Radio Science Bulletin

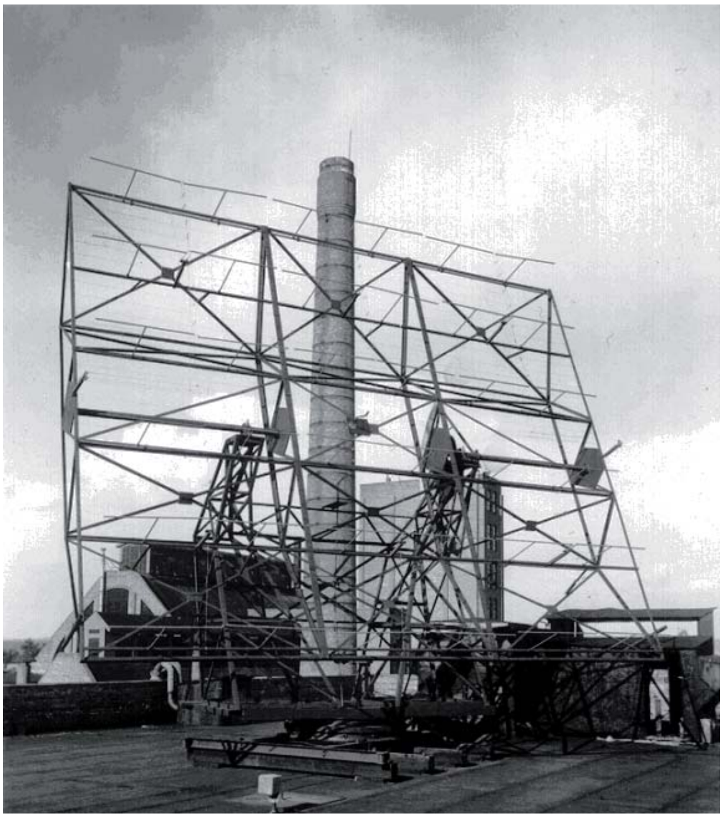
ISSN 1024-4530

INTERNATIONAL
UNION OF
RADIO SCIENCE

UNION
RADIO-SCIENTIFIQUE
INTERNATIONALE

U.R.S.I.

Special Section on Some Less-Well-Known Contributions to the Development of Radar: From its Early Conception Until Just after the Second World War



No 358
September 2016

URSI, c/o Ghent University (INTEC)
St.-Pietersnieuwstraat 41, B-9000 Gent (Belgium)

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Cover: The planar phased array antenna of the Hungarian radar used to measure the distance between the moon and the Earth. See the paper by István Balajti and Ferenc Hajdú in the special section on "Some Less-Well-Known Contributions to the Development of Radar: From its Early Conception Until Just After the Second World War" (figure courtesy of Pál Szabó; see reference [5] in the paper).

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Glimpses of Early Radar Developments in Ukraine and the Former Soviet Union

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Abstract

The first experimental work on practical radar detection in the USSR was done in 1934, to detect an airplane in flight as a target for flak or antiaircraft artillery. This work was absolutely independent of radar research and development in other countries. The outline of the first work on radar development in the USSR is briefly described in this paper on the basis of generalizations of documents, articles, and books published earlier (mostly in Russian). The attention in this paper will also be focused on the original radar research and development in Ukraine, which was then a part of the USSR. The first three-coordinate radar system was developed in 1938 in Kharkiv, the capital of Soviet Ukraine in the 1919-1934 period. Earlier, in the 1920s, the first powerful UHF and microwave oscillators were also created in Kharkiv, including magnetrons, which served as key engineering components of the future radar systems. Later, many important achievements were made in Ukraine, such as wideband signal generation, and pulse compression using a matched filter, in the middle of the 1950s. Radar development in modern Ukraine was based on its powerful scientific schools and industry.

1. Introduction

Modern radar can be defined as the science and technology encompassing the methods and means of detection, coordinate measurement, recognition, and determination of the motion parameters and other characteristics of observed objects using reflection, re-radiation, or emission of electromagnetic waves. The possibility of detecting objects using electromagnetic waves was expressed at the beginning of the twentieth century, but was prepared by earlier work.

