile an accurate catalogue of the absolute fluxes of these sources over a wide range of wavelengths.

To realise this programme and programmes of studies of the lunar radio emission, a second expedition to Sudak was organised in 1962. Telescopes operating at centimetre and decimetre wavelengths were used. However, the use of larger radio telescopes required that the distance to the black disk be increased, which was not possible at Sudak.

Therefore, decimetre-wavelength measurements of the radio fluxes of the Moon and discrete sources were carried out in 1962–1964 in the Karadag valley. However, here as well, the possibilities for increasing the calibration distances were limited, leading to a search for a "convenient" mountain and surrounding area where it would be possible to separate the black disk and radio telescope by up to 1 km, as was required by the use of large antennas. (The distance from the antenna to the disk must be more than $2D^2/\lambda$, where D is the antenna diameter and λ is the wavelength.) In addition, the mountain must be high enough for the angle at which the artificial Moon was observed to be as large as possible. A suitable place was chosen by Porfir'ev in a clearing on the Karadag massif. The cliff looked so inaccessible that it appeared it might be impossible to mount the disk on it. However, systematic decimetre-wavelength measurements of the fluxes of the Moon and powerful discrete sources began in Autumn 1965. A new artificial Moon was constructed and mounted.

In 1965–1966, radio telescopes with diameters of 4 and 12 m were brought into use, an electrical transmission cable laid, and wooden laboratory buildings and living quarters constructed. In this way, the Karadag radio astronomy station of NIRFI arose, and has been continually operational since.

In subsequent years, another radio telescope with an accurate 7-m surface was installed, and a multi-frequency metre-wavelength interferometer and stand for studies of the sporadic radio emission of the Earth's magnetosphere constructed at the station, which is supervised by Stankevich.

2.2.3 The Staraya Pustyn' Radio Astronomy Station

The Staraya Pustyn' radio astronomy station of NIRFI was founded by Razin in 1964 for studies of the polarisation and spectrum of the Galactic radio emission.

The first polarisation observations there were obtained in 1965 with an 8-m fully steerable radio telescope (Razin, A. N. Rodionov, Khrulev and others). A 12-m telescope was brought into operation in 1967 (later increased to a diameter of 14 m in 1975), a 7 m telescope in 1970–1971 and two 14-m decimetre- and metre-wavelength telescopes in 1980–1981. Currently, the station has three 14-m radio telescopes that form a polarisation-sensitive interferometer with variable baselines (Fig. 2.6). Both fundamental and applied research was carried out using these telescopes (Razin, A. I. Teplykh, E. N. Vinyaikin, L. V. Popova, Khrulev).

In 1967–1971, two fully steerable 7-m radio telescopes operating at centimetre and decimetre wavelengths were brought into use, together with two 25-m towers with standard black disks separated from the antennas by 100 m and 50 m (Zhuravlev, E. A. Miller, Mosalov and others; Fig. 2.7). These radio telescopes were used to realise the method proposed by Tseitlin of obtaining accurate absolute measurements of radio fluxes by focusing the antennas (during calibration observations)

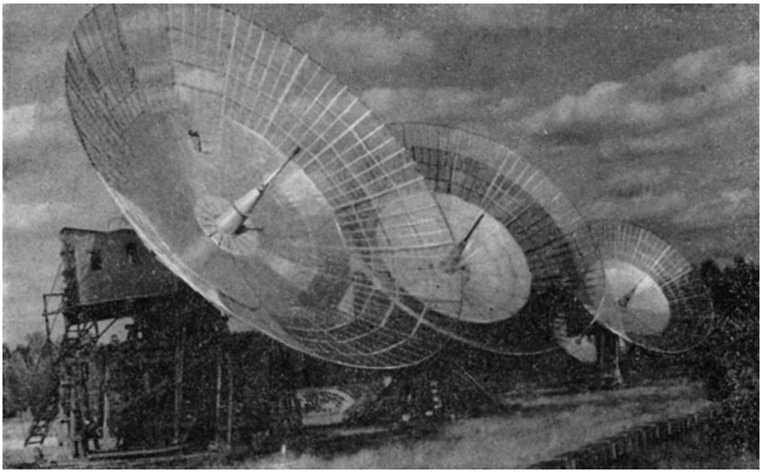

Fig. 2.6 Three-antenna polarisation radio-interferometer with a variable baseline (Staraya Pustyn' station)

