Development of the First Soviet Three-Coordinate L-Band Pulsed Radar in Kharkov Before WWII

Alexei A. Kostenko, Alexander I. Nosich, and Irina A. Tishchenko

The A. Usikov Institute of Radio-Physics and Electronics
of the National Academy of Sciences
ul. Proskury 12, Kharkov 61085, Ukraine
Fax: +380-572-441105; E-mail: kostenko@ire.kharkov.ua

Abstract

The subject of this paper is the complicated, sometimes dramatic, and never-published events around the development of the L-band magnetrons and pulsed radar in Kharkov, Ukraine (then the USSR), in the 1920-30s. Magnetron studies were started in the Kharkov State University by Prof. Abram Slutskin. By the end of the decade, they reached the world's highest level in terms of achieved output power and frequency. This work was continued and greatly extended in next decade, when the Ukrainian Institute of Physics and Technology was established, and Slutskin obtained there his second job, as a head of the Laboratory of Electromagnetic Oscillations. Based on the successful development of sources, in 1935, he started work on developing a three-coordinate radar. At that time, it was far from clear that L band and the pulsed method would be more promising. Two-antenna and single-antenna radars were designed, fabricated, and tested, with all-metal and wire-grid three-meter parabolic reflectors. The war disrupted the plans of the radar team, which had to move the laboratory to central Asia. The radar that was developed was not put into serial production; however, many associated ideas and innovations were well ahead of the contemporary level of technology. The paper also throws some light on how hard it was for scientists and engineers to work in the Orwellian environment of the pre-war USSR.

Keywords: History, magnetrons, antennas, pulsed radar

1. Introduction

Soon after the end of WWII, materials were published [1-4] that covered the history of radar development, starting from the formulation of basic physical principles to the first experiments, and on to the use of radar in combat operations. These papers mainly featured the contributions of the scientists and engineers of the UK and the USA. However, in our opinion, the work on radar by USSR scientists and engineers has been rather scarcely reviewed. Now, more than 60 years later, this work can be considered to be quite fundamental and, in certain aspects, pioneering. It was done in isolation and without publicity, necessitated by the pre-war circumstances and the general Soviet "spy-mania." All the investigations in this field were heavily classified as Top Secret. The first reviews of the related history were published only in the 1960s, and then all in Russian [5-13]. It should be noted that these were usually written from one perspective, featuring only a certain, separate, development, undertaken by a specific research team. A brief – however, fair – evaluation of the subject of our present article (the first USSR L-band pulsed radar, developed in Kharkov in 1937-1938) can be found in the memoirs of Gen. M. Lobanov [5, 10, 12]. He was then a leading specialist on radar in the Principal Department of Artillery of the Peoples Commissariat [or Ministry] of Defense (PDA-PCD). Some data were also presented in the book of Prof. P. Oshchepkov [6]. In the mid-1930s, he was a representative of the Department of Air Defense of the Red Army (DAD-RA), and supervised all the radar work performed by the research institutes and in industry for the Service of Air-Defense Surveillance, Alarm and Communication (SASAC) of the Red Army.

Recent *AP Magazine* publications [14, 15], concerning radar developments in the pre-war and war times in Japan and New Zealand, tended to cover unofficial aspects of the work, such as preliminary ideas, working materials, formerly classified data, visits and meetings, correspondence, private episodes, etc. This has been invaluable in providing a really full view of historical events.

We would like to introduce the reader to the history of the design of a pulsed radar operating in L band, within the broader context of the formation of the Kharkov radio-physics community and of pre-war Soviet radar developments. The radar was designed at the Ukrainian Institute of Physics and Technology (UIPT), and it was a remarkable milestone in Soviet science and technology. This work was unique in terms of the ideas, importance, scope, complexity of tasks, and the time of completion. The basic concepts of radar design and many technical innovations were well ahead of the general trends in radio engineering. However, because of the rapid advance of the Nazis (who occupied Kharkov in the fourth month of the war), this radar, after a successful start, never resulted in serial production. Only an experimental radar was tested, and later used near Moscow and Murmansk for surveillance.

Unfortunately, all the pre-war archives containing official documents on this development were lost in the chaos of the UIPT evacuation to Central Asia, in the fall of 1941. For this reason, our article has been written on the basis of available memoirs, fragments of remaining documents, and private archives of the research staff and their families. In particular, we used the publications [16-18] of the late Alexandr Usikov [19, 20], as well as his archive materials [21] and his interview [22]. A. Usikov was one of the initiators of the radar studies, and, therefore, his point of view was of great importance for recovering a complete image. An exciting and valuable input to this paper was obtained from an interview of Semion Braude [23, 24]. Now, after a career of 67 years [25], he is the only living member of the Kharkov radar team. He remembered many events in detail, so our work would not have been possible without his insightful comments.

2. The Formation of the Kharkov Radio-Physics Community in the KSU

The history of the development of the L-band pulsed radar is inseparable from the history of the formation of the Kharkov radio-physics community (see [26, 27]). Here, we shall briefly recall the essential milestones that are relevant to the radar research.

The birth of the radio-physical community in Kharkov was conditioned by its history. The city was founded in 1655 as a Russian frontier fort, inhabited mainly by Ukrainians. By the beginning of the twentieth century, it had developed into a large industrial, cultural, and scientific center, with lasting university traditions. The Kharkov State University (KSU), the third-oldest university in Russia, was opened by imperial decree in 1805, after the universities in Moscow (1755) and Kazan (1804). Remarkably, KSU had four departments, including a Department of Physical and Mathematical Sciences. During the first hundred years after its opening, the university trained a galaxy of prominent scientists, whose works brought them world-wide fame: mathematicians M. V. Ostrogradsky, A. M. Lyapunov, and V. A. Steklov; biologist I. I. Mechnikov; chemist N. N. Beketov; and others. The university won a reputation as one of the most prestigious schools of higher education in Russia, and became a center of advanced science and technology.

For better insight, one has to keep in mind that after the revolution and bloody civil war, it was Kharkov that was chosen as the capital city of the Soviet Ukraine from 1919 to 1934. Then, Kiev was considered less politically reliable and more devastated, after changing hands nearly 20 times within three years of fighting. Once the Soviet regime was set into place, the universities in Ukraine entered a turbulent period of reforms. The name "KSU" even disappeared for a while, until 1933; however, we shall still use it here, for simplicity.

In 1921, one of the first research departments of physics in Ukraine was established in the KSU, as a new, independent scientific unit [26, 27]. This was during a short time of a relatively greater degree of freedom – both economic and political – in the USSR, and, therefore, a handful of scientists who remained in the country had relative freedom in research, as well. The department was established under the guidance of the prominent physicist Dmitry Rozhansky (Figure 1) [28, 29]. The Kharkov period of his career was devoted to investigating the oscillatory spark discharge, studying the properties of an electric arc, oscillations in coupled circuits, rarefied-gas discharges, etc. As a recognized scientific leader, he had grouped around himself similarly minded associates, creating a supportive atmosphere and determining the topics of research. With a very wide circle of scientific interests, Rozhansky was one of the first who foresaw the future of high-frequency radio engineering, and he initiated research on electromagnetic oscillations. As a matter of fact, this gave a birth to the Kharkov radio-physics community as a whole.

The number-one Soviet physicist of that time, A. Ioffe, wrote that Rozhansky performed investigations on short electric waves, generated by cathode tubes, after methods similar to those developed by Barkghausen and Kurtz, in Germany. In Kharkov, these investigations resulted in discovering "magnetron oscillations" [30]. These were high-powered oscillations, with a wavelength of about several centimeters. After leaving Kharkov, in 1924, Rozhansky kept in close contact with his former staff and students. Braude recalled [24] that he met Rozhansky when he was a young scientist at UIPT. At that time, Rozhansky worked in Leningrad, but he still was supervising research at KSU and UIPT, and he used to visit Kharkov twice per year. Braude remarked that Rozhansky was an excellent teacher and gentleman. At that time, Braude was working on the problem of obtaining ion beams by using a magnetic field. This was his first scientific project. Rozhansky showed a great interest in this work, and willingly advised him on scientific and practical issues. Rozhansky was remembered as a very interesting and sociable person: easy to get along with. He was always particularly encouraging to young scientists, and promoted many of them who later became famous. It was no accident that two of his students, A. Slutskin in Kharkov and Y. Kobzarev in Leningrad (who also graduated from KSU), headed the work on the development of the first Soviet pulsed-radar systems.

Here we come to the central personage of our story. It is no mistake to say that the main discovery of Rozhansky in Kharkov

Figure 1. Dmitry A. Rozhansky (circa 1930).

Figure 2. Abram A. Slutskin (1949).

was the most remarkable man in Ukrainian radio physics and electronics between 1925 and 1950, Abram Slutskin (Figure 2).

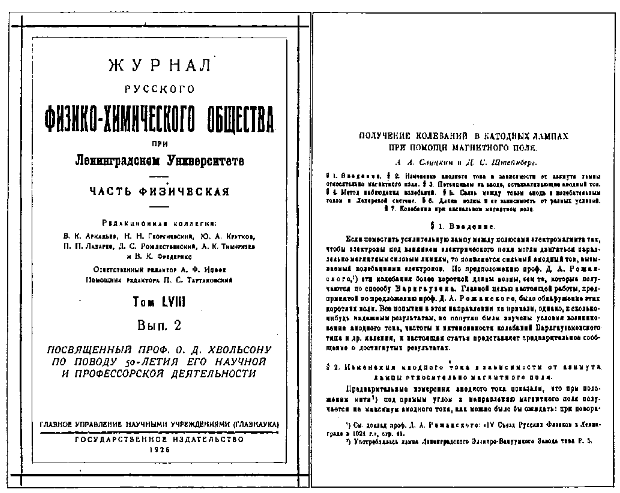
We believe that A. Slutskin (1881-1950) was one of those who played a crucial role in shaping modern radio science. He entered the Physics-Mathematics Department of KSU in 1910, just before Rozhansky's arrival. Rozhansky started a very interesting physical seminar, with active student participation. This, according to Slutskin, determined Slutskin's ever-lasting interest in electronics. Slutskin graduated from the university in 1916, and worked there as an assistant (until 1928), and then as a professor in the Physics Department. In 1928-1930, he was in Germany, where he worked in the laboratory of Barkghausen. In 1937, he was awarded the degree of DSc, without defending a thesis. He was elected a Corresponding Member (1939) and later Academician (1948) of the Academy of Sciences of Ukraine. His work was focused on the magnetron and on pulsed radar [31].

At an early stage, Slutskin managed to foresee many major trends in microwave electronics and physics. In 1924, having succeeded in generating L-band (dm-band, in Soviet notation) oscillations in a magnetron-type oscillator (i.e., reaching the high-frequency part of the then-available spectrum), he became a devoted enthusiast of conquering even shorter wavelength bands. It was due to his intuition and initiative that the three-coordinate L-band pulsed radar was developed at UIPT, although, at that time, there were no evident grounds for selecting this band and the pulsed method. Research and development in new wavelength bands became a scientific credo of his followers. In particular, this was true of A. Usikov, one of the founders and the first Director of the Institute of Radio-Physics and Electronics (IRE) in Kharkov, aimed at the development of the millimeter and sub-millimeter wavelength bands.

The work at KSU on electromagnetic oscillations was substantially extended after a separate section of the Research Department of Physics was established there, in 1926. It was headed by Slutskin beginning in 1930, after his return from Germany. This was the time when the Kharkov radio-physics community began to develop rapidly, as did the communities established earlier in Moscow and Leningrad. Talented students and young scientists of the department were actively engaged in research, with the magnetron as their major focus.

As far as is known, the first publication on magnetron oscillation was by A. W. Hull, whose papers [32, 33] appeared in 1921. Soon, A. Zachek demonstrated (1924) the possibility of generating high-frequency oscillations by connecting an oscillation circuit between the magnetron's cathode and its anode, and applying a permanent magnetic field of a strength close to its critical value [34]. E. Habann revealed (1924) that by splitting the anode into two equal segments (a split anode), between which a high-frequency circuit was placed, the output power could be increased drastically [35]. In 1924 at KSU, by the initiative of D. Rozhansky, A. Slutskin, and D. Shteinberg [36], investigations of the processes occurring in electron tubes under the impact of an external field were undertaken. By using the three-electrode tube R5, produced by a Leningrad electro-vacuum plant, they succeeded in generating electromagnetic oscillations within the wavelength band of 40 to 300 cm (see Figure 3) [37]. Later, they studied the effects associated with the tube-element geometry, operation modes, and the magnetic field strength [38]. At their request, industry manufactured diodes where the anode was made from a non-magnetic material (tantalum). By the end of 1925, these studies enabled Slutskin and Shteinberg to obtain oscillations with a wavelength of 7.3 cm. Unfortunately, we failed to find the publication containing this data. However, it was mentioned in a paper of one of the students of Slutskin [31]. Additionally, this result was stated in a book [27] with a reference to the archive materials [39]. Here, one should keep in mind that important pioneering experimental work was also done by H. Yagi [40] and K. Okabe [41] (1928-1929), with a magnetron having a split anode in the form of two half-cylinders.

It is necessary to note that all the works mentioned were really performed independently. There is no doubt that – together with the other researchers better known in the West – A. Slutskin



ЖУРНАЛ
РУССКОГО
ФИЗИКО-ХИМИЧЕСКОГО ОБЩЕСТВА
ПРИ
Ленинградском Университете

ЧАСТЬ ФИЗИЧЕСКАЯ

Редакционная коллегия:
В. К. Аркадьев, Н. Н. Георгиевский, Ю. А. Крутков, П. П. Лазарев, Д. С. Рождественский, А. К. Тимирязев и В. К. Фредерикс
Ответственный редактор А. Ф. Иоффе
Помощник редактора П. С. Тартаковский

Том LVIII
Вып. 2

ПОСВЯЩЕННЫЙ ПРОФ. О. Д. ХВОЛЬСОНУ ПО ПОВОДУ 50-ЛЕТИЯ ЕГО НАУЧНОЙ И ПРОФЕССОРСКОЙ ДЕЯТЕЛЬНОСТИ

ГЛАВНОЕ УПРАВЛЕНИЕ НАУЧНЫМИ УЧРЕЖДЕНИЯМИ (ГЛАВНАУКА)
ГОСУДАРСТВЕННОЕ ИЗДАТЕЛЬСТВО
1926

ПОЛУЧЕНИЕ КОЛЕБАНИЙ В КАТОДНЫХ ЛАМПАХ ПРИ ПОМОЩИ МАГНИТНОГО ПОЛЯ.