It is worth mentioning James Maxwell's brilliant theory; the works by Heinrich Hertz, who tested and experimentally proved key results of Maxwell's theory; experiments on wireless communications in the Baltic Sea by Alexander S. Popov, who noted in his report that radio communication established between two ships was subject to the interference due to reflection from a third ship when it passed between them; foresight articles and lectures by Nikola Tesla; and Guglielmo Marconi's wireless devices. Many other achievements can be considered as forerunners of radar. However, the first working device that directly implemented the basic principle of active monostatic radar was built by Christian Huelsmeyer, to detect river boats at a distance. It was patented in 1904 in Germany, and named Telemobiloskop. Huelsmeyer's invention had no commercial success then, and it was pretty quickly forgotten. He was ahead of his time.

The creation of modern radar was gradually prepared by the general level of science and technology, and the needs of society. Only in the thirties of the twentieth century did the technical and economic, as well as the social and military conditions, appear and coincide for the development of practical radar. That is why it is not too strange that almost in parallel and independently, purposeful research on the creation of radar devices was started at least in France, Germany, Great Britain, Hungary, Italy, Japan, the Netherlands, the Soviet Union (the USSR), and USA. Normally, Sir R. A. Watson-Watt is pointed to as one of the key founders of the first real radar technology. In July 1935, together with his colleagues, he successfully demonstrated a radar for detecting an aircraft, and for estimating its coordinates. After improvements, a radar network (Chain Home) based on this system was built to provide early detection of enemy aircraft.

The activities in the field of radar performed in the USSR were published later than in other countries. They were less accessible to Western historians of science, and were often not considered by them. In this work, more attention is therefore paid to the history of radar in the former Soviet Union and Ukraine, without intending to claim stronger advances and priority. In reality, these works can be considered to be quite fundamental and, in certain aspects, pioneering. They were done in isolation and without publicity, caused by the pre-war circumstances and the general Soviet "spy-mania." All the investigations in this field were heavily classified as Top Secret.

Up to the 1930s, for air defense, acoustic direction finders together with optical range finders were used to determine the aircraft's location. They were able to quite accurately determine the direction-of-arrival of the sound emitted by the aircraft's engine. Such a system was called "prozhzvuk," which is actually an abbreviation of two words in Russian: "searchlight" and "sound." Such a system could be used only with a cloudless sky. Even then, it had negligible efficiency, as the pilot, once into the spotlight, could dramatically change the course and make the result of the calculating unit unusable for the control of anti-aircraft fire. With increased flight speeds and aircraft altitudes, the direction of sound arrival and the direction to the airplane began to differ so much that the "prozhzvuk" system became generally incapacitated. The need to create a fundamentally new means for the detection of aircraft became apparent.

The idea of testing the possibility of using radio methods to detect aircraft originated from military engineers. The advantages of radio were obvious: the high speed of propagation, the ability to work during the day and night, in the clouds, and behind the clouds, regardless of the weather. However, nobody had any idea how to approach this task, nor who could carry out the entire set of necessary research and development. Of course, in addition they had no idea how difficult this task would be. One of the main initiators was Mikhail M. Lobanov (1901-1984), later a Lieutenant General (Figure 1), and another was Pavel K. Oshchepkov (1908-1992) (Figure 2), later Doctor of Technical Sciences (but a Gulag prisoner for 10 years, beginning in 1937). Both were then young, talented, and very active professionals. At the end of their lives, both of them published their memories [1, 2], which contained lots of interesting facts and details.

Figure 1. M. M. Lobanov (circa 1975).

Figure 2. P. K. Oshchepkov (circa 1935).