Fig. 2.7 Seven-metre radio telescope and tower with the black disk (Staraya Pustyn' station)

on a disk located in the Fresnel zone. New radio astronomy and amplitude–phase (radio holographic) methods for studying antennas were also tested on these instruments (Tseitlin, Dmitrenko, A. A. Romanychev, V. I. Turchin, Yu. I. Belov, N. A. Dugin, A. L. Fogel', V. S. Korotkov and others).

In 1978, the RTVS-12 12-m decimetre-wavelength frame-and-guy radio telescope was constructed (Mosalov, N. V. Bakharev, Dugin and others), based on prestressed constructions for antenna surfaces. In 1980–1981, a two-element radio interferometer consisting of two 7-m radio telescopes separated by 417 m East–West operating at decimetre wavelengths as an Earth-rotation aperture synthesis system

Fig. 2.8 12-m radio telescope and five-metre black disk (Staraya Pustyn' station)

Fig. 2.9 German Grigor'evich Getmantsev (1926–1980)

was brought into use, together with a 5-m black disk intended for use with the RTVS-12 telescope for absolute measurements of the intensities of discrete sources and of the extended radio emission at decimetre and metre wavelengths (Fig. 2.8).

2.2.4 The Vasil'sursk Laboratory

The Vasil'sursk Laboratory is located in the Gorkii region near the place where the Volga and Sura rivers merge. It was organised in 1965.

From the first stages of establishing the laboratory, at the head of all undertakings was Getmantsev, whose untimely death occurred in 1980 (Fig. 2.9). Under his supervision, a well equipped base for scientific studies of non-linear phenomena in the ionosphere, radio astronomy and the propagation of radio waves in the ionosphere was constructed, which formed the basis for the Sura experimental complex built in 1980.

In 1968–1969, a metre-wavelength radio telescope with a 30 × 50 m antenna (rotating in azimuth) whose axis was oriented at 19° to the horizontal was brought into use. A fully steerable 8-m decimetre-wavelength radio telescope was also constructed.

2.3 Main Directions for Radio Astronomy Research at NIRFI

2.3.1 Radio Astronomy Studies of the Moon

Experimental studies of the lunar radio emission began at the Zimenki site in 1950 (Troitskii, Kislyakov, Krotikov, Starodubtsev, V. N. Nikonov, Tseitlin, Fedoseev, A. I. Naumov and others). Over the following two decades, a large series of experimental and theoretical studies were carried out, as a result of which:

- data on the temperature regime, composition and structure of the upper surface layer of the Moon to a depth of 10 m were obtained;
- the thermal and electrical characteristics of the lunar soil were determined;
- the growth of the temperature with depth was detected, and the existence of a hot core in the Moon demonstrated.

A model for the lunar soil was proposed based on these studies, which was used in the planning of the landing modules for the *Luna* series of automated interplanetary stations and the body of the lunar walker. The results of the ground-based radio astronomy observations were confirmed by direct measurements on the lunar surface and laboratory studies of the physical characteristics of the lunar soil.

2.3.2 Radio Astronomy Studies of the Sun

The first solar radiospectrographs, covering frequencies from 1 to 12 GHz with a frequency resolution of 60–100 MHz, were devised at NIRFI (Kobrin, Yudin, Podstrigach, Durasova, Vedeneev, A. I. Korshunov, V. M. Fridman, Prytkov, Rapoport, V. V. Pakhomov and others). A series of observational studies of the structure of the radio spectra of local sources and flares was carried out on the 22-m radio telescopes of FIAN and the Crimean Astrophysical Observatory.

