Chapter 9
Radio Physical Studies of Planets and the Earth at the Institute of Radio Technology and Electronics of the USSR Academy of Sciences

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Abstract Stages in the development of radar astronomy and the main methods and scientific results obtained at the Institute of Radio Technology and Electronics (IRE) beginning in the 1960s are discussed. The fundamental importance for manned space flight of the radical improvement in the accuracy of the astronomical unit achieved using radar measurements of planets is underscored, together with other important results of studies of planetary surfaces. Studies of the atmosphere and surface of the Earth using radio-astronomy methods are described in detail, including satellite techniques. The results of radio-physical studies of the ionospheres of the Moon and planets carried out by analysing signals transmitted by spacecraft and received on the Earth are also presented.

9.1 Radar Astronomy[1]

In the middle of 1960, at the initiative of Academician V. A. Kotel'nikov, the Director of the Institute of Radio Technology and Electronics of the Academy of Sciences of the USSR [IRE], preparations were begun for radar measurements of Venus, which is the planet that approaches the closest to the Earth. Since that time, a series of work on radar studies of planets, led by Kotel'nikov, has been one of the main research directions at the institute.

In the first experiments on radar measurements of the Moon carried out in 1946 in the USA and Hungary, radar stations intended for the detection of airplanes were used. To detect signals reflected from Venus, the energy potential (sensitivity) of the radar installations used had to be increased by a factor of 10 million, and then increased by a further factor of 100 to detect reflected signals from Mars. Thus, signals reflected from other planets could be detected only after considerable development of antenna, transmitter and receiver technology, and the development of methods for signal detection.

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[1] Section 9.1 was written by O. N. Rzhiga and Sect. 9.2 by B. G. Kutuza.

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Fig. 9.1 Antenna of the Deep Space Communication Center in the Crimea, consisting of eight parabolic reflectors 16 m in diameter on a common azimuthal–vertical steerable structure

Creation of a Radar Installation for Planetary Studies Yu. K. Khodarev suggested to use the antenna and transmitter of the Deep-Space Communications Centre (DSCC) that were then being built near Evpatoria for radar measurements of Venus. This antenna was being constructed under the supervision of E. B. Kopenberg, and the transmitter of continuum radiation at a wavelength of 39 cm under the supervision of V. P. Minashin (Fig. 9.1). The base of a rotating gun turret from a linear ship was used as the mount platform (see Essay 1). The antenna, intended for flight control and the reception of information from interplanetary stations, was designed in three months and then constructed in another three months.

In the middle of 1960, O. N. Rzhiga wrote that it would be possible to receive a reflected signal from Venus using the technical facilities of the DSCC during the nearest inferior conjunction in April 1961. It would thus be possible to measure the distance between Venus and the Earth using a signal sent from the DSCC transmitter. He devised a structural scheme for the radar installation and a method for the radar measurements, and also estimated various factors affecting their accuracy.

In view of the uncertainty in various parameters, it was proposed to record the reflected signal on magnetic tape, making it possible to select the optimal parameters for the measuring apparatus when playing back the recording. With this aim, V. M. Dubrovin developed a magnetic-recording system using a reference oscillator to ensure precise time marks when playing the recordings. Dubrovin developed a receiver with a five-fold frequency transformer. The ultra-high-frequency (UHF) part of the receiver, which had a parametric input amplifier, was developed under the supervision of N. N. Nikitskii.

The detection of the weak reflected signal against the fluctuating noise background of the receiver required a long integration time, up to several or even tens of hours, in the case of a very weak signal. The detection of the reflected signal and measurement of its frequency and energy at the receiver output were realised using a multi-channel spectrum analyser designed by V. A. Morozov with the help of E. G. Trunova. The energy of the signal was measured using the fact that the total time when the upper envelope of a certain threshold level is exceeded in each frequency channel of the analyser grows proportional to the energy of the signal. V. I. Bunimovich and Morozov showed that, under the relevant conditions, this method for the reception of a weak signal was essentially the optimal one. The spectrum analyser was constructed under the supervision of G. A. Podoprigory, and had 10 frequency channels with a transmission bandwidth of 20 Hz.

The radiated signal was a periodic succession of pulses and pauses with equal durations, which were used for the radiometer reception of the reflected signal and determination of corrections to the expected signal arrival time. The tie of the signal to Universal Time and determination of the expected signal arrival time were realised using a program-timing device devised by G. M. Petrov. Petrov also developed a device designed to switch off the transmitter before the onset of reception, switch the antenna from the transmitter to the receiver and change the polarisation of the antenna. Rzhiga and L. V. Apraksin developed a generator that could be used to vary the frequency of the transmitter carrier signal in accordance with the expected Doppler shift, in order to ensure reception of the reflected signal near the nominal frequency.

Calculation of the expected (ephemerides) values of the delay time for the reflected signal and Doppler shifts to the transmitter carrier frequency, as well as commands for pointing of the antenna, were carried out using electronic computers. The programming of these computers and conduction of the required computations was supervised by M. D. Kislik; participants in this work included D. M. Tsvetkov, B. A. Stepanov, B. A. Dubinskii and G. A. Zhurkina. The computations used tables of heliocentric positions and velocities of the centres of mass of Venus and of the Earth–Moon system, as well as tables of geocentric positions of the centre of mass of the Moon, compiled at the Institute of Theoretical Astronomy of the USSR Academy of Sciences by D. K. Kulikov and N. S. Subbotin. The computational programs took into account the non-simultaneity of the times for the radiation, reflection and reception of the signals and changes in the configuration of the planets in space over the elapsed time.

The DSCC antenna, which was intended for communicating with satellites and was set up to work with circularly-polarised signals, had to be equipped to receive the mirror-reflected signal from the planet. Kopenberg suggested the introduction of depolarisers in the form of linear grids in the tract to the receiver, between the feed and surface of the antenna, since this was simpler than changing the direction of rotation of the polariser plane between signal transmission and reception.