А. А. Слуцкин и Д. С. Штейнберг.

§ 1. Введение.

Figure 3. The journal title page and the first page of the pioneering paper by A. Slutskin and D. Shteinberg, entitled "Obtaining of Oscillations in Cathode Tubes with the Aid of Magnetic Field" (1926).

and D. Shteinberg can be considered to be pioneers of the magnetron oscillation method.

3. Development of Magnetron Research at UIPT

The next stage in the development of the Kharkov radiophysics community was closely linked to the founding of UIPT, in 1928. This brand-new research and development center strongly influenced the progress in physics in the USSR, and became a leader in several areas of advanced science, particularly in radiophysics and electronics. The key role in organizing this institute was played by Ac. A. Ioffe, who was then the Director of the Leningrad Institute of Physics and Technology (LIPT). He persuaded the government that a certain decentralization of Soviet science was necessary, and suggested that Kharkov, then the capital of Ukraine, was the best choice for a new major laboratory. In the beginning, the main scientific areas investigated at UIPT were solid-state physics and low-temperature physics, but it soon was oriented toward research in nuclear physics [27].

The Institute began its life in 1929, with a staff of 14 scientists including the Director, Prof. I. Obreimov, who came from LIPT. Slutskin and Shteinberg were on this staff, still keeping their university posts. It was only in May, 1930, when the main group of Leningrad scientists from LIPT came to UIPT. These scientists, who later built the backbone of the Institute, were of the younger generation, attracted by the promising research and career opportunities. The engagement of highly qualified specialists, impressive funds rendered by the government for purchasing equipment abroad, as well as the offer of better salaries and service apartments, together with the rapid building of the laboratory and living blocks led to shortening the startup period. The official opening ceremony took place on November 7, 1930, the Revolution day, and the first fundamental research results were obtained as soon as in 1932.

As Ioffe wrote [30], in terms of organization, this institute was the best in the USSR, and compared favorably with many of the large centers in the West. In terms of research, it was on a par with the best physical institutes of Moscow and Leningrad. Obreimov managed to establish active contacts with the West-European scientific community. These contacts were recognized as an example for all research institutes of the USSR. What was most unusual was that the regular journal of UIPT published all the papers in German, to facilitate their international recognition.

Due to this openness, during the first several years of existence UIPT was visited by a number of international science celebrities: N. Bohr, P. Dirac, P. Ehrenfest (Figure 4), R. Payerls, G. Plachek; and Soviet celebrities: V. A. Fok, G. Gamov, P. L. Kapitsa, etc. This added to the extraordinary scientific potential already accumulated at the institute. So, it was no surprise that on October 11, 1932 – for the first time in the USSR – the splitting of a lithium nucleus was done at UIPT. Later the same year, liquid hydrogen and liquid helium were obtained. This proved that Kharkov had turned into one of the most important centers of physical science.

N. Bohr left the following reference, when visiting UIPT in 1934:

> I am glad to get an opportunity to give expression for the feeling of great admiration and pleasure with which I have seen the beautiful new physical-technical institute in Kharkov, where the excellent conditions for experimental work in all branches of modern physics are utilized with greatest enthusiasm and success under most distinguished leadership and in closest collaboration with brilliant theoretical physicists [27].

In 1932, Obreimov offered Lev Landau, later a Nobel Prize winner, employment at UIPT. Landau was only 24, but he was already a world celebrity in theoretical physics. From 1932 until 1937, he headed the Theoretical Department of UIPT, and actively participated in the development of the Institute. Besides this, he lectured at KSU, where he held the Chair of Theoretical Physics [42].

As Petr Kapitsa (also a Nobel Prize winner) later wrote [43], a number of the main works of Landau related to the Kharkov period: the theory of phase transitions of the second kind, the kinetic equation in the Coulomb interaction of particles, the theory of the intermediate state in superconductivity, and some others. This turned Kharkov into the center of fundamental physics in the USSR. It was there that Landau organized a regular theoretical seminar and started writing – at first with L. Pyatigorsky, and then with Y. Lifshits – the famous *Course of Theoretical Physics.* He also initiated a "theoretical-minimum" examination program for the research staff of UIPT.

S. Braude recalled,

> I was lucky to meet Landau when he was working in UIPT. First, like many other researchers, I sat for an examination in the theoretical-physics course before Landau (there were two variants of the program: one for theoreticians and one for experimentalists) and passed two exams in "Mechanics" and "Statistical Physics." As it is known, the full scope of the theoretical minimum consisted of nine exams, and within 30 years, only 43 persons had managed to pass all of them. I should note that the extraordinary depth of physical thinking of Landau, along with the informal atmosphere of the exams, made the theoretical-minimum a very useful and memorable experience for a well-trained applicant, although the evaluations of Landau were often critical, ironic, and virulent. Second, in 1935, being involved in

Figure 4. The staff of UPTI during the visit of P. Ehrenfest in 1930. In the second row, from left to right: P. Ehrenfest, I. Obreimov, T. Afanasyeva-Ehrenfest, A. Ioffe, and D. Shteinberg. The fifth person from the left in the back row is A. Slutskin.

Figure 5. Aleksandr Y. Usikov (1948).

the magnetron research, I developed a method for solving the problem about the effect of a magnetic field on a spatial charge. Previously, this problem had been reduced to a set of non-linear equations. I obtained the solution in quadratures for a planar model of the magnetron, and in terms of a series for a cylindrical model. Then I discussed this result with one of the leading theoreticians of UIPT, Lev Rozenkevich [44], who said that the solution was erroneous. I did not agree with him, and decided to discuss this problem with Landau. It took him only 15 minutes to go deeply into the subject and to derive the same results as I did. After that, the correctness of the solution was never disputed [24].

The Laboratory of Electromagnetic Oscillations (LEMO) was established as a department of UIPT as early as in 1930, and was headed by A. Slutskin. This was the only department headed by a Kharkov scientist, while the other eight were headed by the former LIPT staff. Besides this, it was the only department engaged in electrical engineering and electromagnetic waves. As we shall see, both circumstances played a certain role in what happened further. During this period, Slutskin investigated the mechanisms and conditions of excitation of split magnetrons, and developed a theory of a magnetron oscillator operating in the dynatron mode. This, together with the advanced technical equipment of UIPT, enabled the scientists of LEMO to extend the work of generating high-power oscillations in the L band. According to Usikov, Slutskin enjoyed an extremely high reputation as initiator of a completely new method in science: the magnetron. In the laboratory, general and theoretical research was performed by Slutskin himself, and a number of specific problems were studied by the staff [22].

S. Braude:

Slutskin was my teacher, as he lectured on electrodynamics in KSU where I studied. It was with his personal support that I was assigned to UIPT on my graduation. I have been shaped as a scientist under a strong influence of him. Together we published a series of papers, mainly on the theory of magnetron oscillation. It should be noted that he personally supervised all the research projects of his staff, and every day discussed the results obtained.

Furthermore, Braude tells [24] that at the time he started working in LEMO, in 1933, they were intensively investigating all theoretical and experimental aspects of generating electromagnetic oscillations of the dm and cm wavelength bands. By 1933, a group consisting of A. Usikov (Figure 5), P. Lelyakov, Y. Kopilovich, and N. Vyshinsky had designed multi-segment-anode magnetrons in the waveband of 20 to 80 cm, with a CW output power of 30 to 100 W. In 1934, the results of these investigations were published [45, 46]. These were the champion parameters at that time: the CW output power of the magnetron, in watts, was equal to the wavelength, measured in centimeters. The magnetron studies, aimed at raising the power and the frequency, went on. Braude took part in this work as an engineer, together with Pavel Lelyakov, who was a leading expert of the laboratory, and held the post of Senior Scientist. Lelyakov made an important contribution to the magnetron and radar projects, but his fate was dramatic. Unlike his colleagues, he stayed in Kharkov when it was occupied by the Nazis, and left it with the German Army, in 1942. As recalled by Braude, Lelyakov had already opposed the Soviet regime before the war (although it was very dangerous), and therefore, for his colleagues, such an ending was no surprise. In August-September, 1941, A. Slutskin, being on a mission to Moscow, repeatedly called the Director of UIPT to discuss the laboratory evacuation to Central Asia, and drew the Director's attention to Lelyakov. Later on, Braude came across the papers published by Lelyakov in the US technical journals, but, after 1962, lost track of him [24].

In particular, it was Lelyakov who invented a magnetron with a hollow anode, water-cooled from the inside (Figure 6). Two half-anodes were connected by tunable circuits, consisting of metal tubes for bringing the water and carrying it away. This design later served as a basic design with different modifications. Braude (Figure 7), Lelyakov, and Truten (Figure 8) had developed a water-cooled magnetron in a glass case, which enabled them to achieve an output power of 5 to7 kW at a wavelength of 80 cm. An even higher power level (up to 17 kW in the CW mode) with 55% efficiency was achieved by Braude, in an all-metal "barrel-type" oscillator (Figure 9). Besides this, a sample tunable magnetron was designed (Figure 10), in which the frequency was tuned over a 30% band, by varying the length of the circuit extended off the metal case. These results were published only after the war, in 1946 [47].

At the same time, an extensive investigation of the magnetron's power and frequency control, and the design of a pulsed-mode device, were carried out. This work was led by Usikov, whose role in radar development is hard to overestimate. Along with the magnetron research, and supervision of the design of the radar transmitter, he shouldered the main burden of the scientific management of the whole project. Being a fair and decent person, always attentive and sympathetic toward colleagues but firm in the fundamental issues, he favorably influenced the atmosphere at LEMO [24]. In 1933, Usikov discovered the effect of discontinuous modulation, which could be observed in a magnetron provided that its connection circuit corresponded to the relaxation scheme. Later he, and also Lelyakov and Vyshinsky [48], were investigating the characteristic features of the magnetron's pulsed excitation. Started under his guidance, this important research work resulted in the design of high-power pulsed magnetrons in the L band at UIPT. Usikov recalled [22] that the progress in generating high-power oscillations drew the attention of the government, which considered high-power magnetrons important for the military. Therefore, UIPT was soon given a corresponding task by the Technical Department of the Red Army (TD-RA). The investigations included the testing of the operational modes of oscillation of the magnetron that could provide the maximum pulse power and the required frequency stability. At this time, a packaged un-cooled

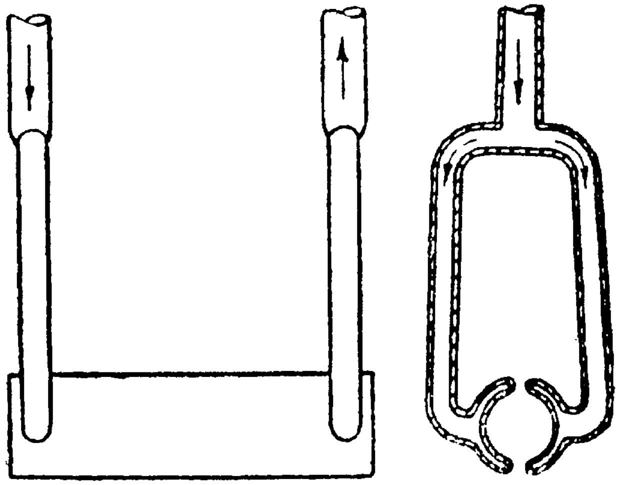


Figure 6a. A drawing of a hollow anode for a high-power water-cooled magnetron in a glass case (from [39]).

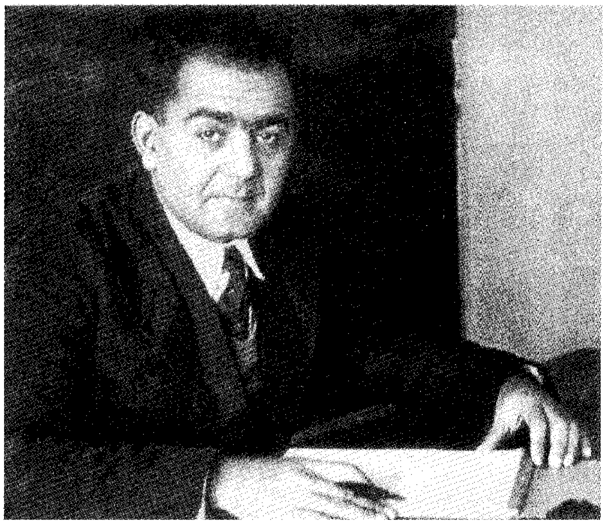


Figure 7. Semion Y. Braude (1948).