Thanks to the high frequency resolution of the spectrographs, fine spectral features were detected in the slowly varying and flare components of the solar microwave emission. Theoretical models for active regions suggested that one possible origin for this fine structure was the presence of inhomogeneities, in particular, neutral current sheets, which are now widely invoked to explain the development of solar flares.

The investigations that have been conducted have opened new paths for studies of active regions on the Sun (in particular, searches and diagnostics for neutral current sheets), as well as pre-flare and flare processes.

On the basis of the unique T-shaped UTR-2 decametre-wavelength antenna near Kharkov and due to the efforts of both NIRFI and the Institute of Radio Physics and Electronics, a solar radio astronomy complex (radiospectrograph, two-dimensional heliograph and radiometer) was constructed and brought into operation, enabling the recording of dynamical spectra of peculiar decametre radio flares and the determination of the locations and sizes of their sources in the solar corona with high resolution.

The UTR-2-based radio astronomy complex is used for investigations of the main properties of the sporadic solar emission at decametre wavelengths, at frequencies of 10–26 MHz. Important observational data on the harmonic modes of type-III flares, the harmonic structure of double III6+III events and the dynamics of the electron flows exciting these flares have been obtained. New and extremely interesting phenomena have been discovered, such as radio echoes of short, narrow-band flares. These studies have appreciably increased our understanding of the physical conditions in the upper corona and the mechanisms generating the sporadic solar radio emission. The detection and investigation of quasi-periodic fluctuations of the solar radio emission stimulated similar studies at other observatories, in particular, in Cuba and the German Democratic Republic.

Beginning in 1966, systematic monitoring observations of the solar radio emission at 9100, 2950, 950, 650, 200 and 100 MHz were conducted at the Zimenki Laboratory. These observations enabled studies of the relationship between the brightnesses of solar flares and radio flares at centimetre wavelengths. They established the temporal connection between radio flares and soft X-ray emission, and the empirical relation between the intensity of the fluxes of protons with energies of 5, 10, 30 and 60 MeV and the integrated fluxes from radio flares at 3 and 10 cm. A statistical relationship between the maximum intensity of the flux of high-energy protons generated in solar flares and the time for the bulk of the protons to travel to the Earth was also detected. This relation can be used to achieve more accurate prognoses of proton fluxes.

2.3.3 Studies of the Radio Emission of Discrete Sources

Regular absolute radio astronomy measurements of the flux densities and spectra of powerful discrete sources (Cassiopeia A, Cygnus A, Taurus A, Virgo A) and of the planet Jupiter have been conducted for over 20 years at the Karadag and Staraya Pustyn' sites (Troitskii, Razin, Tseitlin, Stankevich and others). These studies make use of small (diameters of 7–14 m) radio telescopes calibrated using the radio emission of black disks mounted in both the Fraunhofer zone of the antenna (Karadag) and at closer distances, in the Fresnel zone (Staraya Pustyn'). These measurements have yielded precision (with uncertainties of a few percent) spectra of these powerful discrete sources, which have been used throughout the world as standards. These first reference measurements form the basis for a unified (Southern and Northern hemispheres) absolute scale for the spectra of secondary and tertiary calibration sources. The spectral energy distributions of 11 sources from the Cambridge and Parkes catalogues having fluxes of 10^{-25} W/(m^2 Hz) at a frequency of 1 GHz were measured on large telescopes calibrated using the primary standards. These sources form a group of secondary standards, which can be used to determine the parameters of antennas with diameters of 60–70 m. The NIRFI system of standards was used to measure the parameters of the unique 70-m radio telescope with its quasi-parabolic surface.

Investigations of the evolution of young radio supernova remnants have been carried out over some 20 years. Methods for absolute and relative radio astronomy measurements developed at NIRFI were applied in order to accurately determine variations in the frequency distribution of the intensity; a number of studies were carried out using antennas with high resolutions. These observations enabled the detection of secular decreases (fractions of a percent per year) in the radio flux densities of the Crab, Tycho Brahe and Kepler supernova remnants.