There was the possibility that the onset of the radar observations was delayed by delays in the manufacture of the depolarisers, antenna switch and parametric amplifier box. In February 1961, after the launch of the *Venera-1* automated interplanetary station, Academicians S. P. Korolev and M. V. Keldysh came to the DSCC complex. After Dubrovin and Rzhiga had reported on the state of the planetary-radar project, Korolev, who was interested in ensuring a successful flight of the interplanetary station, decreed that the work be urgently completed. The manufacture of the antenna

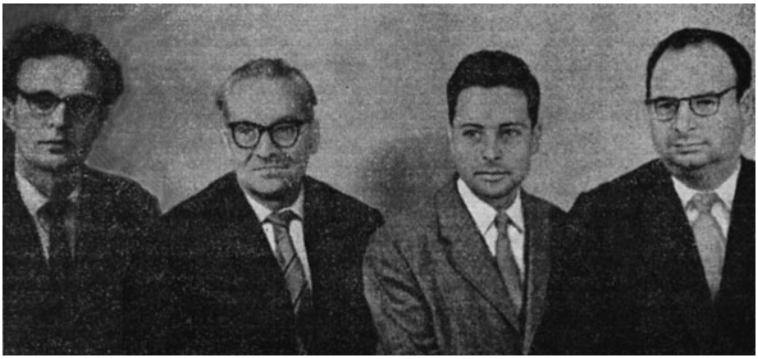

Fig. 9.2 Photograph done not long before the first radar observations of Venus. *Left to right*: A. M. Shakhovskoi, Academician V. A. Kotel'nikov, O. N. Rzhiga and V. M. Dubrovin

equipment was completed in the plant in a single night, and was sent to Evpatoria by fast train.

At the beginning of the observations, the radiated power was 10 kilowatts. During the observations themselves in the middle of April 1961, under the supervision of Minashin, four klystron transmitters were put together, increasing the radiated power by a factor of four, which played a decisive role in the success of these first observations.

The radar installation for planetary studies was established in the six months until the next inferior conjunction with Venus. This work was made possible by the experience and enthusiasm of the entire group of researchers involved. Some, from the Institute of Radio Electronics of the USSR Academy of Sciences, had experience in constructing receivers and regulating devices for observations of the first artificial Earth satellites and of automated stations sent to the Moon at the end of the 1950s; others had worked on the problem of distinguishing weak signals from noise. They were joined by a large number of staff from the leading organisations involved. A leading role in composing the group and organising the radar observations was played by A. M. Shakhovskii (Fig. 9.2). Much work in manufacturing, adjusting and servicing the equipment developed at the Institute of Radio Electronics was contributed by Yu. A. Alekseev, L. V. Apraksin, Yu. P. Vasil'ev, V. O. Voitov, A. V. Grigor'ev, O. K. Dmitriev, N. M. Zaitsev, A. V. Kaledin, P. P. Korsakov, B. I. Kuznetsov, P. V. Kuznetsov, E. F. Kushchenko, I. V. Lishin, Yu. M. Lobachev, L. P. Lundina, Yu. N. Paukov, G. A. Podoprigora, V. Kh. Sinitsa, N. M. Sinodkin, G. I. Slobodenyuk, O. S. Stepanov, A. L. Tamarin, B. K. Chechulin, A. S. Chikin and Yu. V. Filin. A large amount of help in organising and conducting the first observations of Venus was given by P. A. Agadzhanov, A. P. Rabotyagov and G. A. Sytsko.

Academician Kotel'nikov directly oversaw the creation of a unique radar installation at the DSCC, as well as the preparation for and conducting of the observations. The participants in the first observations remember working 16 hours or more in a day in order not to miss the optimal period for the Venus observations. The inexhaustible energy and optimism of Kotel'nikov supported a cheerful mood in the group even at the most difficult moments.

First Observations of Venus The first signal to Venus was sent on April 1, 1961. The main observations were carried out on April 18–26, 1961. At that time, the distance between the Earth and Venus was 43.5–47.5 million km. The observations were carried out at a wavelength of 39 cm, with circularly polarised radiation. A total energy of approximately 15 Watts was incident on the visible surface of Venus over a time of about five minutes. Approximately 20 s before the expected time of arrival of the reflected signal, the transmitter was switched off to that it would not contribute interference, the antenna was switched over to the receiver, the polarisation of the antenna was changed to linear and the reflected signal was received for five minutes.

The reflected signal was not detected in these first observations. This led to the suggestion that the spectrum of the reflected signal was smeared over a broader band than had been supposed ($\sim$20 Hz); the widths of the frequency channels in the spectrum analyser were accordingly expanded to 60 Hz. The real reason for the absence of a reflected signal was discovered on April 18, soon after the power of the transmitter had been increased fourfold. It turned out that one of the frequency dividers had been adjusted incorrectly, so that the changes in the pulses and pauses in the radiation, as well as the switching of the receiver apparatus to a radiometer regime, were essentially occurring at random times, hindering accumulation of the signal.

During the main observations (after re-adjusting the frequency divider), the repetition period for the pulses and pauses in transmission was either 0.256 s or 0.128 s, to enable unambiguous determination of the distance to Venus. Of the various possible values for the astronomical unit calculated based on the measurements of the distance to Venus, the value initially chosen was that closest to the value derived earlier using astronomical methods, which proved to be incorrect.

Immediately after the end of the observations, an analysis was carried out of the magnetic recordings of the reflected signal, which were obtained using electromechanical filters with a transmission bandwidth of 4 Hz placed in the channels of the spectrum analyser. The use of these filters, developed by M. G. Golubtsov, made it possible to remove ambiguity in the distance measured from the Doppler shift of the central frequency and correctly determine the width of the received spectrum.

In the mean spectrum of the signal reflected from Venus on April 18, 1961 obtained by analysing five receiver sessions of about five minutes each (Fig. 9.3), the width of the spectrum does not exceed 4 Hz—the transmission bandwidth of the filters placed in the spectrum-analyser channels.

As a result of the radar observations carried out in 1961 in the Soviet Union, the signals reflected from Venus were detected and their parameters measured, making it possible to estimate the effective area of Venus for back scattering, the rotational period of Venus, the distance of Venus from the Earth and Venus' radial velocity, as well as to refine previous estimates of the astronomical unit. The astronomical unit was found to be 149,599,300 km (assuming the speed of light is 299,792.5 km/s), with a root-mean-square uncertainty of 650 km. The rotational period of Venus determined from the broadening of the reflected signal was found to exceed 100 days, if the reflective properties of Venus were similar to those of the Moon.

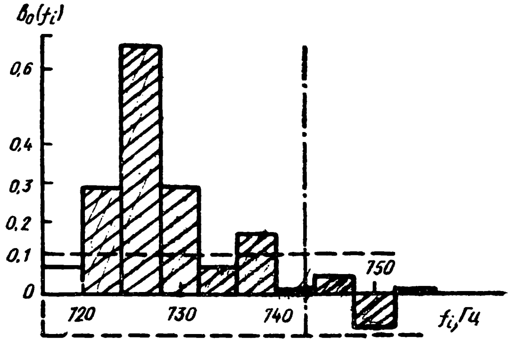

Fig. 9.3 Mean spectrum of the signal reflected from Venus, obtained on April 18, 1961: f_i are the frequencies of the spectral components of the signal at the receiver output in Hz; $b_o(f_i)$ is the ratio of the mean power of the signal in a given frequency channel of the analyser to the spectral power density of the noise; the transmission bandwidth of the filters in the analyser channels was 4 Hz, and the repetition period of the pulses and pauses in the signal was 0.256 s

In 1961, successful observations of Venus were also conducted by several radar installations in the USA and England at wavelengths from 12.5 to 74 cm, and gave results close to our own.