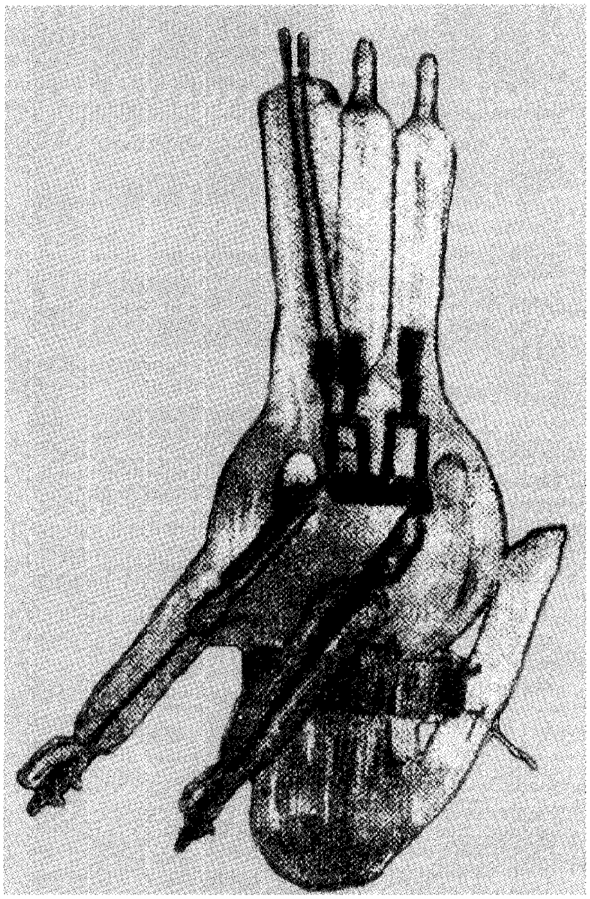


Figure 6b. A high-power water-cooled magnetron in a glass case (from [39]).

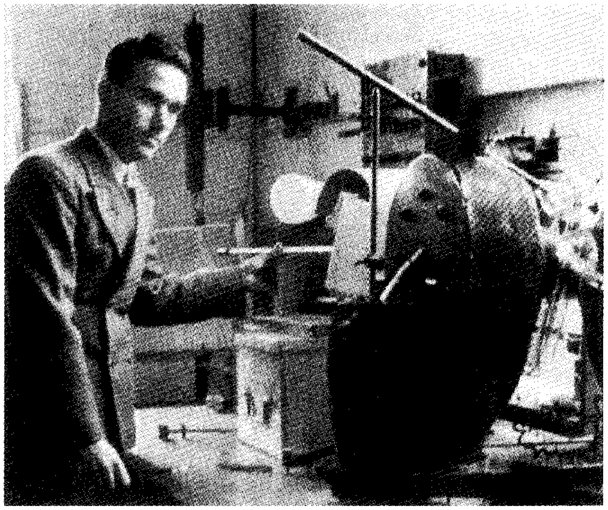


Figure 8. Ivan D. Truten (1947).

magnetron, with a linear cathode inserted in a glass case, was developed (Figure 11). It provided pulsed power up to 60 kW at a wavelength of 60 to 65 cm. Two other members of the research team were Ivan Truten [49] and Iosif Vigdorchik [50].

S. Braude recalled [24] that I. Truten was a person with extraordinary capabilities, famous for non-standard thinking. He developed a number of original radar units, in particular, a super-heterodyne receiver and gas dischargers [spark gaps], which provided for the operation of a radar with a single antenna. A fundamental approach was always present in his research, and was especially brightly displayed when he guided the work of developing the mm-band magnetrons in the 1950s and 1960s at IRE. At the same time, he is remembered as an extremely decent person, enjoying huge respect among the staff. The modesty of Truten was sometimes in the extreme. When, taking into account his great contribution to the development of magnetrons, the USSR Supreme Qualification Commission decided to award him a Doctor of Technical Sciences degree without defending a thesis, he refused. I. Vigdorchik was characterized by Braude as an enthusiastic and innovative colleague, who took a most active part in the radar project.

Simultaneously, new ideas were being explored in LEMO. In particular, the possibility of using a net as an electrode for controlling the output-signal amplitude was demonstrated in 1935, in the PhD thesis of Usikov. Later, V. Tkach designed a magnetron with a net that was able to generate power ranging up to several tens of watts in the dm band; these results were presented in his PhD thesis, in 1940. These investigations were further continued by S. Braude and A. Ivanchenko, who designed an efficient magnetron with a net control, able to generate pulses of 5 to 20 μs, and a pulsed power of several tens of kW [51]. These results were summarized in 1943 in the DSc thesis of Braude.

One can judge the scale of research carried out at LEMO-UIPT by the impressive number of papers published in the technical journals during the pre-war time. Many of the results obtained during that period were of fundamental character, and have not lost their importance even now. In particular, research on developing higher-frequency sources resulted in the discovery of a special type of mm-band magnetron operation, by Truten, in 1945. It consisted of the interaction of the electrons not with the first harmonic, but with one of the delayed, higher-order spatial field harmonics. These working modes were later called "the Kharkov magnetron operation modes" in Soviet literature. They enabled one to considerably reduce the static magnetic-field magnitude and the manufacturing tolerances of the anode resonator. As a result, a series of mm-band magnetrons were produced having a champion power (e.g., a pulsed power of 100 kW at a wavelength of 4 mm). One of the methods of magnetron modulation with the aid of electrostatic lenses, proposed by Usikov in 1936, later served as a basis for designing surface-wave magnetrons with lens optics (in the 1970s, together with G. Levin).

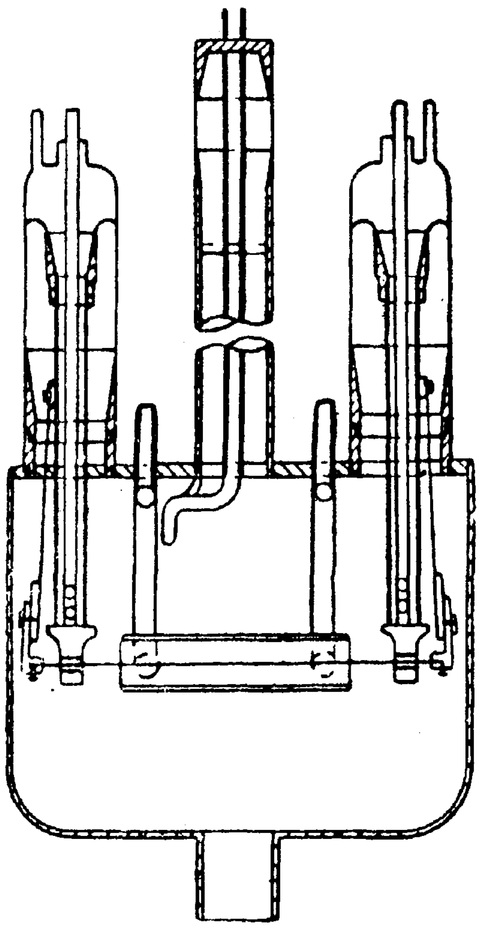


Figure 9a. A drawing of a high-power magnetron in a "barrel-type" metal case (from [39]).

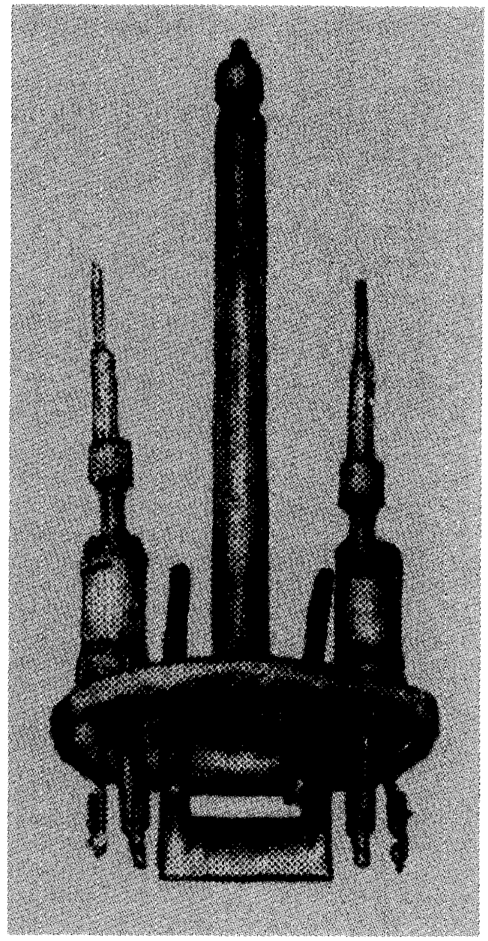


Figure 9b. The high-power magnetron without the metal case (from [39]).

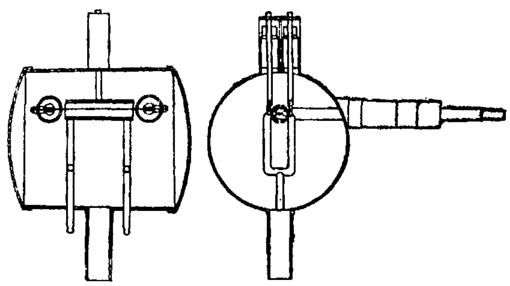


Figure 10. A drawing of a tunable magnetron.

Thus, by the end of 1936, LEMO-UIPT had carried out wide-range fundamental research on the magnetron method, and had a complete set of L-band devices, both for CW and for pulsed operation. This was a solid background for launching complex work on developing pulsed radar.

4. Pre-War Soviet Research on Radar

4.1. Anti-Aircraft Gun-Aiming Radar Developments

It appears natural to present the development of the Kharkov three-coordinate pulsed radar against the background of various events surrounding the origination of radar as a new direction in defense science and technology. In the 1930s, which were remarkable for rapid progress in the aircraft industry, the capabilities of combat aircraft increased drastically, including speed, altitude, and navigation. Existing optical and acoustical surveillance methods could not provide reliable detection of hostile aircraft, especially in the nighttime and under complicated weather conditions. Therefore, in the UK, the USA, Europe, and the USSR, new radar methods were developed, practically simultaneously.

The economics of the USSR, strangled by state planning, as a rule did not allow any competition. The only – but remarkable – exception was the military industry, where, to design advanced weapons in the shortest time, research and development efforts were often doubled and tripled by different teams and labs. A good example was the aircraft industry, where in order to develop a new fighter or bomber, as well as to provide infrastructure and equipment, it was common to organize tenders between several (or at least two) competing design bureaus. The same approach was used with radar research. Therefore, the first Soviet studies related to radar were performed in parallel by the initiative and with the support of two military departments: the PDA-PCD (Principal Department of Artillery of the People's Commissariat of Defense), for the anti-aircraft artillery, and the DAD-RA (Department of Air Defense of the Red Army), for air surveillance. In turn, these departments, as customers, engaged different research and development organizations into parallel developments of radar. Thus, in October, 1933, after preliminary tests, the PDA-PCD allocated a project to the Central Radio Laboratory (CRL) in Leningrad for the detection of radio waves reflected from an aircraft. This was the first USSR legal document that became a basis for starting planned research, development, design, and testing in radio detection. It was also the first document stating the systematic financing of such kinds of work [10, 52].

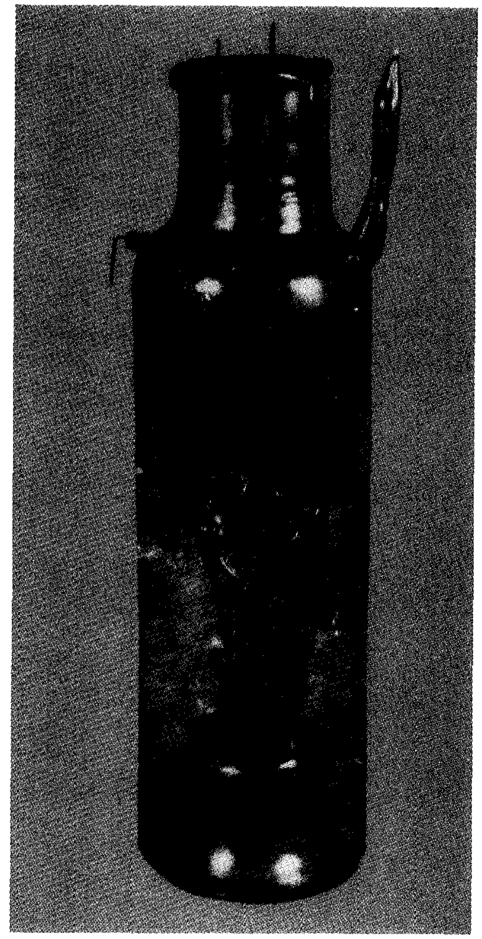


Figure 11b. The pulsed magnetron in a glass case (circa 1935) from the IRE, Kharkov.

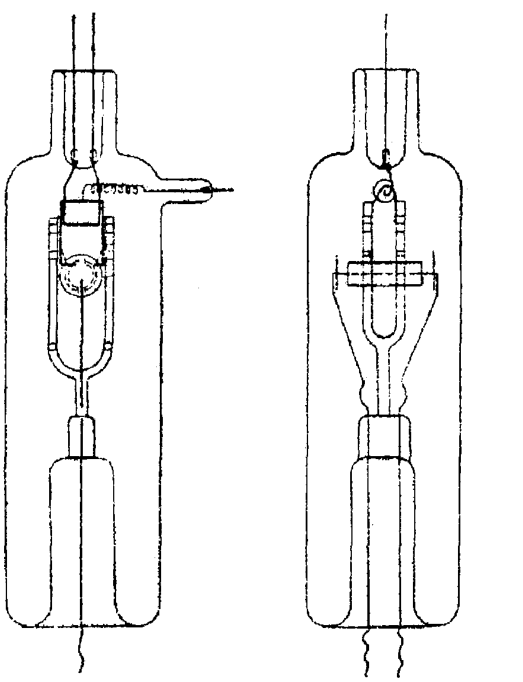


Figure 11a. A drawing of a pulsed magnetron (circa 1935) kept in the IRE, Kharkov.

According to the project, Engineer Y. Korovin used already existing radio-communication equipment, designed at CRL and operated in CW mode at wavelengths from 50 to 60 cm. On January 3, 1934, the first tests of radio detection of a flying boat were carried out. Korovin observed the Doppler effect in the form of the pulsation of the sound signal when the aircraft entered the line-of-sight zone. The flying boat was detected at a distance of 600 to 700 m, at a flight altitude of 100 to 150 m [42]. Later, Korovin continued his work with the Central Military-Industrial Radio Laboratory (CMIRL) in the city of Gorky [now, Nizhny Novgorod]. However, despite an improved detection range (11 km), his "radio-catchers" [53] showed an unstable operation, and the work was terminated in 1937.