In the case of the young supernova remnant Cassiopeia A, the NIRFI measurements revealed a dependence of the rate of the flux decrease on the frequency, time variations of the radio spectral indices, strong time variations in the rate of the flux decrease and intense lines within a limited range of frequencies in the metre-wavelength radio spectrum. Variability in the flux density of the Crab supernova (Taurus A) reaching 15–20% and with a period of the order of several years was also discovered.

Lunar occultation observations (1964 and 1974) were used to study the structure of the Crab Nebula. Variations in the radio brightness distribution and a shift of the centre of gravity of the radio brightness were detected, as well as a relationship between these phenomena and the activity of the central region of the nebula containing the pulsar. The RATAN-600 radio telescope and a feed with linear-polarisation switching developed at NIRFI were used to obtain one-dimensional distributions of the linear polarisation of the radio emission of the Crab Nebula, the two-component core of the radio galaxy Centaurus A and the Moon at 13 cm with an East–West resolution of $2'$. Together with observations at other wavelengths, these data testify to the non-monotonic wavelength dependence of the integrated degree of linear polarisation of the northeastern component, and the large difference in the rotation measures of the core components of Centaurus A.

2.3.4 Studies of the Polarisation and Spectrum of the Galactic Radio Emission

After Razin's detection of the linear polarisation of the Galactic radio emission in 1955–1956 (at the Zimenki Laboratory, at wavelengths of 1.45 and 3.3 m), the main polarisation studies were conducted at the Staraya Pustyn' site (Razin, Khrulev, A. A. Mel'nikov, Popova, Vinyaikin, Teplykh and others).

Observations of the linear polarisation of the Galactic radio emission are an effective means of studying the physical conditions in the Galaxy. The angular distribution of the polarised radio emission on the sky and the frequency spectra of the polarisation parameters yield information about the distribution of ionised gas and relativistic electrons in interstellar space, as well as the structure of the Galactic magnetic field. With these goals in mind, studies of the angular distribution and frequency spectra of polarised regions in Loop III (Polar Region 147+8), the Northern Galactic spur and the vicinity of the North star were carried out, and the wavelength dependence of their angular sizes determined. A bright spot of linearly polarised radio emission with a polarisation temperature comprising 20% of the total temperature of the sky at 334 MHz was discovered in the direction of Polar Region 147+8 (declination $\delta = 60°$, right ascension $\alpha = 4^h 30^m$). In addition, the non-monotonic character of the frequency dependence of the degree of polarisation of the radio emission from this region was established.

Simultaneous measurements of the angular distributions of the linearly polarised and unpolarised Galactic radio emission at 334 MHz and interferometric measurements at 200 MHz demonstrated an anti-correlation between the temperatures of these two components, with the temperature of the total radio emission being proportional to the effective size of the Galactic disk. Thus, it was possible to determine directly and observationally that the linearly polarised radio emission is generated throughout the thickness of the Galactic disk.

The collected polarisation measurements obtained by NIRFI at 100–1000 MHz and data on the distribution of the brightness temperature over the sky at 85, 150 and 829 MHz show that the Galactic magnetic field out to distances of 3–10 kpc from the Sun in the sector with longitudes $l = 70$–$180°$ and latitudes $b > 0°$ is elongated along the Galactic plane and has a loop-like structure. The regular component of the field is directed toward $l = 55°$. The dispersion of the interstellar magnetic field in Galactic latitude is much less than unity, while the dispersion in longitude is equal to 0.5.

The anisotropy of the synchrotron radiation of the interstellar medium in a magnetic field with this structure can explain the distribution of the brightness temperature on the sky using a simple model with a radiating disk in the form of an ellipsoid of rotation with semi-axes of 14 and 0.8 kpc (without an intense radio halo).