Radar Observations of Venus in 1962 In 1962, the energy potential of the radar installation was increased sixfold by employing a quantum paramagnetic amplifier (QPA) at the receiver input, and also by increasing the power of the transmitter. The QPA was developed by A. V. Frantsesson under the supervision of M. E. Zhabotinskii. At that time, the energy potential of the DSCC radar installation was higher than those of foreign installations.

It became possible to carry out extended and more precise measurements of the distance between the Earth and Venus, and to determine important physical characteristics of the planet. A periodic linear frequency modulator was used to enhance the accuracy of the distance measurements. Academician Kotel'nikov proposed a method providing strict linear variation of the instantaneous frequency-modulation oscillations, which B. I. Kuznetsov and Lishin used as a basis for the construction of a special generator. As was shown by Kotel'nikov in 1962, the periodic linear frequency modulation made it possible to construct a two-dimensional radar map of the surface of the planet.

The root-mean-square uncertainty for the unified measurements of the distance to Venus in 1962 did not exceed 15 km, while it had been 2700–4000 km in 1961. The 1962 observations indicated the value of the astronomical unit to be 149,597,900 ± 250 km. It was also found that Venus was located 270 km ahead of its ephemerides position in its orbit relative to the Earth, and that the radius of Venus was 80 km smaller than the value of 6100 km that had been accepted earlier. Similar refinements to the ephemerides were found by American researchers.

Using linear frequency modulation, the energy distribution of the reflected waves was first obtained using the linear frequency modulation in 1962, from the high-resolution delay information, which made it possible to determine the nature of

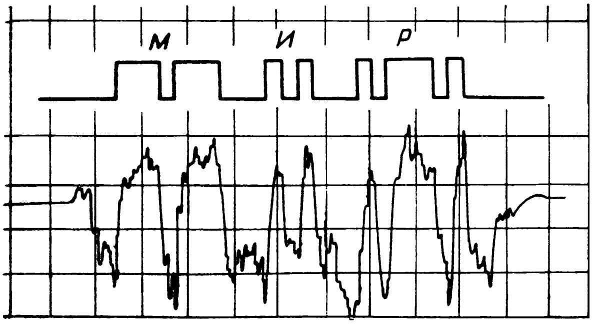

Fig. 9.4 The Russian word "MIR" ("Peace," or "World") transmitted by Morse code via reflection off Venus on November 19, 1962. The duration of a dot is 10 s and of a dash is 30 s

the reflective surface of Venus. A reflective patch was detected at the centre of the visible disc of the planet, where the waves are incident perpendicular to the surface. This phenomenon was expressed even more clearly for Venus than for the Moon.

The ratio of the effective area for the back scattering off Venus to the area of the planet's perpendicular cross section varied from 0.12 to 0.18, which is, on average, about twice that for radar observations of the Moon at the same wavelength. These data suggest that the relative dielectric permeability of the surface layer of Venus is four to six, which corresponds to the value for terrestrial rocky material in a dry state.

These investigations established that the reflection of decimetre radio waves is due to the presence of a hard surface on Venus. The atmosphere of Venus proved to be transparent to these waves, enabling the researchers involved to obtain the first evidence about the surface of the planet.

One of the very important results of the radar observations in 1962 was determining the period and direction of rotation of Venus, which were derived from day-to-day variations in the width of the spectrum of the reflected signal, which is proportional to the angular speed of the apparent rotation of the planet relative to the radar antenna.[2] It was found that the spectral width of the reflected signal is minimum at the inferior conjunction, which demonstrates that Venus' rotation is retrograde (opposite to the planet's motion around the Sun). The variation in the width of the spectrum corresponds to a rotational period of about 300 Earth days. Based on observations made in the USA in 1962, the rotational period of Venus was estimated to be about 250 days (also for retrograde rotation).

The fairly high signal-to-noise ratio that was obtained when Venus was located relatively near the Earth made it possible to use Venus as a passive reflector for telegraphic transmissions. A message transmitted on November 19, 1962 using this telegraphic method, which traversed a path of 82 million kilometres, is shown in Fig. 9.4.

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[2] This apparent rotation was comprised of two parts: the rotation of the planet itself relative to the fixed stars and the translational motion relative to the radar antenna. The first component (which we wish to determine) is constant, while the second (variable) component can be calculated ahead of time.

Observations of Mercury, Mars and Jupiter The enhanced energy potential of the radar installation also enabled the first detection, in 1962, of a reflected signal from Mercury, which is at a greater distance and is smaller in size than Venus.

Observations of Mercury were carried out on June 10–15, 1962, when the planet's distance was 83–88 million kilometres—about twice the distance during the 1961 observations of Venus. An energy of about one Watt was incident onto the entire visible surface of Mercury. The mean effective area for the back scattering turned out to be 0.06 times the cross-sectional area of the planet. This result was subsequently confirmed by American researchers, who carried out radar measurements of Mercury using the Goldstone Deep Space Network antenna in 1963. The independent measurement of the astronomical unit obtained from the Mercury radar experiments confirmed the value that had been obtained from the observations of Venus.

The first experiments attempting to detected reflected radar signals from Mars and Jupiter took place in 1963.

Mars and the Earth were positioned at opposite ends of their orbits in 1963, and the distance to Mars exceed 100 million kilometres, providing unfavourable conditions for radar measurements. With the available sensitivity, it was expected that detection of the reflected signal would be possible only if there were present on the Martian surface fairly flat, horizontal regions that would not cause appreciable broadening of the reflected signal, despite the rapid rotation of the planet. Observations of Mars were carried out on four nights on February 6–10, 1963.

Our observations carried out later using a radar system with a higher energy potential demonstrated that the frequency filters used in February 1963 for the analysis of the reflected signal were not optimal, casting doubt on the conclusions that had been drawn about the reflective properties of the surface.

In our 39-cm observations of Jupiter in 1963, the estimated energy of the received reflected signal for an integration time of 22 hours was 1–1.5 times the root-mean-square uncertainty due to noise fluctuations. The low level of the reflected signal suggested that decimetre radio waves are nearly completely absorbed in the deep atmosphere of Jupiter, and are not scattered into the surrounding space.