Already, at an early stage of the work mentioned, the PDA-PCD came to the conclusion that parallel research had to be performed by the Leningrad Electro-Physical Institute (LEPI). On January 11, 1934, a corresponding research and development project was allocated by the PDA-PCD, and B. Shembel, later a well-known radio engineer, was assigned as project leader. By the summer of 1935, an experimental radio-direction finder was assembled. It was able to locate two angular coordinates of a target: the azimuth and the elevation. Its design used a quadruple-split CW magnetron, generating a power of over 10 W, at a wavelength between 21 and 29 cm. The tests had shown that a small airplane, such as the U-2, could be detected at a distance of 8 km. In the fall of 1935, LEPI was merged with the Radio Experimental Institute (REI), and was reorganized into the R&D Institute No. 9 (RDI-9). It was oriented towards defense-related research, and headed by a remarkable scientist, radio engineer, inventor, and manager, M. A. Bonch-Bruyevich. Under the contract of the PDA-PCD, in 1936 RDI-9 fabricated a sample radio-searcher "Burya," with a magnetron source having a CW radiation power of 6 to 7 W and a wavelength of 21 to 23 cm. The tests of this radio-searcher demonstrated the detection of a squadron of small R-5 aircraft at 10-11 km. In the discussion of the field tests, it was noted that the results obtained did not meet the requirements of the anti-aircraft artillery, and a number of measures were planned to enlarge the detection range, and to improve this device's accuracy and reliability. In 1937, managerial and technical rearrangements were undertaken to widen the research. In particular, a laboratory, headed by Prof. B. Vvedensky, later a scientist in microwave propagation, was affiliated with RDI-9. This group strengthened the RDI-9 vacuum laboratory in the effort to design and produce magnetrons in the 12 to 90 cm wavelength band [10].

S. Braude recalled [24] that once a large group of scientists from RDI-9, headed by Vvedensky, came from Leningrad. From the beginning, everybody was deeply impressed by Vvedensky's open and friendly style. The LEMO staff, except for Slutskin, was much younger than Vvedensky, but nobody felt this, nor any other difference in position. This "non-bossy" style was especially remarkable by comparison with the behavior of some of the other scientists of RDI-9, who considered Kharkov as a provincial place, and spoke in patronizing manner. Although they later admitted that the LEMO magnetrons were, in some aspects, better than theirs, the relations had already been spoiled. When Vvedensky felt this, his reaction was immediate. He called together both teams, and made a brief but impressive speech, highly estimating the LEMO achievements. Thanks to such efforts, the two teams agreed to carry out joint developments.

In 1937-1939, RDI-9 performed wide-ranging research, aimed at designing a reliable gun-aiming radar. By the fall of 1937, a stationary radio-searcher, RS-4, was designed and assembled. The detection range of a small aircraft, such as the U-2, was 25 km. That same year, two radio-direction finders, "Burya-2" and "Burya-3," were designed and assembled. In order to enhance the detection accuracy without shrinking the radiation pattern, both used the method of an equal-signal zone. The tests demonstrated reliable detection within a range of 17.5 km, and a high accuracy of locating the angular coordinate (1°). However, both radio-searchers provided low reliability at target altitudes over 4000 m.

As a result of the work of CRL/CMIRL and LEPI/RDI-9 in 1934-1939, a basis was prepared for the industrial manufacturing of radio-searchers. The war in Europe forced this to be hurried up. On July 4, 1940, the recently organized State Defense Committee (SDC) ordered RDI-9 to release the field-tested anti-aircraft radio-searcher to the PDA-PCD by October 1, 1940. The radio industry was given six months to produce a new prototype radio-direction finder, "Luna." Later, the SDC ordered the radio industry to complete the prototype device by August 5, 1941, and to start serial production by August 20, 1941. The beginning of the war with Germany disrupted these plans. Evacuation of the radio industry to the east and termination of the activity of RDI-9 made it impossible to finalize the development of Luna. It should be noted that all the devices mentioned were based on the Doppler principle in the CW radiation mode. Only one attempt was made at LEPI (1935) to design pulsed equipment. However, the pulse power and the receiver sensitivity of this setup were too low for detection of an aircraft, and the project was soon terminated.

4.2. Air-Defense Radar Developments

The problem of the reliable detection of airborne targets was getting more and more urgent for air surveillance, as well. At the initiative of military engineer P. Oshchepkov, a special conference was held, as early as January 16, 1934, in LIPT. It was chaired by the LIPT Director, Ac. A. Ioffe. The topics were methods of aircraft detection at night and under bad weather conditions, when visual methods were not applicable, for the purposes of air defense [6]. Besides Ioffe, the conference was attended by many leading Soviet scientists, including Rozhansky. In the final document, the participants agreed that radio-detection methods, using waves of "essentially short" length, were the most promising. As Oshchepkov later wrote [6] during the final editing, he made an attempt to insert a clearer sentence about dm- and cm-waves. However, when signing this document, the Chairman, A. Ioffe, crossed out that phrase. This detail shows that by the mid-1930s, there was no clear evidence that the dm-band might offer better opportunities for designing an efficient and reliable radar.

On February 19, 1934, the DAD-RA assigned a research and development project to LEPI on aircraft detection (code "Rapid," project leader B. Shembel). According to the project, research on measuring the waves reflected from objects of various shapes and materials had to be carried out. This development was again based on the Doppler method in the CW radiation mode. It implied creating an electromagnetic "curtain" between a distant transmitter and receiver. By July, 1934, a prototype device had been designed and fabricated (the source wavelength was 4.7 m, and the power was 200 W). The detection range of Rapid, for an all-metal fighter plane, was 5 to 7 km. The DAD-RA terminated the contract with LEPI at this stage. Nevertheless, Rapid served as a prototype of the RUS-1 system, which was later developed in the R&D and Testing Institute of Communications of the Red Army (RDTIC-RA), and was released to the Army. The total number of RUS-1 units produced amounted to 45; these were employed in air defense in Karelia, the Far East, and the Trans-Caucasus during the Soviet-Finland war and in WWII.

In October, 1934, a special design bureau (DB) was established in the DAD-RA, which was charged to develop general radar methods and necessary specific non-standard components. The Chief of the DB-DAD-RA was P. Oshchepkov. In order to solve the problem in the shortest time, research and experimental work was performed at LEPI and other institutions. Thus, according to the contract dated November 15, 1934, UIPT started delivering experimental CW magnetrons in the wavelength band from 30 to 80 cm, and with power ranging from 10 to 1000 W, to the DB-DAD-RA. The number of magnetrons manufactured reached

50 devices a year. Here, it should be noted that this contract was considered by LEMO as a burden, as it required a lot of effort that was not usual for a research and development laboratory. The DB-DAD-RA allocated a number of other contracts to design the radio-detection equipment "Vega" and "Konus." In fact, the operating principle of the Vega system was the same as that of Rapid. Alternatively, the Konus system was designed to not only detect an aircraft, but also to determine the target's distance and azimuth. As the tests showed, the difficulties associated with using the FM method in the CW radio-direction finders remained unresolved, and the contracts with the radio industry were cancelled in 1935. Nevertheless, the magnetrons were still delivered from UIPT to the DB-DAD-RA for further experiments.

The idea of developing radar systems operating in the pulsed mode appeared in the search for methods of enhancing detection range and simplifying location techniques. On March 19, 1935, the DB-DAD-RA allocated a project to LIPT, where a laboratory of radar research was established. At first it was headed by Rozhansky, and after his death, in September, 1936, it was headed by Kobzarev. At that time, the DB-DAD-RA was transformed into the Experimental Section, the research activity of which included, in addition to design duties, a complex investigation of radar problems.

Between October, 1935, and April, 1936, LIPT carried out experimental investigations of the RCS properties of aircraft irradiated in the CW mode, with wavelengths from 3.2 to 4.7 m. These enabled one to estimate the capabilities of a pulsed radar system. By the spring of 1937, all the design work on an experimental pulsed radar was completed. The transmitter for this radar was based on the serial tubes G-165, and provided a pulse duration of 10 μs at a pulse power of only 1 kW. Nevertheless, the first tests, on April 17, 1937, were successful. A small R-5 aircraft was detected at a distance of 17 km. After that, it was decided to develop a high-power transmitter. However, at that moment the work was strongly handicapped by some purely Soviet phenomena. 1935-1938 were the years of the most severe purges by Stalin and the NKVD [later, the KGB]. These not only "beheaded" the government, industry, the army, science, and education, but they also simply wiped out entire laboratories, and many thousands of personnel. The victims were especially numerous among the defense scientists and engineers, as many advanced groups and laboratories were actively promoted by the purged commanders of the Red Army. In the summer of 1937, Oshchepkov, the head of the Experimental Section of DAD-RA, was arrested. His section was liquidated, with all the projects being transferred to the RDTIC-RA (Research, Development, and Testing Institute of Communications of the Red Army). As a result, the equipment produced at LIPT was released for testing only in August, 1938. The transmitter used the IG-8 tubes, with a pulsed power of 40-50 kW, and a pulse duration of 10 μs. When a test of the radar was carried out in Mytishchi, near Moscow, it demonstrated reliable detection of an SB-type of bomber at distances of up to 55 km and a height of 1500 m.

As admitted by Gen. Lobanov [10], this was a bright success of the pulsed technology. First, it showed that the problem of long-distance radio detection had been solved, in principle, and its further realization required only engineering effort, Secondly, the pulsed-type radar had evident advantages over the CW-mode radar, based on the Doppler frequency usage. After the experiments of Korovin, in January, 1934, and the tests of the first radio-detectors of Shembel, in July, 1934, these tests were a significant milestone in the history of Soviet radar.

In August, 1939, field tests of a mobile version of the radar "Redut" were carried out near Sebastopol, the main Black Sea Navy base, with a receiver and transmitter installed on two automobiles. The Redut system was developed jointly by LIPT, the RDTIC-RA, and the R&D Institute of Radio Industry No. 20 (RDI-20), in Moscow. RDI-20 later became the leading institute in long-range radar development. The tests showed a champion detection range of a flying boat: up to 150 km. The prototype device was designed at RDI-20 in May, 1940. On July 26, by order of the Minister of Defense, this serially produced radar was released to the air defense and named RUS-2. This system was later improved: the transmitter and receiver were integrated with a common antenna, and a radar with a fixed platform and a rotating antenna was designed. During WWII, several modified versions of this radar were produced, for a total amount of 700. However, these devices, as well as all meter-band systems, had a serious drawback: they failed to determine the third coordinate of the airborne target, i.e., the height of flight. Gen. A. Batitsky, Commander of Air-Defense Forces in the 1960s, recalled in his memoirs [54] that for this reason, the radar-surveillance stations were used in close interaction with the visual-observation posts, which determined the altitude and identity of the aircraft. Later on, supplementary height-measuring blocks for the radar stations were designed.

In wartime, however, the most widely used radar of the Army, Navy, and Air Force was not Soviet made. From the beginning, the UK, and then USA allies, agreed to supply the Red Army with modern equipment. Of course, during the first six months of the German advance, there were apparently more urgent needs – like elementary combat communication and control – than deploying and integrating radar surveillance and aiming units. However, according to the SDC decree dated February 10, 1942, a new institute/factory (PO Box 465) started backward engineering of the UK gun-aiming radar GL-MkII. This was done in the shortest possible time. The Soviet designation of the radar was SON-2a. By the SDC decree, dated December 20, 1942, the SON-2a radar was released to the Army. It was produced serially in a total quantity of 124 units during WW II. In addition, starting in 1943, long-range radar equipment was delivered from the UK, the USA, and Canada, via the Lend-Lease program. During the final stage of the war, the combat forces of the Red Army used mainly these systems. It must be admitted, however, that on the Soviet-German front, radar was never a major factor, compared to its role in the Battle of Britain.

5. Development of the Pulsed Radar "Zenit" in Kharkov

From 1937, by decree of the PCD (People's Commissariat of Defense, the defense ministry), the contracts for developing radio-detection equipment service were to be a duty of the Department of Communications of the Red Army (DC-RA), via its RDTIC-RA. Along with the problems associated with long-range surveillance, the RDTIC-RA had initiated a parallel development of a gun-aiming radar. Having studied the state-of-the-art of the preceding developments in CMIRL, RDI-9, and LIPT, the experts of the RDTIC-RA concluded that a duplication of the projects of the PDA-PCD was necessary, but that they should employ the pulsed method.