The contribution of the radio halo at 85 MHz in the direction of the Galactic North pole is no more than 15% of the total sky temperature, and decreases with increasing frequency. Analyses have shown that no bright, well defined radio arms are observed in the sector $l = 70$–$180°$.

A series of studies of the spectrum of the non-thermal radio emission at 6.3–375 MHz was carried out in 1960–1980 (Getmantsev, Razin, Tarasov, Yu. V. Tokarev and others). These data refer to large-scale radio structures of the Galaxy, and can provide information about sources, accumulation volumes and the motion of cosmic rays, as well as about the intensity and spectrum of the metaGalactic radio emission. The efficiencies of various mechanisms for producing non-thermal cosmic radio emission have also been analysed.

2.3.5 Studies of the Cosmic Microwave Background

Proving the cosmological origin of the cosmic microwave background radiation required measurements of its spectrum in order to establish how well it corresponded to the spectrum of a perfect blackbody with a temperature of approximately 3 K. Investigations carried out at NIRFI were of prime importance for this problem (Kislyakov, Stankevich and others). A method based on using the radio emission of cooled absorption standards was developed as a means of obtaining accurate absolute measurements of the background radiation. This method was used to measure the temperature of the cosmic microwave background at various wavelengths: 2.55 mm (1968), 8.2 mm (1967, in collaboration with A. E. Salomonovich of FIAN), 3.2 cm (1966), 8.9 cm (1969) and 15, 20.9 and 30 cm (1968). At some wavelengths, the NIRFI data were the first obtained. The method of blocking the cosmic background radiation with the Moon was applied to obtain measurements at longer wavelengths, and the corresponding observations carried out by Stankevich at 47 and 73 cm using the 64-m Parkes radio telescope (Australia). These measurements showed that the Rayleigh–Jeans part of the spectrum was in full agreement with the spectrum of a blackbody with a temperature of 2.7 K. A high degree of small-scale isotropy (to 0.01%) was also demonstrated. These measurements were obtained at 11 cm with a resolution of $8'$ on the 64-m Parkes radio telescope.

2.4 Studies at Millimetre Wavelengths

Radio astronomy studies at short millimetre wavelengths ($\lambda < 4$ mm) were begun at Gorkii by Kislyakov in 1954. By 1960, a modulation radiometer with a superheterodyne receiver operating at 4.1 mm had been devised at NIRFI, as well as a broadband (3–7 mm) detector radiometer. Kislyakov used these radiometers to obtain data on the phase dependence of the lunar radio emission at 4.1 mm and the spectrum of the solar radio emission at 3–7 mm. A method for calibrating millimetre-wavelength radio telescopes using the radio emission of the atmosphere taking into account the specifics of this wavelength range was developed, and detailed studies of the dependence of the atmospheric absorption at 4 mm on the meteorological parameters and the elevation of the observing site above sea level conducted (Kislyakov, Nikonov, Strezhneva).

Further, a unique series of detector radiometers operating at 1.8 mm (Naumov), 1.3 mm, 0.87 mm and 0.74 mm (Yu. A. Dryagin, Fedoseev) were developed at NIRFI, which were used for observations of the Moon and Sun, as well as studies of the atmospheric absorption of radio waves (L. M. Kukin, L. V. Lubyako, Fedoseev). At this stage, data on the phase dependence of the lunar radio emission over the entire interval of wavelengths from 0.8 to 4 mm were obtained. These measurements showed the adequacy of a one-layer model for the lunar surface to describe variations of its radio emission during lunation.

Studies of the radio emission of the Sun and Moon at 4 mm were then continued in collaboration with FIAN, using the FIAN 22-m radio telescope and instruments provided by NIRFI. These results showed the radiometric homogeneity of the equatorial band of the Moon, while at the same time differences in the physical properties of the upper layers of the lunar seas and continents were detected (Kislyakov, B. Ya. Losovskii, A. E. Salomonovich). The first high-resolution observations of sources of the S component on the Sun simultaneously at 4 and 8 mm were carried out (Kislyakov, Salomonovich). In this same period, Kislyakov, A. D. Kuz'min and Salomonovich conducted the first investigations of the radio emission of Venus at 4.1 mm (see Essay 1).