Simultaneous with the Jupiter radar experiment in October 1963, Trunova and Rzhiga carried out measurements of the intrinsic radio emission of Jupiter, which had not yet been observed at 30–50 cm at that time. The equivalent temperature of Jupiter at 39 cm reduced to the visible disk of the planet was 12,000 ± 2,000 K. This result confirmed that the sharp growth in Jupiter's emission detected at shorter wavelengths continued at decimetre wavelengths.

The first radar studies of the planets were very well known, not only in the Soviet Union, but also abroad. In 1964, V. A. Kotel'nikov, V. M. Dubrovin, M. D. Kislik, V. P. Minashin, V. A. Morozov, G. M. Petrov, O. N. Rzhiga and A. M. Shakhovskoi were named laureates of the Lenin Prize for their radar investigations of Venus, Mars and Jupiter.

Computer Reduction of the Observational Results On June 12, 1964, with this goal, several sets of data for reflected signals from Venus were recorded on magnetic tape in digital form. These data were processed using a BESM-2M computer, which calculated the coefficients of the Fourier series and estimated the spectral density of the signal power averaged over the observations. The computer program was developed by Yu. N. Aleksandrov and V. A. Zyatitskii. The apparatus used to digitally code and record the signals onto magnetic tape, and then to transfer the data to the computer, was designed by A. I. Smurygov and N. M. Bondarenko. Features due to regions of the surface of Venus with higher reflectivity than the surrounding areas were detected in the spectrum of the reflected signal.

In essence, this was one of the first applications of the method of aperture synthesis in radar, making it possible to obtain high special resolution. The detection of high reflectivity on the surface of Venus opened the possibility of radar mapping of the surface, and also refining the rotational parameters of the planet based on the angular distribution of surface features, as can be done for planets whose surfaces are accessible to optical observations.

Joint Observations of Venus with Jodrell Bank Observatory In Summer 1963, at the invitation of the USSR Academy of Sciences, Bernard Lovell, the Director of the Jodrell Bank Observatory of Manchester University, visited the Deep-Space Communications Centre. Lovell was very impressed by the technical outfitting of the DSCC. Soon after this visit, Lovell approached Academician Kotel'nikov with a proposal to carry out joint radar observations of Venus.

The use of the Jodrell Bank 76-m-diameter MkI radio telescope as the receiver tripled the sensitivity of the radar measurements. In addition, continuous signal reception over an extended period of time became possible, since the transmitter was below the horizon, and so did not give rise to any interference.

The DSCC transmitter operated for several hours a day at a constant frequency. A reflected signal from the Moon was detected at Jodrell Bank on December 21, 1965. The first successful detection of a radar signal from Venus was on January 9, 1966. The signal frequency turned out to be below the nominal value of 30 Hz, and the signal was detected only after a frequency search was carried out at Jodrell Bank. Joint observations of Venus were carried out until March 1966.

The processing of the resulting recordings at IRE was carried out on a BESM-2M computer using programs developed by Aleksandrov and Zhurkina.

The higher signal-to-noise ratio and lowering of the fluctuation noise using long integration times enabled more reliable determination of the positions of spectral features. Using the measured radial velocities, V. K. Golovkov was able to fix the centres of regions with enhanced reflectivity on the surface of Venus.

Very good agreement was found for spectra obtained at the inferior conjunctions of 1964 and 1966, indicating that Venus turned roughly the same face towards the Earth during these different lower conjunctions. After identifying spectral features in these observations, Golovkov derived the refined estimate of the rotational period of Venus, 243.9 ± 0.4 days.

Thus, it was established that Venus' rotational period was close to the value 243.16 days for which the planet would turn exactly the same hemisphere toward the Earth at all inferior conjunctions (a situation called synodic resonance). In the interval between conjunctions, which repeat, on average, every 583.92 days, an observer on Earth would see four full rotations of Venus if its atmosphere were optically transparent. The mean duration of a solar day on Venus is 116.8 Earth days. Attempts to determine the period and orientation of Venus' axis from optical observations were made in the past, but only the radar technique enabled the acquisition of reliable data on the rotation of Venus, as well as the direction of the planet's rotational angular momentum.

Since the rotation of Venus was very important from the point of view of the evolution of the solar system, work on refining the rotational period was continued. Reduction of observations carried out in the Soviet Union, including measurements made in 1977, yielded the value 243.04 ± 0.03 days for the rotational period of Venus.

Observations of Venus and Mars During the Flight of Unmanned Spacecraft In view of the large uncertainties in the ephemerides calculated using classical theories, beginning in 1969, the DSCC radar installation was used to conduct regular measurements of the distances and radial velocities of planets, with the aim of predicting their positions during the final approaches of unmanned interplanetary spacecraft, as well as refining the theory of planetary motions. The improved program for the computation of the ephemerides for the time delay of the reflected signals and Doppler corrections to the transmitter carrier frequency were developed by Yu. K. Naumkin under the supervision of E. L. Akim and V. T. Geraskin.

By the beginning of the 1969 radar observations, Aleksandrov, with the help of R. A. Andreev, had developed equipment for digitally recording the reflected signals and a program for their reduction on the M-220 computer of the DSCC. A fast-Fourier transform algorithm was used to reduce the processing time. This program was able to process a 5-minute recording in 30 seconds. In 1965, Petrov developed a specialised, multi-channel digital device designed to observe the spectrum of the reflected signal during reception and obtain estimates of the spectral parameters.

The digital-recording complex was applied to the analysis of radio signals emitted by the *Venera-7* spacecraft during its landing on the surface of Venus in December 1970. It was established that the spacecraft had successfully landed on Venus, and data transmitted from the surface were received at the Earth, although the power of the received signal after landing fell by several orders of magnitude.

By the time of Mars observations take in 1971, the energetic potential of the radar equipment had been increased by an order of magnitude since the first attempts to detect a signal reflected from Mars in 1963, due to an increase in the transmitter power, improvement of the antenna, which was now able to receive reflected waves with the opposite circular polarisation, and replacing the radiometer receiver with a direct comparison of the signal spectrum with a noise spectrum. The power of the reflected signal was enhanced by another factor of ten due to the fact that Mars was nearly twice as close to the Earth in the grand opposition of 1971.

In spite of these measures, the reflected signal was so weak that its spectral density at maximum was only 0.5–2% of the spectral density of the receiver noise. In order to obtain a reliable detection of the signal, it was necessary to integrate the signal energy over the entire interval when the planet was visible. In connection with this, a method was developed to take into account inhomogeneities in the frequency characteristics of the receiver tract, which could easily be mistaken for the spectrum of the reflected signal in the case of long integrations.