Beginning in March, 1937, according to a project with a task that was formulated by the RDTIC-RA, the UIPT began the complex work of designing a pulsed electromagnetic gun-aiming "searchlight" (tentative name) at L-band, with a wavelength of 60 to 65 cm. This work, coded "Zenit," was performed under the guidance of A. Slutskin by the staff of LEMO: S. Braude, A. Chubakov, Y. Kopilovich, P. Lelyakov, A. Maidanov, I. Sorkin, I. Truten, A. Usikov, and I. Vigdorchik, who contributed at various stages and to various extents. The following record was found in Usikov's archive [21]:

5.1 Transmitter

The development of the transmitting unit was led by Usikov; Vigdorchik and Lelyakov took part in this work, as well. At first, they studied the features of the pulsed excitation of magnetrons. The results of comprehensive testing of several magnetrons, with different cathodes and anodes, had shown that the performance could be essentially improved. Assembly, adjustment, and the first tests of the Zenit setup were carried out by using an un-cooled packaged magnetron. A modulator was connected in series with the magnetron. It used the standard GK-3000 tubes. A relaxation-generator circuit, exploiting a TG-212 thyratron, was selected as a control device. The following characteristics were obtained for the first variant of the radar (1938):

Pulse power	3 kW
Wavelength	60 cm
Pulse duration	7 to 10 μsec
Magnetron voltage	18.3 kV
Pulse current	20 A
Magnetron lifetime	50 hours

The improved Zenit radar (1940) used a magnetron with the following parameters:

Pulse power	10 to 12 kW
Wavelength	64 cm
Pulse duration	10 to 20 μsec

5. 2 Receiver

The development of the receiving unit was performed by Braude, Kopilovich, Maidanov, and Truten. They had studied and designed a magnetron receiver where a double-anode magnetron was used as a super-regenerative detector. This receiver enabled them to carry out the tests of detecting an aircraft with the first version of the Zenit radar (1938). However, this could not serve as the basis for developing a radar able to meet the requirements of the anti-aircraft artillery, because of the strong dependence of the receiver sensitivity on the magnetic field and the magnetron emission current. Hence, along with this device, the research team had investigated a super-regenerative receiver, based on a triode of the "acorn" type 955. This had a much higher sensitivity, and was implemented in the improved version of Zenit. To enhance the sensitivity of the receiver, Truten developed a superheterodyne receiver with an L-band amplifier (1940).

5.3 Antenna System

The Zenit radar was designed as a two-antenna system. The antennas used identical all-metal parabolic reflectors of 3 m diameter, fed by in-focus half-wave dipoles (Figure 12).

A. Usikov recalled that making the parabolic reflectors required a lot of specific material: a metal with a certain environmental resistance and certain electrical properties. Hence, he came up with the idea that it could be made of galvanized iron. This led him to a necessary but also risky adventure. Somebody in his team noticed that the Institute buildings were equipped with rather impressive rainwater pipes, of about 30 × 30 cm cross section, made of what was needed. One night, all these pipes were taken off, flattened, and used to make reflector segments. Usikov was fined as the initiator of this action [22].

The beamwidth of the amplitude radiation pattern of the antenna was about 16° in the "equatorial plane." As we have mentioned, there is no available technical documentation about Zenit and its antennas. Therefore, these data, together with the terminology, are based on the memories of those who heard it from the designers. Here, one should keep in mind that reflector-antenna theory did not exist in the 1930s, nor did horn feeds. Therefore, the Zenit's performance was probably far from optimal in terms of edge illumination, gain, and sidelobe level. According to today's estimates, done by the numerical method in [55], a five-wavelength dish antenna, fed by a dipole, can provide an 18° (24°) main beam of the amplitude radiation pattern, with sidelobe levels of −7 (−10) dB in the E (H) plane.

5.4 Design

A magnetron source with a stabilizing resonant circuit was located on the back side of the transmitter's reflector, in a hermetically sealed metal case. A two-wire feed, inductively connected with the magnetron circuit, was loaded with a half-wave dipole placed in the focal plane of the paraboloid of revolution. The receiver's reflector was of similar design, with the circuitry located in a hermetically sealed case at the back. Synchronized rotation of the reflectors was achieved by using selsyns.

A. Usikov described this radar as two-reflector laboratory setup, in which the reflectors of the transmitter and receiver were separated about 50 m from each other in order to reduce the jamming of the sensitive receiver by the high-power pulses of the transmitter. Both reflectors rotated in a synchronous manner in the horizontal (0-360°) and vertical (0-90°) planes, thus providing a stable, parallel orientation of the radiation-pattern axes [22].

5.5 Test Results

Preliminary calibrations of the receiver and transmitter were done by Truten and Kopilovich at the 8 km line-of-sight test range between the UIPT hillside compound and the Kharkov Tractor Industry. In the summer of 1938, an experimental electromagnetic "searchlight," Zenit, was assembled. The first tests of aircraft detection were carried out on October 14, 1938. The receiver and transmitter antennas were placed at a distance of 65 m from each other, and the optical axes of their reflectors were fixed to be parallel at an elevation angle of 20°. An SB-type middle-sized bomber flew at a distance of 3 km from the radar, crossing the radiation pattern of the antenna. Under such conditions, a stable effect of reflection of dm waves from the aircraft was observed. As Gen. Lobanov later admitted [10], for a beginning, such a result was quite what should have been expected: it was similar to the first tests at CRL and LEPI, but with different technical parameters for the radar, namely, a different wavelength and different radiation power, and different methods of generation and reception.

The test results enabled the designers to understand what should be done to improve the parameters of Zenit. Satisfied with the work, the CD-RA allocated a new project to LEMO-UPTI in May, 1939. The task was to raise the radiation power, to improve the reliability, and to manufacture a prototype radar, ready for transfer to industry. In less than four months, war started in Europe, accompanied by the Soviet campaigns against Poland, the Baltic States, and Finland. This added to the activation of military-oriented research and development work in the USSR. In September, 1940, a modified Zenit radar was presented to a joint commission of virtually all of the interested customers – the Red Navy, the DAD-RA, the PDA-PCD, the RDTIC-RA, and the RDI-20 – for tests of the detection and coordinate determination of a single aircraft and of a squadron of airplanes.

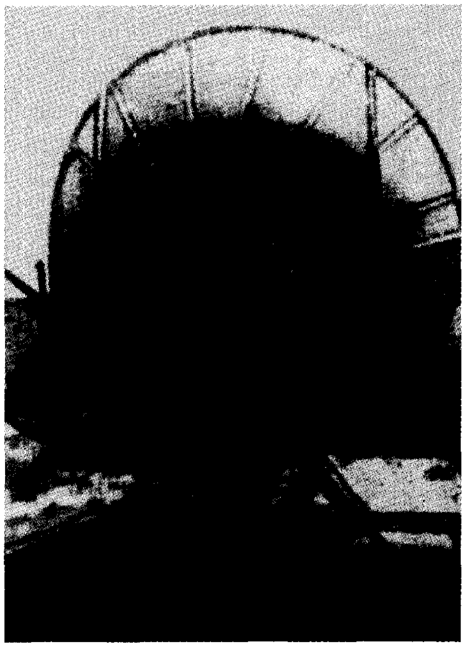


Figure 12a. The back side of the transmitter antenna with a magnetron block for the two-antenna radar "Zenit" (1939-1940).

Figure 12b. The Zenit radar's all-metal reflector, with a dipole feed at the focus

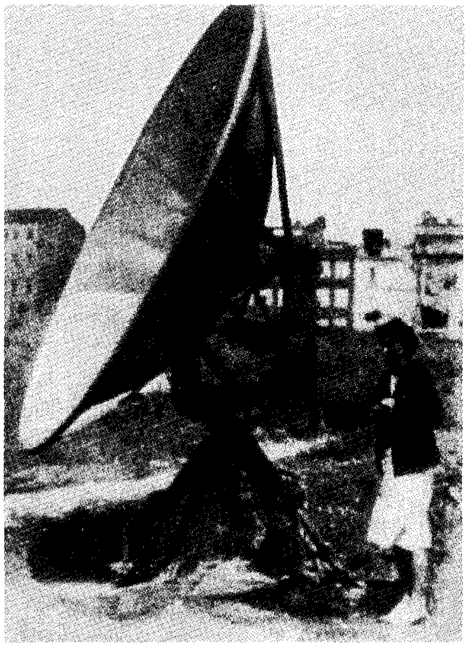


Figure 12c. A general view of the Zenit transmitter antenna.

S. Braude was an eyewitness of this test. He wrote [24] that the mission of a bomber aircraft was to execute several turns on the flight course. First, the aircraft flew away from the radar for 50 km, then turned right, flew 50 km more, then turned back, flew 100 km, and so on, repeating this route six times. During the fifth flight, the pilot turned to the opposite side, as he did not take the experiments seriously, and hoped that this deviation, in the clouds, would escape detection. He was deeply impressed that his unplanned maneuver was recorded at the ground base-station. From that moment on, he became an active zealot of radar. Later, when the war with the Nazis started, this pilot played an important role in the fate of the Zenit project.

The results of the tests of the Zenit radar, in 1940, according to the commission's final report, were as follows [21]:

1. The device could locate the coordinates of a single aircraft at various heights. The tests confirmed locating an aircraft at heights of from 2000 to 5000 m.

2. A comparison of the target heights found by the Zenit radar with the barograph indications revealed an average error in the height determination of 8.9% in the first test, and 5.2% in the second one.

3. At heights of from 4000 to 7000 m, a target was reliably located at a distance to the radar of between 6 and 25 km; at a distance of between 25 to 35 km, the detection was unreliable.

4. The time required to determine the target coordinates was as follows:

Elevation and distance	13 sec
Azimuth and distance	17 sec
Elevation, azimuth, and distance	38 sec

5. A squadron of aircraft could be detected reliably at heights of 3000 and 4000 m in the specified space sector.

6. If a squadron was flying in tight order, the oscilloscope indicated the beating of the pulses reflected from each aircraft. If one of the airplanes was behind the others, one could observe the variation of the width of the maximum corresponding to the reflected signals.

7. If a squadron was flying in a column, with the airplanes separated by 2 km, the oscilloscope screen clearly indicated the pulses reflected from each individual aircraft, in the form of isolated maxima. If the distance to the airplanes was less than 15 km while the separation between the airplanes was more than 3 km, then two airplanes could not be seen on the screen simultaneously. In this case, each separate airplane had to be tracked independently by changing the azimuth.

8. The current design and location of the radar did not permit continuous tracking of an airplane flying a zigzag route in a sector of 60° at a distance up to 30 km. The course could be determined when the airplane was flying towards the radar, or, oppositely, away from it. Other courses could be determined, provided that the performance of the radar was more reliable.

Estimating the overall performance of Zenit, the commission noted that the first Soviet laboratory device had been designed at UIPT that enabled one to locate a flying airplane in three coordinates (distance, azimuth, and elevation). As Gen. Lobanov wrote [10], this was a great success for the young research team of UIPT. In comparison with the experimental radio-searcher Burya, developed at RDI-9, Zenit had substantial advantages in its detection range and its ability to determine all three coordinates of the target.

At the same time, the commission noted some serious drawbacks of the system. The most important of these were slow and inaccurate determination of the angular coordinates, difficulty in locating the target (caused by a narrow radiation pattern), and the presence of a dead zone within which gun aiming was not possible. However, here it should be noted that the project did not suppose a continuous location mode, i.e., continuous determination of the target's angular coordinates and their continuous transmission to a gun-fire-control device. There was also no requirement in the project about the absence of a dead zone for anti-aircraft gun aiming [12]. The commission concluded that the main points for the improvement of Zenit were the design a single-antenna radar, and the development of a technique for continuous location to provide continuous feeding of the gun-fire-control device.

The military, whose leading expert was Gen. Lobanov, admitted that at UIPT a group of able young scientists succeeded in the theoretical calculations and experiments necessary for developing a laboratory version of the Zenit pulse radar. However, having limited funds and production capacity, the Institute met with considerable difficulty in manufacturing this device. The fact that UIPT had managed to produce the radar on its own, without any external support, was credited to the efforts and enthusiasm of the team in solving this urgent and complicated defense problem [10].

Here, we have to make a comment, which was never found in the previous Soviet publications on radar history but is well known to all who worked at UIPT or were acquainted with the staff. Along with the mentioned technical problems, the working conditions at LEMO were certainly handicapped by the general atmosphere at UIPT during the years of Stalin's terror, in 1935-1938. At that time (see [27] for details), UIPT, a leading research center, was literally smashed by a series of severe repressions, with Landau being the main target.

S. Braude recalled that LEMO was one of a handful of research groups at UIPT able to keep their scientific activity. United by a common goal, Slutskin's people kept perfectly friendly relations, despite sharp discussions [24]. This was obviously very important: even the views of Lelyakov remained secret outside of LEMO. However, the climate in the Institute was not favorable for healthy working conditions. Braude stated:

> Some of the UIPT scientists were arrested; others were interrogated; frequent political meetings of the [Communist] party, trade union and Komsomol brought fear and embarrassment in the collective. In addition, some of the leading scientists, first of all theoreticians, displayed a neglect towards the radio-physics research, considering it a second-rate physics. The gap became even deeper when UIPT started working on defense projects, which dominated in R&D carried out by LEMO.

In fact, according to an analysis by Ukrainian historians of science Y. Pavlenko, Y. Ranyuk, and Y. Khramov, the latter point was at the very core of the conflict at UIPT. They wrote [27] that the main reason for the conflict at UIPT was that from the moment UIPT started defense-oriented research, the scientific leaders (i.e., the principal scientists of the Institute), who determined the science policy and headed the scientific activities, were put aside. Why this happened is not clear. It could be that they refused to participate in these military projects of their own will, feeling that this would inevitably limit the freedom of research. It was also possible that they were not allowed by the then-Director of the institute, or by the Principal Political Department [in Russian, this reads as "GPU," the then-current name of the NKVD/KGB]. In the meantime, military projects had preference, and the scientists involved were paid greater salaries. This resulted in splitting the Institute into two warring fractions, each of them having its sympathizers beyond the Institute.