By 1965, the first broadband radiometers based on superheterodyne receivers with microwave intermediate frequencies in the Soviet Union had been devised at NIRFI (Kislyakov, Yu. V. Lebskii, Naumov). This made it possible to substantially increase the sensitivities of radiometers, and to turn to a new series of studies of the Moon, planets and discrete radio sources. Further improvement of millimetre and submillimetre radiometers was based on original ideas for the application of quasi-optical tracts (Fedoseev, Yu. Yu. Kulikov).

Studies of the solar radio emission at 1.35–1.7 mm on the 22-m radio telescope of the Crimean Astrophysical Observatory yielded data on the spectrum of the S component and protuberances at these wavelengths, as well as some information about the manifestations of solar flares (Kislyakov, Moiseev, V. A. Efanov, Fedoseev, Naumov, Lebskii and others). Spectra of the radio emission of Venus, Mars, Mercury and Jupiter obtained in collaboration with researchers at the Crimean Astrophysical Observatory were used to draw some conclusions about the conditions in the atmospheres and on the surfaces of these planets (Kislyakov, Efanov, Moiseev, Naumov, V. N. Voronov, I. I. Zinchenko and others). In another collaboration with the Crimean Astrophysical Observatory, a survey of discrete radio sources at 4 mm was carried out, which was the first in the Soviet Union and the most complete survey at that time. The spectra of a number of galactic sources, quasars and radio galaxies were continued to short millimetre wavelengths.

The construction of the RT-25×2 radio telescope made possible a survey of dark nebulae at several millimetre wavelengths, with the aim of detecting continuum emission. These searches yielded positive results in some cases (Kislyakov, Chernyshev, Zinchenko, A. A. Shvetsov and others). The existence of condensations in dark Galactic nebulae was later confirmed by millimetre observations with the Crimean 22-m telescope, and was also indirectly supported by the results of observations in lines of isotopes of the CO molecule (Kislyakov, B. E. Turner, M. A. Gordon). These last observations were carried out in collaboration with researchers at the National Radio Astronomy Observatory (USA) using one of the NRAO telescopes. New lines of this molecule were discovered and the presence of cyanamide at the Galactic centre demonstrated (Kislyakov, Turner, H. S. List, N. Kaif). The continuum emission from condensations in dark nebulae corresponds to emission from an optically thin absorbing layer (apparently dust).

The RT-25×2 radio telescope was used to study the brightness distribution over the disk of the quiet Sun, including limb effects, at wavelengths of 4.1, 6 and 8 mm, as well as chromospheric granulation, using simultaneous observations at 1.35 and 4.1 mm (Kislyakov, Chernyshev, Fedoseev, S. A. Pelyushenko and others).

Beginning in 1977, radio astronomy studies at short millimetre and submillimetre wavelengths were continued at the Institute of Applied Physics of the USSR Academy of Sciences, which was organised in Gorkii on the basis of several subdivisions of NIRFI. This period is characterised by a transition from spectroscopy with only crude frequency resolution to spectroscopy with high (10^{-5}–10^{-6}) relative frequency resolution. Multi-channel spectrometers operating at wavelengths near 2 and 3 mm with stabilised heterodynes based on backward-wave tubes were devised at the Institute of Applied Physics (A. B. Burov, Voronov, A. A. Krasil'nikov, Lebskii, N. V. Serov). This enabled the first observations in the USSR of interstellar molecules such as HCN (Burov, Zinchenko and others) and CO, in collaboration with the Bauman Technical University (Burov, Kislyakov, A. A. Parshchikov, B. A. Rozanov and others). The detection of HCN lines from dark nebulae led to a revision of lower limits for the density of hydrogen in these objects.