Observations of Mars were carried out from June 14 to September 19, 1971 in groups of three observing days each. On the first day, the continuum signal at a constant frequency was studied and the reflected signal detected. On the second day, a signal with a linear frequency modulation with deviations of 4 kHz was used, enabling measurement of the distance with an accuracy of 20 km. On the third day, the frequency deviations were increased to 32 kHz, corrections determined from the data obtained on the previous day were applied to the ephemeris values for the time delays and new measurements aimed at determining the distance to within 5 km were carried out.

J. Clemens developed a theory for the motion of Mars based on the results of these measurements. It was found that Mars was located closer to the ephemeris positions before than after the opposition. In the observed interval, the deviation of the distance from the ephemeris values varied linearly with a rate of about 2 km/day.

In the middle of 1971, at the request N. A. Savich, who was supervising studies of the Martian ionosphere, help was given with the recording and processing of radio signals at two coherent frequencies transmitted through the ionosphere. Dubrovin and Aleksandrov provided an apparatus for magnetic recording and digital processing of the signals, making it possible to carry out such observations when the *Mars-2* spacecraft was setting behind the planet. In 1974, during the flights of the *Mars-4* and *Mars-6* spacecraft, this equipment was used in experiments leading to the discovery of a night-time ionosphere on Mars, and yielded measurements of the pressure and temperature on the planet's surface. It was also used to determine the characteristics of the Venusian ionosphere during the *Venera-9* and *Venera-10* flights in 1975–1976. Petrov and A. L. Zaitsev developed a digital Doppler synthesiser with quadratic frequency variation for this same experiment.

Observations of Planets Using the New Radar Installation of the DSCC Possibilities for planetary studies using radar measurements expanded considerably in connection with the construction of a new fully steerable 70-m-diameter antenna under the supervision of V. A. Grishmanovskii. The increase in the effective area of the antenna, lowering of the noise temperature of the antenna-feeder tract and receiver and increase in the power of the transmitter, which were supervised by I. E. Mach, made it possible to increase the energy potential of the radar system at 39 cm by a factor of 50. An energy of about 250 W now fell onto the visible surface of Venus at lower conjunction. The maximum distance feasible for radar measurements was increased by more than two and a half times. This meant that it was now possible to observe Venus virtually during its entire orbit.

Petrov, Zaitsev and A. F. Khasyanov radically modernised the radar apparatus, including the digital synthesiser for the linear frequency modulation and the programming-time device—the radar itself.

The improved capabilities of the radar installation enabled a series of observations of Venus, Mercury and Mars from February through April 1980, during the

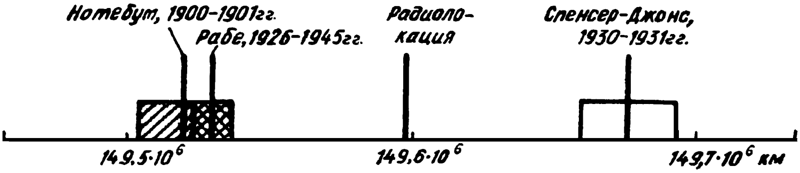

Fig. 9.5 Results of determining the astronomical unit from the parallax shift of the asteroid Eros and from radar observations. The errors in the radar values cannot be seen in the figure because they are smaller than the thickness of the line. The *horizontal axis* shows distances in km. The four measurements, *from left to right*, are those by Nomebum (1900–1901), Rabe (1926–1945), radar, and Swenson and Jones (1930–1931)

Venus observations, the uncertainty in the distance was 300–500 m at an overall distance of up to 140 million kilometres; this was made possible by taking into account the instrumental function of the radar and the beam for the back scattered signal from the planetary surface when analysing the spectrum of the reflected signal, a technique that was developed by Khasyanov. The achieved accuracy enabled continuation of studies of the surface profile of Venus that had been begun earlier, and led to the discovery of two extensive mountainous regions with altitudes of 2.5–4 km.

The radar observations of Mars and Mercury in 1980 were markedly improved from those made earlier in 1971 and 1962. With the new antenna and transmitter, it became possible to measure the distances to the surfaces of these planets with a root-mean-square uncertainty of 0.6–1.5 km in 5 to 15 minutes at an overall distance of 100–135 million kilometres. These measurements enabled refinement of the surface profile of Mars, in particular, in the region of the extinct volcano Olympus Mons—the largest known mountain in the solar system, with an altitude of 27 km.

Joint Refinement of Astronomical Constants. Construction of a Unified Relativistic Theory for the Motions of the Inner Planets One of the main results of the first radar observations of Venus that was extremely valuable for manned space flight was the refinement of the astronomical unit—the distance from the Sun to the Earth. Observations of the parallactic shift of the small asteroid Eros, which had previously been the main means of determining the astronomical unit, yielded various estimates that differed by several hundreds of thousands of kilometres, which was large enough to threaten unavoidable misses of space stations (Fig. 9.5). The value of the astronomical unit obtained from radar observations in 1961 and 1962 in the Soviet Union, England and the USA were in good mutual agreement. The XII General Assembly of the International Astronomical Union in 1964 recommended the radar value of the astronomical unit for use in astronomical almanacs.

At the same time, the radar observations showed that, even after the associated corrections to the astronomical unit, there remained appreciable systematic discrepancies between the actual and ephemerides positions of Venus relative to the Earth, reaching several hundreds of kilometres. Similar discrepancies were observed in the position of Mars.

Studies aimed simultaneously at refining several astronomical constants using radar observations were carried out in the Soviet Union and the USA. Petrov used radar data for Venus obtained in the Soviet Union in 1962 and 1964 to derive a more accurate value for the radius of the surface of Venus, 6046 ± 15 km.

Based on the accumulated observational material, work was carried out in the Soviet Union to refine the orbits of the Earth, Venus, Mars and Mercury, and to develop a theory for the motions of these planets that would provide predictions of their relative distances that were much more accurate than those given by the analytical theory of S. Newcomb created in the late 1800s.

The observations of Venus, Mars and Mercury in 1980 appreciably augmented the results of earlier radar observations of these planets, especially for Mercury and Mars, for which the last available data were published in 1965 and 1971. This provided a basis for constructing a unified theory of the motions of the inner planets of the solar system, in other words, for finding a simultaneous solution for the orbital elements for the motions of Mercury, Venus, the Earth and Mars in a time interval of about 20 years.

The main defining characteristic of the new computation method was the use of relativistic differential equations to describe the heliocentric motions of the planets.