According to Ranyuk [56], part of the UIPT scientists, including Landau, proposed to separate LEMO from the Institute. In fact, further developments proved that this could have been the best solution. The matter was that in the atmosphere of a search for enemies in the 1930s, this internal conflict was actively exploited by the NKVD. Fortunately for LEMO, work on the radar project played the role of a protective shield, thus allowing them to study the fundamental microwave problems, as well. It can be added that this was always a common practice: in the early 1950s, the leaders of Soviet physics successfully used nuclear programs to save the theory of relativity and quantum mechanics from the Stalinist ideological mobsters (the less fortunate fields of genetics and computer science were crushed) [57]. In our story of the Kharkov radar, it is important that the undisputed scientific leader of UIPT, Lev Landau – being a bright personality – did not stay away from the internal conflict. Both the insiders [56] and the NKVD informers – whose observations were summarized in the voluminous file on Landau in the KGB [58] – agreed that his attitude toward the radar project at LEMO and toward Slutskin was negative. Although this was his general attitude toward the military research in the USSR throughout all of his life, he later never expressed it openly [58]. He had reasons for this. It was only his worldwide fame that saved him in 1937, when the NKVD pointed to him as a leader of the "Trotskist-sabotage group of Rozenkevich and others" accused of "trying to spoil defense works in UIPT" [27]. Landau then escaped to Moscow, to work in the Institute of Physical Problems of Ac. P. Kapitsa. However, he was arrested in 1938, and spent one year in the NKVD jail before being saved, both for science and life, due to the extraordinary efforts of Kapitsa (who personally appealed to Stalin). Later, along with many other Soviet scientists, he himself

УПРАВЛЕНИЕ
ЗОНЫ ПВО
ХАРЬКОВСКОГО
ВОЕННОГО ОКРУГА
15.9. 1941 г.
№ 234
г. Харьков

СПРАВКА

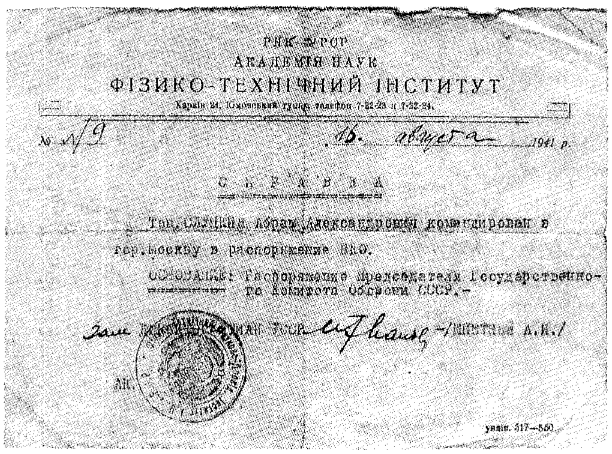
Тов. Слуцкин А.
командирован в гор. Москву в рас...
...ения НКО для участия в ...

ОСНОВАНИЕ: Распоряжение Пред...
...теля Государственного
Комитета Обороны СССР.

... до 15.10.41 г.

НАЧАЛЬНИК ШТАБА ЗОНЫ
ПВО Х.В.О.
КАПИТАН /...

Figure 13a. One of the official mission certificates of A. Slutskin, used in August, 1941, for traveling to Moscow and testing the Zenit radar in the combat zone. This was issued by the air defense commander of the Kharkov region.



РНК УРСР
АКАДЕМІЯ НАУК
ФІЗИКО-ТЕХНІЧНИЙ ІНСТИТУТ
Харків 24, Чюгуївський тупик, телефон 7-22-23 і 7-22-24.

№ 19 16. августа 1941 р.

СПРАВКА

Тов. Слуцкин Абрам Александрович командирован в гор. Москву в распоряжение НКО.

ОСНОВАНИЕ: Распоряжение Председателя Государственного Комитета Обороны СССР.-

Зам. ... /Шестин А.Н./

уповн. 517—550

Figure 13b. A second official mission certificate of A. Slutskin, used in August, 1941, for traveling to Moscow and testing the Zenit radar in the combat zone, issued by the UIPT administration.

used military nuclear-program research as a shield against the persecutions of "Big Brother" [57].

In 1939-1940, the situation inside UIPT became somewhat more favorable for LEMO. The work schedule of the laboratory for 1941 foresaw solving the problems around the improvement of Zenit and the development of a single-reflector radar, "Rubin."

But the start of the war destroyed these plans. As is now well known, Moscow experienced its first air raid on the night of July 22, 1941. Soon, the city was protected with three lines of anti-aircraft defense, and the CD-RA offered to let the regional command in Moscow test the efficiency of the Zenit radar in combat anti-aircraft defense. Even before, at the very beginning of the war, the pilot who took part in the 1938 tests of Zenit in Kharkov wrote a letter to Stalin, and urged him to deploy this promising detection system. On August 16, the LEMO staff members S. Braude, A. Chubakov, L. Kitaevsky, Y. Kopilovich, A. Maidanov, A. Slutskin, A. Terpilo, I. Truten, A. Usikov, and I. Vigdorchik were sent to Moscow, and attached to the RDTIC-RA. They brought the experimental Zenit radar, which was installed in the town of Mytishchi, into combat service. The radar was connected directly with the command post for air defense in Moscow. The certificates given to A. Slutskin in his mission to Moscow for testing the radar are shown in Figure 13. They played the role of ID's, guaranteeing a safe passage to Moscow.

Braude told the following story about the work in Mytischi [24]. A number of soldiers were assigned to the radar team. The moral atmosphere at the beginning was full of tension. Actually, at that time, very few people had even a basic understanding of radio detection, and a group of healthy men staying in the rear were commonly considered to be escaping from military service. The situation changed when the team succeed in detecting – by radar – that during a raid on Moscow, one of the German bombers left the flight order and made a loop to the east. Thanks to a report to the air-defense command post, this bomber was shot down by the anti-aircraft artillery.

In September, 1941, after additional tests, a commission, headed by the deputy commander of the air-defense corps, reported [21]:

• The station could not detect near-flying aircraft within a range up to 15 km, because of reflections from local objects;

• The detection range was 60 km at flight heights above 5000 m;

• The mean location error was 2.5° in azimuth, and not more than 1.5 km in height.

The tests demonstrated that after improving the radar, the detection range increased by a factor of two, but the dead zone also increased by more than twice. The commission noted that the present Zenit radar could not be employed for precise aiming and tracking of anti-aircraft artillery, but its accuracy was sufficient for barrage fire. Besides, this station could be used for the guidance of fighter aircraft, as supplementary equipment to the RUS-2 surveillance radar. Further modifications could be developed only under laboratory conditions. However, such work was not possible, at that time, either in Moscow nor in Kharkov. Because of the evacuation of the RDTIC-RA to Bukhara, on October 17, 1941, the Zenit radar and the whole LEMO team were dispatched there.

In the meantime, UIPT itself was already on the way to central Asia. As is known, in the summer of 1941, the situation on the Soviet-German front developed dramatically. In the first days, the cities of Riga and Minsk were lost, and soon the German tank armies were threatening Moscow. The more-successful defense of the elite Soviet troops in the Kiev direction put a serious strategic problem before the German commanders. On August 23, 1941, at a meeting in the headquarters of the "Center" group of armies, Hitler rejected a proposal by Gen. Guderian to concentrate all the forces for an offensive on Moscow, and decided to attack East Ukraine from the north. According to one interpretation, Hitler's words at this meeting were, "Kharkov is more important for me than Moscow." As is known, this led to the annihilation of the strongest divisions of the Red Army between Kiev and Kharkov, but gave the USSR the time needed to bring fresh forces from Siberia, and to defend Moscow. For our story, it is important that according to the plans of Hitler, Kharkov happened to be in the mainstream of the new offensive. After the fall of Kiev, at the end of September, the fate of Kharkov was determined, and on October 24, the Red Army left it. However, much earlier, in July, 1941, the State Defense Committee (a small group of leaders around Stalin) decided to evacuate the heavy industries of Kharkov to the East. UIPT was not an industry, but it was still considered a valuable organization, and had to be evacuated, as well.

6. Development of the Single-Antenna Radar "Rubin" and Observation of an Atmospheric-Duct Effect in Bukhara

In 1939-1940, along with designing the Zenit radar, LEMO-UIPT performed three research and development projects for the CD-RA: "Generator and Receiver Operating in the cm-Band," "Application of the Independent Excitation Principle for Generating Frequency-Stable dm-Band Pulses," and "Design of a High-Power Pulse Source of the dm-Band Stabilized by a Resonant Circuit" [10]. The results of these studies, as well as the experience accumulated in the work on Zenit, enabled LEMO to proceed to the design of the "Rubin" radar in 1941, again by a contract via the RDTIC-RA. This system had to be improved in terms of the range of target detection and the accuracy of its coordinate location, and it had to be designed with a single, common antenna. However, as we have mentioned, the disastrous and rapid approach of the front line forced UIPT to stop work as early as July, 1941, and to pack the equipment for a long trip. The final destination for the UIPT was Alma-Ata [now Almaty, Kazakhstan]. However, LEMO had a different destination. Several railway trains, moving slowly from Kharkov and Moscow to the east – in the mess of the overall evacuation in the fall of 1941 – headed to the sunny and sleepy twenty-centuries-old city of Bukhara, over 3500 km away, and 1500 km from Alma-Ata. Located in the heart of Central Asia, Bukhara had a glorious past, as certified by its gorgeous mosques and majestic Emir's Palace. Before 1920, it had been the capital of the Emirate of Bukhara, a multi-national Moslem country that fell under the Russian protectorate in the 1870s. However, during the civil war, the Red Army stormed the city, the Emir was forced to abdicate, and the territory was divided among the Soviet republics of Tadjikistan, Uzbekistan, and Kyrgyzstan. Since then, Bukhara was obliterated to a small provincial town.

Thus, in fact, what was proposed by "pure physicists," purged in 1937, was done by the war: the radio-physics laboratories of UIPT were separated from the other departments. After WWII, UIPT returned to Kharkov, and all its laboratories were again working together. Here, the history took a curious twist: in the 1940s and 1950s, the Institute was a major research and development organization behind the NKVD-managed nuclear project code-named "Lab No 1." At that time, all the departments of the UIPT were enjoying the benefits of working on extremely important defense topics, except for two radio-physics departments (the former LEMO, headed by Slutskin, and the new Department of Radio-Wave Propagation, headed by Braude). Obviously, to avoid new conflicts and also due to a rising interest in developing mm-wave plasma-diagnostics technologies for Tokamak fusion machines, it was decided to separate these departments from UIPT, and to establish a new institute, the IRE (Institute of Radio-Physics and Electronics). It is worth noting that Slutskin was against this separation, which was approved only after his death.

In 1942, the work on the Rubin project was resumed in Bukhara, in collaboration with the RDTIC-RA, which was also evacuated to there (Figure 14). The scientists of RDTIC-RA, M. Kulikov, K. Motorin and N. Nechayev, actively participated in this work. By that time, LEMO had lost some of its leading staff members, including Lelyakov, who remained in Kharkov. Instead, L. Kitayevsky joined the project as a radio engineer.

Figure 14. A. Usikov (first from the left in the second row), L. Kitayevsky (fourth from the left in the second row), A. Terpilo (first from the right in the first row), and unidentified staff members of RDTIC-RA in Bukhara on February 23, 1942, at the time of the development of the "Rubin" radar. The domes and minarets of the famous Bukhara mosques are visible in the background.

In order to eliminate drawbacks found during the tests of the Zenit device, the causes of the errors due to the direction-finding technique selected (a null-reading method) were analyzed, and several methods of continuous detection were considered. As a result, a continuous-location scheme, utilizing the stationary-dipole method, was selected; its implementation and accuracy were tested; and the key blocks were finalized. However, the lack of necessary industrial capacity (radar was then produced in Tashkent) resulted in a failure to apply the new scheme for target location.

The receiver and transmitter circuits of the Rubin radar were similar to those of the Zenit. However, to increase the power and stability of the source, and to raise the sensitivity of the receiver, some corrections and changes were introduced into the design. The pulsed power of the magnetron was increased up to 15 kW. The improved receiver was essentially a wide-band superheterodyne, with double frequency transformation, and had a high-frequency block (an L-band amplifier, the first mixer, and the first heterodyne) and an intermediate-frequency amplifier, all placed in a hermetically sealed case on the back of the antenna reflector. The power-supply unit, the remote-adjustment blocks, and the amplifier control console were located in an automobile. The heterodyne wave-meter for controlling the source frequency was also placed there. While developing the Rubin radar, Truten had succeeded in solving the extremely "hot" problem of protecting the receiver from the impact of a high-power source pulse, by employing a gas discharger. This blocked the input of the receiver circuit when a high-powered pulse arrived. As an additional measure, blocking of the intermediate-frequency amplifier's first cascade was foreseen.

The antenna of Rubin was designed as a grid paraboloid of revolution, 3 m across, with transmitter and receiver dipoles located at the focus (Figure 15). The dish was deployable, and consisted of six removable segments, made from 2-mm diameter wire. As recalled by Usikov [22], the wind loading was incredible for such large-size reflectors. Hence, it was clearly necessary to resort to a grid-antenna design. These were made from wires stretched on the ribs, and soldered with a spacing of 20 × 20 mm. All this was handmade by the team members.

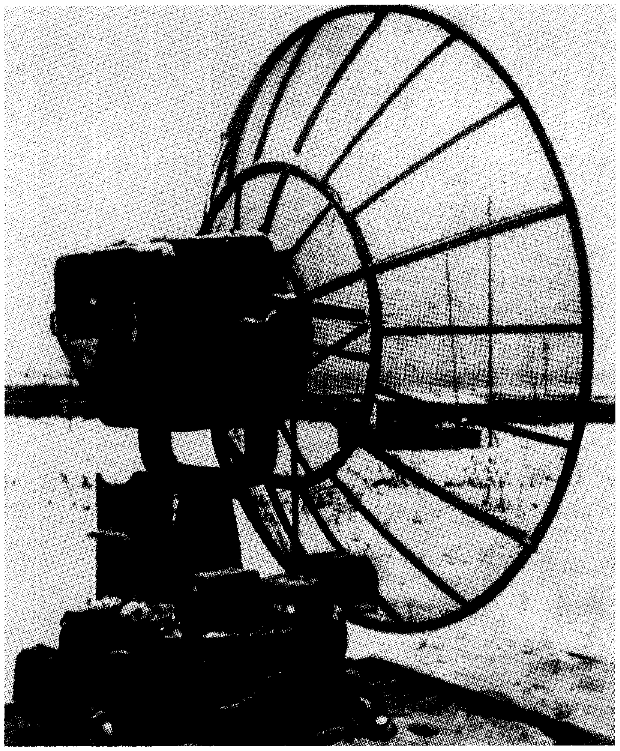


Figure 15a. A gridded paraboloidal reflector with in-focus transmitter and receiver dipoles for the Rubin single-antenna radar (1943).