The application of multi-channel spectrometers in atmospheric research made possible studies of telluric lines in the rotational spectrum of ozone at wavelengths of 1.3–3.3 mm, which began at NIRFI (Kulikov, Fedoseev, Shvetsov, V. G. Ryskin and others). The possibility of remote monitoring of the total content and vertical profile of ozone was demonstrated, including during night-time and in the presence of light clouds. Radio astronomy methods for measuring the atmospheric absorption of radio waves were also used in systematic observations, whose results form the basis for making prognoses of the magnitudes of signals in Earth–Space communication sessions (Kislyakov, Fedoseev and others). This last work was carried out in collaboration with the Institute of Radio Physics and Electronics (V. F. Zabolotnii, Zinchenko, I. A. Iskhakov, A. V. Sokolov, E. V. Sukhonin, Chernyshev).

2.4.1 Development, Study and Application of Radio Astronomy Methods

Radio Interferometry with Ultra-high Resolution The first work on the creation of instrument complexes for radio interferometers with independent receiving systems designed to yield high resolution was begun at NIRFI in 1965 at the initiative of Troitskii. During 1965–1981, instruments operating at frequencies of 6, 9, 25, 86, 327, 408, 5300 and 22235 MHz were devised (Troitskii, Nikonov, Krotikov, V. A. Alekseev, E. N. Gatelyuk, A. E. Kryukov, B. N. Lipatov, A. S. Sizov, A. I. Chikin, M. V. Yankavtsev and others). Astrophysical investigations using large-scale Soviet radio telescopes began in 1969. The first measurements of the angular size of Cassiopeia A at decametre wavelengths were made; an angular resolution of 10^{-3} arcminute was realised in measurements of the angular sizes of cosmic masers at 1.35 cm with a baseline of 1100 km; interferometry of cosmic masers was used to synchronise time standards in different locations. This work was carried out in collaboration with the Lebedev Physical Institute, Space Research Institute, Institute of Radio Physics and Electronics, Crimean Astrophysical Observatory and Byurakan Astronomical Observatory.

The development of a methodical and technical basis for a new scientific research direction—precision radio astrometry using Very Long Baseline Interferometry (VLBI)—led to the proposal of the following methods: (1) aperture-frequency synthesis for obtaining radio images of cosmic radio sources with very high angular resolution; (2) differential long-baseline radio interferometry for establishing celestial and terrestrial coordinate systems, measuring the rate of rotation of the Earth and the motion of the poles, and studying tides in the Earth's crust, precessional–notational motions and tectonic and seismic phenomena. The principles of space radio astrometry were also considered. The potential accuracy of these methods when applied with VLBI is more than two orders of magnitude higher than the accuracies that can be achieved by other measurement methods.

Radio Astronomy Methods for Studying Antennas Radio astronomy methods for determining the energetic parameters of antennas were first proposed as early as 1955 by researchers at NIRFI and FIAN. Further, as a result of investigations conducted at NIRFI, these methods were developed and applied to complex antenna systems, including interferometric and phasometric systems (Troitskii, Tseitlin, Dmitrenko, Dugin and others).

In the 1960s, radio astronomy and radiometer methods using both cosmic radio sources and the radio emission of absorbing and scattering surfaces were developed at NIRFI. The most accurate antenna characterisations were achieved using the radio emission of "black" disks placed in both the Fraunhofer and Fresnel zones of the antenna—a method developed at NIRFI (Troitskii, Tseitlin).

Measurements of the radio fluxes of primary and secondary standard sources obtained at NIRFI enable the determination of the parameters of a whole range of antenna types with unprecedented accuracy (to within 5%). The application of these methods in industrial facilities during the development and production of antennas, and also in other types of facilities during the exploitation of antenna systems, proved to be very effective. Radio astronomy and radiometer methods for antenna measurements have a number of advantages in many applications, and sometimes provide the only means possible to obtain such measurements.

On the basis of work done at NIRFI, methods for characterising antennas are being successfully developed in a number of organisations in the USSR.