The root-mean-square deviations of the measured distances beginning in 1967–1970 were 0.9 km for Venus, 2 km for Mercury and 2.5 km for Mars. Taking into account the surface profiles of the planets decreased the deviations for Venus to 0.5 km and for Mars to 1 km. At the same time, the root-mean-square deviations of the results of optical measurements in this time interval are virtually constant and about 100 times larger when translated into linear distances.

The achieved agreement between the experimental and computed data provides experimental verification using direct astronomical methods of the general theory of relativity, which encompasses all possible relativistic effects in the motions of the planets and the propagation of electromagnetic waves. Radar observations of Venus carried out in the Soviet Union from December 1981 until February 1982 confirmed the high accuracy of the theory. The discrepancies between the predicted and measured distances did not exceed 1.2 km.

In 1982, Yu. N. Aleksandrov, V. K. Abalakin, V. A. Brumberg, M. D. Kislik, Yu. F. Kolyuka, G. A. Krasinskii, G. M. Petrov, Gr. M. Petrov, V. A. Stepan'yants, K. G. Sukhanov, V. F. Tikhonov and A. M. Shakhovskoi were awarded a State Prize of the USSR for establishing a unified relativistic theory of the motions of the inner planets of the solar system.

Investigations of the Integrated Characteristics of the Scattering of Radio Waves from Planetary Surfaces Measurement of the polarisation of the reflected radiation and the distribution of its intensity over the disk of the planet demonstrated that, in contrast to optical radiation, radio waves reflected from the Moon and planets display primarily a mirror character.

At the same time, part of the radiation is reflected diffusely. In 1968, Aleksandrov and Rzhiga analysed this diffuse component, and showed using Venus as an example that the relative dielectric permeability of the planetary surface calculated using the mirror-reflection coefficient was 20% lower than was obtained by assuming that all the 39-cm radiation was mirror-reflected. It was shown that the relative dielectric permeabilities of various regions of the Venusian surface derived from the 39-cm observations were in the range 2.7–6.6, and the corresponding densities in the range 1.3–3 g/cm^3. These data were subsequently confirmed by surface-density measurements made from interplanetary spacecraft.

A complex analysis of the physical properties of the surface layer of Mars based on radar, radio astronomy and infrared observations was carried out by Rzhiga in 1967.

In 1968, Aleksandrov, B. I. Kuznetsov and Rzhiga showed that the characteristics of the mirror-reflected radiation from Venus were consistent with a model with a wavy, uneven surface, with an exponential spatial altitude auto-correlation function; the diffuse component corresponded to Lambert scattering. The most probable inclination of the Venusian surface implied by the 39-cm observations was, on average, 2.6°. The surface of Venus is smoother than the surface of the Moon, but rougher than the surface of Mars.

Studies of the Absorption and Refraction of Radio Waves in the Atmosphere of Venus Methods for analysing the reflection characteristics of planets were applied by Aleksandrov and Rzhiga in 1968 to investigate limb-darkening due to the absorption of the reflected radio radiation in the atmosphere of Venus. It was shown that this limb-darkening was consistent with the atmospheric absorption that was implied by a decrease in the effective area of Venus detected in radar observations at centimetre wavelengths carried out by the Lincoln Laboratory of the Massachusetts Institute of Technology. This fact was very important for elucidating the origin of the observed decrease in the reflectivity of the planet.

Also in 1968, Rzhiga showed that the back-scattering measurements were in better agreement with the hypothesis of non-resonance absorption of the radio waves in gaseous components in the atmosphere of Venus. In 1970, he constructed a model adiabatic carbon-dioxide atmosphere, which predicted that the atmosphere of Venus should give rise to an additional delay of about 2 milliseconds in radar signals.

The measurements of the *Venera-4* spacecraft ceased at an altitude above the planetary surface where the pressure was about two million Pascals (MPa). Assuming that the absorption indicated by the radar data was due entirely to carbon-dioxide gas and water vapour, and extrapolating the atmosphere's parameters along the relation for an adiabatic gas, Rzhiga found that the mean surface pressure on Venus was 11.1 ± 3.0 MPa, while the mean surface temperature was 740 ± 35 K. These results were taken into account in the construction of the *Venera-7* spacecraft. The actual pressure and temperature measured by the *Venera-7* and *Venera-8* spacecraft were 9.1–9.6 MPa and 740–750 K, confirming the earlier estimates.

Developing the original ideas of L. I. Mandel'shtam and N. D. Papaleksi, and continuing from the first lunar radar experiments of the Gorkii Radio Physics Research Institute, the Institute of Radio Technology and Electronics of the USSR Academy of Sciences, in collaboration with a number of other institutions that participated in the development and outfitting of the radar system and in observations with the system, in particular with colleagues at the DSCC in the Crimea, established a new direction in astronomy in the Soviet Union—radar planetary astronomy.

Beginning in April 1961, with the first detection of reflected signals from Venus, a number of fundamental results were obtained. The value of the astronomical unit was substantially refined. The rotational period and direction of rotation of Venus were determined. The distribution of the reflectivity across the disk of Venus was obtained, as well as the degree of polarisation of the reflected signal, making it possible to establish the nature of the Venusian surface. Reflected signals from Mercury were detected for the first time. A unified relativistic theory for the motions of the inner planets that enabled computation of their mutual positions with an accuracy 100 times better than provided by classical theories was obtained.

9.2 Studies of the Earth and Planets Using Radio Physical Methods

Studies of Thermal Radio Emission of the Earth and planets were begun at IRE in 1960. The main initiator and supervisor of this work was Professor A. E. Basharinov (1920–1978).

Interest in studies of the thermal emission of the atmosphere using radio astronomy methods at IRE was associated with the problem of establishing the relationship between the noise emitted by the atmosphere at millimetre wavelengths and meteorological parameters. Objects of study included not only the cloudless atmosphere, but also clouds, precipitation, and turbulent inhomogeneities. Further objects added to this list include ice, the sea surface, ground vegetation, the soil, etc. These investigations represented a development of studies on diagnostics for low-temperature plasma formations, begun earlier at the suggestion of Basharinov and carried out by V. M. Polyakov and his coworkers.