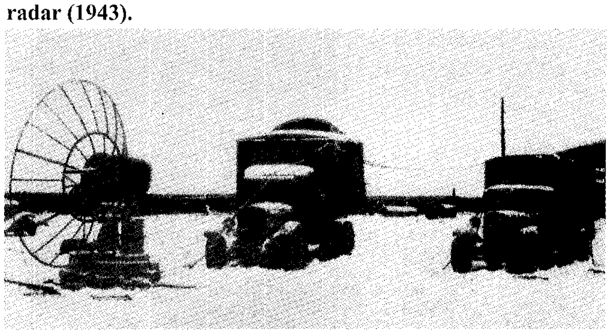


Figure 15b. The fully deployed Rubin radar system.

The main beamwidth of the radiation pattern (at the half-amplitude point) was 16° in the "equatorial plane" and 24° in the "meridian plane." The magnetron source, with a resonant circuit, and the receiver circuit were encased in a hermetically sealed case on the back of the reflector. Rotation of the antenna in the vertical (0-90°) and horizontal (0-400°) planes was remotely controlled.

The whole Rubin equipment was placed on two cars: one for the power supply (a ZIS-6 truck), and one for the electronics (a GAZ-3A truck). On the first car, the antenna system was installed on special rails. When the radar was deployed at a combat position, it was rolled out. A control console and a power-generating unit were also placed there, consisting of a three-phase generator (PNT-100) and a petrol engine (L-12). The modulation and oscilloscope blocks of the radar, and an antenna remote-control system, were located on the electronics vehicle. The deployment and setting-up of the Rubin radar took about three hours.

It was there, in Bukhara, that the LEMO scientists met a mysterious phenomenon, never before reported. The following is its description by Usikov [22].

At the moment when the assembly and testing of the new radar were under way, a specific, never-before-observed effect of intensive repeated jamming disrupted all the work. It occurred in the form of unusually strong reflections from local objects, at all distances within a range of up to 180 km. This was a sort of radar "blinding," which suppressed the radar signals reflected from an aircraft, and from local objects serving as benchmarks. Powerful jamming reflections were observed in May-July 1942 by Usikov, Truten, and Vigdorchik. Reflections occurred at different times, usually in the afternoon, and their origin was hard to locate. Scanning the antenna beam within the spatial sector of 90° in azimuth and 70° in elevation was practically useless. Often, these difficulties forced cancellation of the planned tests.

Since this phenomenon had never been observed in either Kharkov or in Moscow, Usikov and his team called it "the Bukhara effect." They guessed that its nature could be explained by specific climatic conditions characteristic for the sandy desert terrain around Bukhara. More specifically, they came to the conclusion that the Bukhara effect was caused by a drastic decrease of the natural attenuation of decimeter waves propagating over the Kyzyl-Kum and Kara-Kum deserts. This enabled one to observe strong radar reflections from local objects situated all the way to the Aktau Mountains, 150-180 km to the northeast from Bukhara. A failure to locate these objects (i.e., the impossibility of avoiding the reflections by rotating the radar) was attributed to the multi-lobe structure of the radiation pattern [17, 22].

Here we remind the reader that the first, classical description of the surface-duct effect was given in 1946 [59]. Within the duct, the field propagates as a cylindrical wave, instead of as a free-space spherical wave, although other propagation mechanisms may also contribute. As a result, the maximum radar range under ducting conditions may exceed the free-space radar range by a factor of 15 or more [60], with the long-distance record being 1700 miles, between India and Arabia [61]. However, we must admit that we have failed to find any published study of a ducting effect in the desert.

In 1943, Rubin was transported to Moscow, where it was tested until November. As the situation near Moscow remained complicated, in early 1944 – by agreement with the Red Navy Command – the DC-RA sent the radar to a polar port and naval base in Murmansk. From February 1 until March 31, 1944, the tests of the radar were performed there, led by Usikov. The place for the deployment of the radar, selected by the Command of the North Fleet, was at the Kolsky Bay coast in the Vayenga Fiord. There, the maximum width of the fiord was 4750 m. The bay offered a variety of testing opportunities, due to intensive sea traffic: Soviet and foreign navy ships and convoys frequently used Murmansk as the single non-freezing port in the Soviet Arctic. The following are the data found in Usikov's archive [22].

6.1 Aircraft Location Tests

The target-location tests consisted mainly of observation of occasional aircraft. For checking the accuracy of location, a Hurricane fighter once made a special flight along a fixed route. The aircraft, flying above the sea, was first detected at a distance of 60 km. Its location within a range of 40 km was reliable. In the tests, they repeatedly detected the aircraft flying at very low heights above the sea, 30 to 50 m. The mean errors in the accuracy of determining the coordinates were as follows:

In distance:	not more than 120 m;
In azimuth and elevation:	not more than 0.8°.

The time required for measuring each of the angular coordinates by the null-reading technique never exceeded seven seconds.

6.2 Ship Location Tests

It should be noted that the terrain (a rather small, open space, and a rocky coast 5 km away from the radar) considerably complicated the testing. Despite this, the tests demonstrated that:

Rubin enabled one to detect ships of all types – cruisers, freighters, destroyers, surfaced submarines, motor speedboats, and wooden boats – at distances from 500 m out to the limiting accessible range, i.e., about 5000 m;

The amplitude of the reflected signal depended on the type and the size of the ship;

The amplitudes of reflected signals were not stable and varied in time, with the oscillation frequency depending on the size of the ship and its speed;

The mean errors in the accuracy of determining the target's coordinates were not more than 120 m in distance and 0.8° in azimuth.

Usikov had always been proud of this achievement, and claimed that his team obtained the best results in radar in the USSR for that time. Until the end of the war, Rubin was employed in the polar sector of the Soviet-German front for air and naval surveillance.

7. Conclusions

Thus, in 1938, the first USSR laboratory pulsed L-band radar, able to locate a flying aircraft in all three coordinates, i.e., in distance, azimuth, and elevation, was developed at UIPT. The concept of this radar was well ahead of all of the contemporary trends in the development of radar in the UK, the USA, and the USSR. However, for many reasons, serial production of this radar was hindered. The reasons that prevented implementation of the Zenit radar as an industrial prototype were summarized in a letter dated April 26, 1948, and addressed by A. Usikov to the State Committee on Radar of the Council of Ministers of USSR [12]:

> The first success of UIPT led to a sharp and erroneous change in its work. Instead of undertaking further physical investigations, necessary for solving fundamental problems around developing a radar able to meet the exploitation demands, the customer, CD-RA, insisted on developing an industrial prototype of the radar by the efforts of the UIPT laboratory. Here, one should note that the customer requirements for the radar's performance did not foresee a continuous location mode, i.e., continuous determination of the target's angular coordinates and their feeding to the gun's fire-control device. Besides, there was no requirement [in the project task] concerning the absence of the gunfire dead zone. All this considerably devalued the results obtained at UIPT.

The work schedule of UIPT for 1941 foresaw solving these problems. However, the unexpected defeat of the Red Army in the border fighting, and the almost complete loss of Ukraine disrupted the realization of this goal. Further development and manufacturing of the modified Rubin radar was done, in cooperation with the RDTIC-RA in Bukhara. As a result, the dead zone was reduced, a single-antenna radar was designed, a proper technique of continuous location was elaborated, and the experimental testing of the radar's accuracy was performed. It was only a lack of industrial facilities in Central Asia that prevented implementing the new location technique, and the previous one was kept. This led the DAD-PCD to the conclusion that, despite a quite satisfactory performance of the radar in terms of range and accuracy, it was not suitable for integration with a gun's fire-control device.

Besides this, the decision not to start the serial production of Rubin was apparently influenced by the ambitions of the Moscow-based laboratories, and the conservative thinking of the military. From their point of view, it was senseless to use the dm band, when the GL-MkII stations in the UK and the SCR-268 stations in the USA, operating in the meter band, had already been designed and produced. Finally, the wartime circumstances dictated their own requirements, and so a UK-designed gun-aiming radar, the GL-MkII, was re-engineered in 1942, and put into serial production under the name SON-2a. This was done at the time when the small team of LEMO-UIPT was still struggling to develop Rubin under the very hard working conditions of Central Asia, without any serious support. Hence, it is no surprise that Rubin lost this competition, at that moment.

Nevertheless, the work on this radar was of great importance, both for the general development of radar science and microwave engineering, and for progress in forming the Kharkov radio-physics community. The experience in designing a pulsed radar enabled A. Usikov to develop a radio-sounding device for the remote location of the place and nature of the faults in high-voltage transmission lines (1944), and a device for performing diagnostics of subsurface power cables (1946). These devices were widely used in repairing the electric-power networks destroyed during the war, in Kharkov and other USSR cities, and in the arctic regions. Radar experiments had shown the necessity of large-scale radio-wave propagation research. This was performed by S. Braude and his colleagues in the 1940s and 1950s. Further magnetron studies, carried out by the team headed by I. Truten, resulted in designing a series of mm-wavelength-band magnetrons, with champion characteristics. These men and their teams later became the core of the IRE, which was established in 1955.

8. Acknowledgements

We are pleased to express our deep thanks to Ac. Semion Braude for his interest, detailed reminiscences, and useful discussions; to Alexandr Slutskin, Vera Truten, and Lazar Kitayevsky for their kind permission to use family archives; to Prof. Yury Ranyuk for the interesting information from his studies; to Aleksandr Kirichenko and Viktor Lapty for the useful citations from their private talks with A. Usikov; and to the IRE Director, Prof. Vladimir Yakovenko, for his encouragement and permission to use the IRE archives. The second author thanks Universite de Rennes 1, Rennes, France, for its hospitality when preparing this material for publication. This work was supported by the IEEE Life Member Committee and by the IEEE Antennas and Propagation Society; this support is acknowledged with gratitude.

9. References

1. R. B. Colton, “Radar in the US Army,” *Proceedings of the IRE*, no 1, 1945.

2. W. C. Tinus, W. H. C. Higgins, “Early Fire-Control Radar for Naval Vessels,” *The Bell System Technical Journal*, **25**, 1, 1946, pp. 1-48.

3. D. G. Funk, *Radar Engineering*, New York, McGraw-Hill, 1947.

4. *Ground-Based American and English Radar Stations (short descriptions)*, Moscow, Voyenizdat, 1947 (in Russian, translated from unidentified sources).

5. M. M. Lobanov, “On Emergence and Development of National Radar,” *Voyenno-Istorichesky Zhurnal (J. Military History)*, no 8, 1962, pp. 13-29 (in Russian).

6. P. K. Oshchepkov, *Life and Dream: Notes of Engineer, Inventor, Designer and Scientist*, Moscow, Moskovsky Rabochy, 1965 (in Russian).

7. M. M. Lobanov, *From the Past of Radar*, Moscow, Voyenizdat, 1969 (in Russian).

8. P. Y. Khoroshilov, *So It Started*, Moscow, Voyenizdat, 1970 (in Russian).

9. Y. B. Kobzarev, “The First Soviet Pulse Radar,” *Radiotekhnika*, **29**, 5, 1974, pp. 2-6 (in Russian).

10. M. M. Lobanov, *The Beginning of Soviet Radar*, Moscow, Sov. Radio, 1975 (in Russian).

11. B. K. Shembel, *At the Origin of Radar in USSR*, Moscow, Sov. Radio, 1977 (in Russian).

12. M. M. Lobanov, *Development of Soviet Radar Technologies*, Moscow, Voyenizdat, 1982 (in Russian).

13. Y. B. Kobzarev, “On the History of Development of the First Radar, *Radiotekhnika*, **53**, 10, 1988, pp. 11-17 (in Russian).

14. G. Sato, “A Secret Story about the Yagi Antenna,” *IEEE Antennas and Propagation Magazine*, **33**, 3, 1991, pp. 7-18.

15. R. S. Unwin, “The Development of Radar in New Zealand in World War II,” *IEEE Antennas and Propagation Magazine*, **34**, 3, 1992, pp. 31-39.

16. A. Y. Usikov, *Modern Achievements in Radio-Physics and Electronics*, Kiev, Znanie, 1981 (in Russian).

17. A. Y. Usikov, “Works in Radio-Engineering, Radio-Physics, Electronics and Communications in Ukraine in the Past 60 Years,” *Radiotekhnika (Kharkov)*, no 12, 1982, pp. 5-14 (in Russian).

18. A. Y. Usikov, *Moments of Life*, Kiev, Mystetstvo, 1990 (in Russian).

19. A. Y. Usikov (1904-1995) graduated from the Physics Department of KSU in 1928, and started working in LEMO-UIPT in 1932. He obtained his PhD and DSc degrees in 1936 and 1964 in Physics, the latter one without a thesis. In 1958, he was elected a Corresponding Member and, in 1964, an Academician of the USSR Academy of Sciences. From 1950 on, he was the head of the Radio-Physics Department of UIPT. From 1953 on, he served as a Vice-Director of UIPT in science. From 1955 on, his career was with the IRE: as Director (1955-1973), head of the department (until 1987), Administration Adviser (until 1992), and eventually a Life Honorary Director. He was awarded the title of Honored Scientist of Ukraine, and won the Lenin Prize (1960) and the Ukrainian National Prize (1981) as a team member. The IRE has been named after A. Y. Usikov since 1995.