Radio Astronomy Methods for Analysing the Parameters of the Troposphere In 1948–1952, methods for separately measuring tropospheric absorption by water vapour and oxygen based on the radio emission of the troposphere were proposed and developed at NIRFI (Troitskii, Tseitlin). Over the last 25 years, the most complete studies in the world of the absorption and emission of radio waves in the troposphere from millimetre to metre wavelengths have been carried out (Troitskii, Zhevakin, Tseitlin, Razin, Plechkov, Kislyakov, Stankevich, Khrulev, Dmitrenko, A. V. Troitskii, Naumov and others). Absorption and emission radio spectra of the troposphere at these wavelengths have been obtained, and their dependences on meteorological conditions analysed, which is very important for radio communications, radar and other applications. The work in this area carried out at NIRFI also stimulated radiometer studies of the troposphere in other organisations in the Soviet Union.

As a result of many years of such tropospheric investigations, the possibility of determining the temperature, total water content and humidity of the troposphere by analysing tropospheric radio emission received simultaneously at several frequencies was demonstrated. Over the last 15 years, radiometer methods for obtaining tropospheric measurements, algorithms for solving inverse problems and principles for the construction of receivers have been developed. This led to the creation of a multi-channel radiometer system enabling the operative and continuous reception of information about the physical state of the atmosphere: profiles of the temperature and humidity, the total contents of liquid water and water vapour and the altitudes of clouds.

The developed instruments and methods for remote atmospheric measurements made it possible to conduct important meteorological studies in tropic zones of the Atlantic and Pacific Oceans and in regions within the polar circles, and to investigate the spatial (mesoscale) and temporal (hourly) variations in the total mass of water vapour and the water content of clouds.

Radio Astronomy Polarisation–Faraday Methods for Ionospheric Investigations (Razin, Teplykh, Popova) One of the important characteristics of the ionosphere is the total electron content along the line of sight (N_{II}). There exist several methods for measuring N_{II}, among which the most accurate and efficient are measurements of the Faraday rotation of the plane of polarisation of linearly polarised radio emission from sources located beyond the ionosphere. As a rule, geostationary satellites are used as sources for this purpose. Radio astronomy polarisation–Faraday measurements, which make use of the radio emission of polarised regions of the Galaxy, are very promising in connection with their economy and simplicity.

The first measurements of N_{II} using the radio astronomy polarisation–Faraday method were carried out in 1970 at the Staraya Pustyn' radio astronomy station. These measurements were carried out regularly at a wavelength of 1 m beginning in 1976. The sources used were a polarised region with declination $\delta = 61^\circ$ and right ascension $\alpha = 4^h30^m$ and the region of the North star. Numerous data on the behaviour of N_{II} during the night near the solar-activity maximum have been accumulated up to the present; the episodic appearance of a relative night-time maximum of N_{II} has been demonstrated and the statistics of this behaviour analysed.

When the manuscript for this collection was already at the publishers, we learned of the sudden death of the eminent Soviet scientist and teacher, professor and doctor of technical sciences Mikhail Mikhailovich Kobrin (Fig. 2.10)—one of the oldest radio astronomers in the Soviet Union and also one of the editors of this collection. M. M. Kobrin was one of the organisers of NIRFI, and was the Assistant Director of Scientific Research at NIRFI for many years, then the Assistant Head of his Department. He was the Dean of the Radio Physical Faculty of Gorkii State University, and the Science Rector of this university. The fruitful scientific activity of M. N. Kobrin in the area of radio astronomy is reflected in this essay. His contribution to

Fig. 2.10 Mikhail Mikhailovich Kobrin (1918–1983)

radio astronomy studies of the Sun was especially large. He was the Chairman of the Solar Radio Emission Section of the Scientific Council on Radio Astronomy of the USSR Academy of Sciences for many years, and did much to unite the efforts of Soviet radio astronomers in the development of this important research direction. He also personally took part in the development of radio astronomy in the German Democratic Republic and in Cuba.