Radiometer studies of natural objects required the development of high-sensitivity microwave radiometers operating at a wide range of millimetre and centimetre wavelengths. At the end of the 1950s, the Specialised Construction Bureau (SCB) was organised at IRE. One direction pursued by this organisation was the development and manufacture of microwave radiometers. A large role was played in this work by V. S. Ablyazov. In the 1960s and 1970s, radiometers for discrete spectral intervals from 3 cm to submillimetre wavelengths (0.8, 1.35, 2.25 cm and others) were developed at the SCB, as well as universal low-frequency modulational-radiometer blocks and other such equipment, which were manufactured in modest quantities. For a long time, the IRE Specialised Construction Bureau was one of only a few organisations specialising in the development of radio astronomy equipment. Most radio telescopes in the Soviet Union have receivers developed at the SCB. Microwave radiometers intended for radio astronomy studies of the atmosphere and surface of the Earth to be carried out on board airborne laboratories and spacecraft have recently been developed under the supervision of Ablyazov. Flying IRE laboratories carried by IL-18, IL-14, and AN-2 aircraft are outfitted with these radiometers. A polarisation-sensitive 2.2-cm microwave radiometer was installed on board the *Interkosmos-20* and *Interkosmos-21* spacecraft, and operated reliably for a long time (Ablyazov, V. P. Bydantsev).

Studies of the thermal radio emission of an atmosphere containing clouds, precipitation, and turbulent inhomogeneities require measurements of radio brightness temperatures and the total absorption in the atmosphere simultaneously at several wavelengths in the millimetre and centimetre ranges. Such experiments were first conducted by IRE staff using the 22-m telescope of the Lebedev Physical Institute, with active help and support from A. E. Salomonovich and R. L. Sorochenko. Experimental studies from the surface of the Earth revealed absorption features in the microwave spectra and the dependence of the brightness temperature of the cloudy atmosphere on temperature, the water content of the clouds, the water droplet size, the intensity of rain, and so forth. In addition, radio brightness contrasts for different types of clouds and rain were measured, and data on the spatial and temporal dependences of the intensity of fluctuations of the radio emission of the atmosphere were obtained. These results were used to construct theoretical models for the radio emission of a cloudy atmosphere and to develop methods for determining meteorological parameters from measurements of the spectral and polarisation characteristics of atmospheric emission (Basharinov, B. G. Kutuza).

The possibility of remote sounding of the atmosphere from spacecraft called forth new interest in studies of the radio emission of the atmosphere in the middle of the 1960s. In this connection, an important role was played by the work of Basharinov, S. T. Egorov, M. A. Kolosov, and Kutuza, which laid out the principles of microwave radiometer methods for deriving atmospheric parameters from flying equipment.

In the middle of the 1960s, investigations of the thermal radio emission of the sea surface and continents were carried out at IRE, leading to the development of microwave radiometer methods for deriving the parameters of the sea surface (Basharinov, A. M. Shutko).

Ground-based experimental investigations of the radio emission of areas covered by ice at centimetre and decimetre wavelengths displayed the dependence of the brightness temperature on the contrast, thickness and temperature of sea ice. The influence of floating ice on the radiative efficiency of the sea surface was estimated, and means of determining the parameters of sea and shelf icebergs based on studies of their thermal radio emission were studied (Basharinov, A. A. Kurskaya).

The first attempt to realise microwave radiometer methods on board a spacecraft was made with the goal of investigating the atmosphere and surface of Venus, about which very little was known at the beginning of the 1960s. Interest then turned to studies of the cosmic radio emission of the Earth as a planet. In 1968, the *Kosmos-243* spacecraft was launched, with a four-channel radio telescope directed toward the Earth on board. Measurements were carried out at wavelengths of 8.5, 3.4, 1.35 and 0.8 cm, with the spatial resolution provided by the antenna corresponding to 20 km on the surface of the Earth. This experiment was prepared and outfitted by groups of the IRE, the Institute of Atmospheric Physics of the USSR Academy of Sciences and industrial organisations, under the supervision of Basharinov, A. S.

Gurvich and Egorov. The space experiment on board the *Kosmos-243* spacecraft was four years ahead of foreign investigations in this area, and showed the effectiveness of microwave radiometer methods for remote sounding of the atmosphere, dry land and the world ocean. As a result of this experiment, the water content of clouds in the form of vapour and liquid droplets was determined, the total humidity of the atmosphere estimated and zones of precipitation traced on a global scale. Measurements above regions of sea yielded data on the latitude distribution of the temperature of the surface of the world ocean, and enabled storms and floating ice to be distinguished, independent of cloud cover. Observations of the continental landmasses made it possible to distinguish zones of humidity on the Earth's surface, and to detect the anomalously low brightness temperatures of the shelf and continental ice masses of the Antarctic.

In recent years, microwave radiometer methods for studying the atmosphere and world ocean have been applied in experiments on the oceanographic spacecraft *Kosmos-1076* and *Kosmos-1151*. A distinguishing feature of these experiments was the joint use of spectral and polarisation measurements of the Earth's radio emission and the enhanced sensitivity of the receivers used, which appreciably expanded the informational potential of the equipment. These microwave radiometers were developed under the supervision of Egorov. The scientific programme of these measurements was compiled at IRE, jointly with the Sea Hydrophysical Institute of the Ukrainian SSR Academy of Sciences and the Dniepropetrovskii State University (B. A. Nelepo, N. A. Armand, B. E. Khmyrov, Yu. V. Terekhin, B. G. Kutuza, E. I. Bushuev).

Studies of the radio emission of the planets were begun at IRE at the beginning of the 1960s, under the supervision of Basharinov and Kolosov. G. M. Strelkov proposed a model for the atmosphere and surface of Venus, and on its basis carried out computations of the spectrum of the emergent radiation as a function of temperature, pressure and other physical conditions at the planetary surface. Basharinov and Kutuza attempted to explain a feature in the radio spectrum of Venus as due to the presence in the planet's cloudy layer of supercooled water droplets, whose microwave absorption spectrum had been studied in a preliminary way under the conditions of the Earth's atmosphere.

Possibilities for studying the radio emission of the planets are expanding substantially with the installation of radio telescopes on spacecraft. Experiments designed for studies of Mars at 3.4 cm were installed on board the *Mars-3* and *Mars-5* Soviet interplanetary space stations, in which IRE took part, together with the Space Research Institute, Lebedev Physical Institute and the Radio Physical Institute in Gorkii. During a close flyby of the planet, the spatial resolution achieved by the radio telescope was 100–400 km. Data on the variability of the dielectric permeability of the Martian surface layer and variations in the temperature distribution over the surface were obtained (see Essays 1 and 2 in this collection). IRE participants in these studies included Basharinov, Kolosov and Shutko.

The experiments conducted on board airborne laboratories showed the potential of applying microwave radiometers to a number of national economic tasks, such as determining the ice conditions in the Arctic during ship passages, detecting active regions in forest fires under complex meteorological conditions, estimating expected harvests, determinating the water content in the atmosphere and soil, etc. The most complete of these is the development of a method for routinely determining the humidity of ground soils (Basharinov, Armand, Shutko). A service for the routine microwave radiometer monitoring of soil humidity on board AN-2 aircraft was established in Moldavia, and maps of the hydrological conditions in territories adjacent to the Karakum Canal were made in Turkmenia. Experimental verification of this approach to routine determination of ground-soil humidity in fields in various regions of the Soviet Union have demonstrated the high efficiency of this method.