20. G. S. Mikhailov (ed.), *Alexandr Y. Usikov*, Kiev, Naukova Dumka, 1984 (in Russian).

21. A. Y. Usikov, Draft Memo on “Zenit” and “Rubin” Radars, IRE Archive, Kharkov, circa 1944 (in Russian).

22. Interview of A. Usikov, January, 1994, recorded by V. Lapty.

23. S. Y. Braude was born in 1911 in Poltava. In 1932, he graduated from the Physics Department of KSU. As a student, he got involved in scientific work in UIPT, where he had worked in LEMO since 1933. He obtained his PhD degree in 1937, his DSc degree in 1943, and was given the title of Professor in 1944. In 1958, he was elected a Corresponding Member, and in 1969, an Academician. From 1943 on, he headed a laboratory, and from 1947, a department, at UIPT. For 1955-1980, he was a Vice-Director of IRE. After the Institute of Radio-Astronomy branched off from IRE, in 1983, he became an Administration Adviser there. He was a USSR State Prize (1952) and Ukrainian National Prize winner (1997), and was awarded a title of Honored Scientist of Ukraine and the A. S. Popov Gold Medal of the USSR Academy of Sciences. His most significant results were associated with fundamental analysis of the magnetron-excitation mechanisms, pioneering investigations of electromagnetic-wave propagation along the Earth's surface, and the design of the world's largest decameter-band radio telescope, the UTR-2.

24. Interview of S. Braude, November, 1998, recorded by A. Kostenko.

25. Y. M. Bruk (ed.), *Semion Y. Braude*, Kiev, Naukova Dumka, 1981 (in Russian).

26. Y. A. Khramov, *History of Formation and Development of Physical Schools in Ukraine*, Kiev, Feniks, 1991 (in Russian).

27. Y. V. Pavlenko, Y. N. Ranyuk, Y. A. Khramov, *The Case of UIPT*, Kiev, Feniks, 1998 (in Russian).

28. D. A. Rozhansky (1882-1936) graduated from the Physics-Mathematics Department of the St. Petersburg University in 1904. After that, he worked in the Physics Department of the Electro-Technical Institute, headed by A. S. Popov. In 1905-1906, he studied in Gettinghen at N. T. Simon, where he defended a master's thesis in 1911. On returning and until 1922, he worked at KSU, first as a Docent and, from 1912 on, as a Professor. From 1914 until 1921, he was the head of the Department of Physics. In 1922-1923, he worked at the Nizhni Novgorod Radio Laboratory, and, after moving to Leningrad (1923), at CRL. From 1925 on, he worked at LIPT, where he initiated a special laboratory on the radar detection of aircraft with meter-band waves, using the pulsed method. In 1933, he was elected a Corresponding Member of the USSR Academy of Sciences.

29. Y. B. Kobzarev, L. A. Sena, V. M. Tuchkevich, Dmitry A. Rozhansky, *Uspekhi Fizicheskikh Nauk (Progress in Physics)*, **138**, 4, 1982, pp. 675-678 (in Russian).

30. V. Y. Frenkel (ed.), *Physics about Themselves*, Leningrad, Nauka, 1990 (in Russian).

31. V. K. Tkach, Abram A. Slutskin, *Trudy Fizicheskogo Otdeleniya Fiz-Mat Fakulteta HGU (Proc. of Physics Div. of Physico-Math. Dept. of KSU)*, no 4, 1953, pp. 17-22 (in Russian).

32. A. W. Hull, "The Effect of a Uniform Magnetic Field on the Motion of Electrons Between Coaxial Cylinders," *Physical Review*, **18**, pp. 31-57, 1921.

33. A. W. Hull, "The Magnetron," *AIEE Journal*, **49**, 9, 1921, pp. 715-723.

34. A. Zachek, "Uber Eine Methode zur Erzeugung von Sehr Kurzen Elektromagnetschen Wellen," *Casopis pro Pest. Math. a Fyz. (Prague)*, **53**, 1924, p. 378.

35. E. Habann, "Eine Neue Generatore," *Zeitshrift fur Hochfrequentztechnik*, **24**, 1924, pp. 115-120.

36. Dmitry S. Shteinberg (1888-1934) worked as an assistant in the Physics Department of KSU, where he held the Chair of Magnetic Measurements since 1931. From 1929 on, he also worked at LEMO-UIPT. Besides the radio-physics research, his fields of interest included magnetic phenomena and solid-state physics.

37. A. A. Slutskin, D. S. Shteinberg, "Obtaining the Oscillations in Cathode Tubes with the Aid of Magnetic Field," *Zhurnal Russkogo Fiziko-Khimicheskogo Obshchestva (J. of Russian Physico-Chemical Soc.)*, **58**, 2, 1926, pp. 395-407 (in Russian).

38. A. A. Slutskin, D. S. Shteinberg, "Electronic Oscillations in Two-Electrode Tubes," *Ukrainski Fizychni Zapysky (Ukrainian J. of Physics)*, **1**, 2, 1927, pp. 22-27 (in Ukrainian).

39. TsGAOR (The October Revolution Central State Archive), fond 166, opis 2, delo 1212, pp. 5454-559 (in Russian).

40. H. Yagi, "Beam Transmission of Ultra-Short Waves," *Proceedings of the IRE*, **16**, 6, 1928, pp. 715-741.

41. K. Okabe, "On the Short-Wave Limit of Magnetron Oscillations," *Proceedings of the IRE*, **17**, 4, 1929, pp. 652-659.

42. A. A. Abrikosov, *Academician L. D. Landau. Brief Biography and Review of Publications*, Moscow, Nauka, 1965 (in Russian).

43. P. L. Kapitsa, *Experiment, Theory, Practice*, Moscow, Nauka, 1987 (in Russian).

44. Lev V. Rozenkevich (1905-1937) worked at LIPT in 1927-1930, and then moved to Kharkov and worked at UIPT on low-temperature physics. On October 28, 1937, he and two other UIPT scientists were arrested by the NKVD. They were accused of "the counter-revolution Trotskist-sabotage activity" and shot 11 days later. In 1956, a new investigation proved that their case had been fabricated, and the latter was voided by a decision of the Supreme Court.

45. A. A. Slutzkin, P. P. Leljakow, E. A. Kopilowitsch, I. A. Wyschinsky, A. J. Usikow, "Faktoren Welchedie Leistung und den Wirkungsgrad von Magnetronschwingungen Beeinflussen," *Physicalische Zeitschrift der Sowjetunion*, **5**, 6, 1934, pp. 887-901.

46. A. A. Slutzkin, P. P. Leljakow, E. A. Kopilowitsch, I. A. Wyschinsky, A. J. Usikow, "Erzeugung von Elektromagnetischen Wellen Kurzer als 50 cm mit Schlitzanodenmagnetronen," *Physicalische Zeitschrift der Sowjetunion*, **6**, 1-2, 1934, pp. 150-158.

47. A. A. Slutskin, S. Y. Braude, I. D. Truten, "Obtaining High-Power Oscillations of the dm-Band in Continuous-Wave Magnetrons," *Radiotekhnika*, **1**, 9, 1946, pp. 12-17 (in Russian).

48. P. P. Leljakow, A. J. Usikow, I. A. Wyschinsky, "Intermittent Oscillations in the Split-Anode Magnetron," *Physicalische Zeitschrift der Sowjetunion*, **10**, 2, 1936, pp. 266-268.

49. I. D. Truten (1909-1990) started his scientific activity at UIPT in 1932, as a student of the Kharkov Polytechnical University. Having graduated in 1935, he enrolled in a PhD course of A. Slutskin, and defended his thesis in 1942. After the establishment of IRE, he headed the Department of Pulse Sources there from 1955-1969. He was a Lenin Prize winner in 1960.

50. I. M. Vigdorchik (1910-1980) graduated from KSU in 1932, and obtained his PhD degree in 1939. He worked at UIPT from 1932-1953. From 1952-1963, he taught at several universities in Kharkov. From 1963 until 1979, he held the position of Senior Scientist and, later, head of a laboratory in the Department of Pulse Sources of IRE.

51. S. Y. Braude, A. M. Ivanchenko, "A Magnetron with a Net Control and its Applications in Medium, Ultra-Short, and Decimeter Waves," *Zhurnal Tekhnicheskoi Fiziki (J. of Technical Physics)*, **14**, 10-11, 1944, pp. 611-622 (in Russian).

52. I. V. Brenev (ed.), *Central Radio Laboratory*, Moscow, Sov. Radio, 1973 (in Russian).

53. At that time, there was no commonly accepted terminology, so systems of similar nature often had different names. Here, in the text, "radio-detector" means a radar system that locates the target in two coordinates (azimuth and elevation). Similar systems were also called "radio-catcher," "radio-searcher," and "radio-direction-finder."

54. P. F. Batitsky (ed.), *Air-Defense Forces*, Moscow, Voyenizdat, 1968 (in Russian).

55. S. S. Vinogradov, P. D. Smith, E. D. Vinogradova, A. I. Nosich, "Accurate Simulation of Spherical Reflector Front-Fed by a Huygens CSP Beam: A Dual Series Approach," *Proceedings of the International Symposium on Antennas (JINA-98)*, Nice, 1998, pp. 550-553.

56. Y. N. Ranyuk, L. D. Landau, and L. M. Pyatigorsky, *Voprosy Istorii Estestvoznaniya i Tekhniki (Problems of History of Science and Technology)*, no 4, 1999, pp. 80-91 (in Russian).

57. V. P. Vizgin, "'Nuclear Shield' in Russian Physicists' 'Thirty-Year War' Against Incompetent Criticism of Modern Theories," *Uspekhi Fizicheskikh Nauk (Progress in Physical Sciences)*, **169**, 12, 1999, pp. 1363-1389 (in Russian).

58. Y. I. Krivonosov, Landau and Sakharov in the KGB files, *Voprosy Istorii Estestvoznaniya i Tekhniki (Problems of History of Science and Technology)*, no 3, 1993, pp. 123-132 (in Russian).

59. H. S. Booker, W. Walkinshow, "The Mode Theory of Tropospheric Refraction and its Relation to Waveguides and Diffraction, in *Meteorological Factors in Radio-Wave Propagation*, London, Physical Society and Royal Meteorological Society, 1946, pp. 80-127.

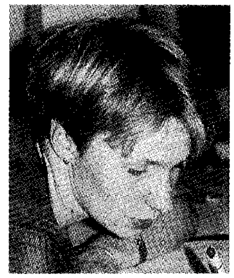
60. A. Schneider, "Oversea Radar Propagation within a Surface Duct," *IEEE Transactions on Antennas and Propagation*, **AP-17**, 2, 1969, pp. 254-255.

61. W. E. Gordon, "A Hundred Years of Radio Propagation," *IEEE Transactions on Antennas and Propagation*, **AP-33**, 2, 1985, pp. 126-129.

Introducing the Feature Article Authors

Alexei A. Kostenko was born in 1946 in Kharkov, Ukraine. He graduated from the Kharkov State University and obtained his MS and PhD degrees, both in Radio-Physics, in 1969 and 1983, respectively. Since 1974, he has been on the research staff of IRE NASU, in the Departments of Electronics and Wide-Band Introscopy, as a research scientist. He is a secretary of the Scientific Council of NASU on Radio-Physics and Microwave Electronics. He served as an organizer of the Kharkov Symposium on Physics and Engineering of MM and Sub-mm Waves (MSMW) in 1988-1998. His research interests are in quasi-optics, mm-wave technologies, and the history of radio physics and electronics.

Alexander I. Nosich was born in 1953 in Kharkov, Ukraine. He graduated from the Kharkov State University, and earned his MS, PhD, and DSc (higher doctorate) degrees, all in Radio-Physics, in 1975, 1979, and 1990, respectively. Since 1979, he has been on the research staff of IRE NASU, in the Departments of Electronics and Computational Electromagnetics, as a research scientist. From 1992-2000, he held Visiting Professorships and Guest-Scientist Fellowships in Turkey, Japan, Italy, and France. In 1995, he was the organizer and first Chairman of the IEEE AP-S East Ukraine Chapter (now joint with MTT, ED, AES, GRS, and LEO), the first one in the former Soviet Union. Since 1996, he has been the Chapter Secretary-Treasurer. Since 1995, he has been on the Editorial Board of *Microwave and Optical Technology Letters*. From 1990-2000, he was an organizer and Technical Program Committee Co-Chairman of the series of international conferences on Mathematical Methods in EM Theory (MMET) in the USSR and Ukraine. His research interests include wave scattering, radiation, propagation, and absorption studied using analytical regularization techniques, and the history of microwaves.



Irina A. Tishchenko was born in 1977 in Kharkov, Ukraine. She obtained her MA degree in Roman Languages Philology from the Kharkov State University in 1999. Since then, she has been with the Information Department of IRE NASU. Her interests are in the early history of microwave research and development at KSU and IRE NASU.

Correction

The following corrections should be made in the feature article by Allan W. Love, "Radiation Patterns and Gain for a Nominal Aperture of 105 Meters in the Arecibo Reflector" (*IEEE Antennas and Propagation Magazine*, **43**, 1, February, 2001, pp. 20-30):

In Equation (16), the second term in the expression for the component N_y of the vector triple product should read

$$N_y = \sin\Theta\cos\Phi\sin\psi\cos\phi + \cos\Theta\left[\sin^2\phi\cos(\beta-\psi)+\cos^2\phi\cos\psi\right]. \qquad (16)$$

In Section 2.3, the number (17) belongs with the equation for the variable u at the top of the second column, rather than with the Bessel-function equation at the bottom of the first column.

The first sentence in the first paragraph of Section 2.4 should be changed to read, "The phase $k\Delta$ in Equations (20) and (21), for the axial direction $\theta = 0$,...."

The second sentence in the first full paragraph in the right-hand column on p. 26 should read as follows: "It is to be expected that this will cause more loss in gain than would quadratic error of the same amount, for the error due to aberration occurs at a region of higher aperture illumination ($\psi = 8°$, see Figure 2) than at the edge ($\psi = 11.46°$), where quadratic error is maximized."

In the caption for Figure 14, the frequency should be 3 GHz.

The *Magazine* regrets these errors.