Investigations Carried out Using Radio Waves Emitted by Spacecraft[3] The space age brought intense studies of the Moon and other planets of the solar system using various radio-physical methods. The idea behind such methods is to measure the characteristics of radio waves emitted by a transmitter on a spacecraft after their passage through the troposphere and ionosphere of the Moon or a planet (akin to radiography), or after their reflection from the surfaces of these bodies. Such studies began at IRE in 1962, and were carried out until 1982 under the supervision of Professor M. A. Kolosov (1912–1982). The methods most applied in practice were bistatic radar, proposed by O. I. Yakovlev (1965), the adaptation of the radiographic method initially developed by Yakovlev (1964) to make it suitable for studies of the surface of Venus by A. G. Pavel'ev (1974) and dispersion interferometry, proposed by N. A. Savich (1963).

The first experimental studies using the *Luna-11* and *Luna-12* spacecraft were conducted in 1966 using the bistatic (or bipositional) radar technique, based on analysing signals transmitted from a spacecraft after they have been scattered by a surface, with the observations carried out on the Earth. Dependences of the reflection coefficients for the scattering of metre-wavelength radio waves on the angle of incidence were obtained, making it possible to determine the mean dielectric permeability ($\varepsilon = 2.8$) and density ($\rho = 1.4$ g/cm^3) of the lunar rocks. These studies were continued at metre and decimetre wavelengths during the period when the *Luna-14* and *Luna-19* spacecraft were operational. The relationship between the shape of the energy spectra of the reflected signals and characteristic features on the lunar surface was also established.

Further, this method was successfully applied to study the surface of Venus as well. Experiments were conducted in 1975 using the *Venera-9* and *Venera-10* spacecraft. Processing of the data obtained provided new information about a number of important characteristics, such as the dielectric permeability of the Venusian soil, the density of surface rocks, the slopes of small-scale inhomogeneities on the surface, and the deviations in altitude from a spherical surface associated with large-scale components of the surface profile. Radar maps of the surface of the planet were also produced.

The first radiographic experiment involving the transmission of radio signals through the atmosphere of Venus was carried out in 1967, during the descent of

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[3] A. I. Efimov took part in the preparation of material for this section.

the *Venera-4* interplanetary station to the planetary surface. This provided information about the conditions for the passage of the radio waves through the Venusian troposphere, as well as data on the turbulency of this medium. Similar experiments conducted using the descending *Venera-5* and *Venera-8* spacecraft made it possible to more accurately determine the characteristics of inhomogeneities in the Venusian troposphere. A large volume of data on the atmosphere of Venus was obtained during the operation of the *Venera-9* and *Venera-10* spacecraft in 1975–1976. In particular, altitude profiles of the temperature, pressure and particle number density were derived, and the dependences of the structural characteristics of the index of refraction on altitude in the atmosphere, the Venusian latitude and the zenith angle of the Sun were determined.

The radiographic method was also successfully applied to studies of the rarefied troposphere of Mars using the *Mars-2*, *Mars-4* and *Mars-6* spacecraft. The altitude dependence of the pressure and temperature was measured at several locations on the planet, as well as variations in these parameters with variations in the solar zenith angle.

The radiographic and dispersion-interferometry methods were used to study the characteristics of plasma envelopes surrounding the Moon and planets. The latter technique could also be considered a multi-frequency radiographic method, with all the signals analysed at the various frequencies being coherent. This approach proved to be especially effective means of studying rarefied plasma envelopes, such as night-time planetary ionospheres and the plasma surrounding the Moon. The first radiographic experiment carried out near the Moon involved decimetre and centimetre signals transmitted during the flight of the *Luna-19* spacecraft in 1972. A thin layer of plasma several tens of kilometres thick with a maximum particle density of 10^3 cm^{-3} and lying at an altitude of 10 km was discovered above the side of the Moon illuminated by the Sun. Such experiments were continued in 1974 using the *Luna-22* spacecraft. The altitude profiles of the electron density for various strengths of illumination of the lunar surface were derived.

The Martian ionosphere was probed using coherent decimetre- and centimetre-wavelength radio signals transmitted by the *Mars-2*, *Mars-4* and *Mars-6* spacecraft during 1971–1974. The most important result to come from these experiments was the detection of the night-time ionosphere of Mars. It was established that this ionosphere is strongest at a well defined altitude of 110–130 km above the planetary surface, where it has an electron density of about 5×10^3 cm^{-3}. The day-time ionosphere of Mars has an electron density of 2×10^5 cm^{-3} and is located at an altitude of about 145 km.

The dispersion-interferometer method was used to study the ionosphere of Venus during the flights of the *Venera-9* and *Venera-10* spacecraft. The altitude profile of the electron density was found above various regions of the planet. The night-time ionosphere of Venus was found to have regions of maximum electron density at two well defined altitudes.

Researchers at IRE and other organisations, including M. A. Kolosov (the project leader), N. A. Armand, N. A. Savich, O. I. Yakovlev, R. V. Batik'ko, Yu. I. Bekhterev, M. B. Vasil'ev, A. I. Efimov, L. V. Onishchenko, A. L. Pilat, B. P. Trusov and D. Ya. Shtern, were awarded a USSR State Prize in 1974 for their series of investigations of the propagation of radio waves in deep space using the *Luna*, *Venera* and *Mars* spacecraft.

Experience with radar observations of planets from the Earth was based mainly on radio mapping of Venus carried out in 1983–1984 using the *Venera-15* and *Venera-16* automated spacecraft (with Rzhiga as the scientific supervisor of this work). The radar system, which was developed at the Moscow Energy Institute under the leadership of Academician A. F. Bogomolov, enables imaging of the planet's surface with a resolution of 1–2 km and measurements of altitude profiles with an uncertainty of only 30 m. The synthesis of the radar images and surface profiles and reconstruction of photographic maps of Venus using digital methods is performed at IRE (Yu. N. Aleksandrov, A. I. Sidorenko). In the eight months following November 1983, the entire Northern hemisphere of Venus above 30° latitude has been imaged. Unique images of the surface showing mountain ridges, craters, plateaus, folds and fissures in the Venusian crust have been produced. Signs of tectonic activity on Venus have also been found. These data have enabled the creation of maps that can be used to study processes occurring on the surface of Venus, as well as the history of this planet.