Being a field synthesized of science and technology, radar has incorporated advances in the theory and technology of antennas, radiowave propagation, transmitters and receivers, signal processing, automatic control, information display, etc. It is impossible to pay appropriate attention to all these issues in a single paper. This paper summarizes the information known to the author from the literature, as well as from personal communication with some of direct participants in the hard and long process of radar development. In particular, the author was lucky to have a long period of communication with Profs. Yakov S. Itskhoki (1906-1984), Yakov D. Shirman (1919-2010), Yakov S. Shifrin, and Moisey I. Finkelshtein (1922-1992). He even met and in 1975 spoke to Yuriy B. Kobzarev (1905-1992). In the same year, 1975, the book by M. M. Lobanov [2], entitled *Beginning of Soviet Radar*, was published (in Russian). In spite of the obvious influence of "Soviet patriotism," this book contains a lot of important facts and documents, a part of which is cited in this article. In addition, we have archival material and interviews with participants in the events that were collected and saved by their younger counterparts.

Following the advice of Prof. Yakov Shifrin, who today is the oldest scientist in Ukraine who contributed to radar, in [3] we divided the process of radar development into five stages: 1) The very first works (1920-1941); 2) the period of WW II since the occupation of Ukraine (1941-1945); 3) the postwar period (1945-1955); 4) the period of intensive radar development (1955-1990); 5) modern radar (1991 to present). In this article, the period of the first two stages is mainly considered in detail, that is, since 1920 to the middle of the 1940s. A couple of later achievements (around 1955) are briefly described.

Table 1. A list of the abbreviated names of the institutions in this paper.

ARTA	Artillery Radio-Technical Academy (in Kharkiv, Ukraine); later name: VIRTA: Voennaya Inzhenernaya RadioTechnicheskaya Akademiya (Military Engineering Radio-Technical Academy)
CRL	Central Radio Laboratory
DC	Department of Communications
GAU	Glavnoe Artilleriyskoe Upravlenie (Principal Department of Artillery: PDA in English)
IRE	Institute of Radio Physics and Electronics NASU (National Academy of Sciences of Ukraine)
KA	Krasnaya Armiya (RA in English)
KhSU	Kharkiv State University
LEMO	Laboratory of ElectroMagnetic Oscillations
LEPI	Leningrad Electro Physics Institute
LETI	Leningrad Electro-Technical Institute
LIPT	Leningrad Institute of Physics and Technology
NII-9	Nauchno-Issledovatelskiy Institut No9 (Research and Development Institute #9: RDI-9)
NIIIS	Nauchno-Issledovatelskiy Ispytatelniy Institut Svyazi (RDTIC in English)
PCD	People's Commissariat of Defense (the name of Ministry of Defense of the USSR in 30s)
PDA	Principal Department of Artillery (GAU in Russian)
RA	Red Army (KA in Russian)
RDI-9	Research and Development Institute #9 (NII-9 in Russian)
RDI Radio-Industry	Research and Development Institute of Radio-Industry
RDTIC	Research, Development, and Testing Institute of Communications (NIIIS in Russian)
UIPT	Ukrainian Institute of Physics and Technology

Today, almost 80 years later, we have the possibility of compiling and generalizing the memoirs, papers, interviews, and recorded conversations to recreate an eye-opening picture of the research, development, and implementation of the first radar facilities in the USSR, also taking into account that this picture was painted in the harshest years of the twentieth century.

Figure 3. Yu. K. Korovin, a pioneer of radar in the USSR, developer of a CW radar.

2. First Experiments on Radio Detection of Airplanes

2.1. Radio Detection in UHF Band

Mikhail Lobanov, a military engineer, served in the Glavnoe Artilleriyskoe Upravlenie – GAU (Principal Department of Artillery – PDA) of the People's Commissariat of Defense (PCD), actually the Ministry of Defense, since 1932 (see Table 1 for a list of abbreviations of the names of institutions that appear in this paper). He was one of the initiators and organizers of the first research and development on radio detection for anti-aircraft artillery. In his memoirs [2], Lobanov told the following story. The idea to use radio waves for detecting airplanes (particularly bombers) was expressed in the PDA, but military engineers did not know who would be able to fulfill the necessary research. In 1933, during a private talk, Lobanov asked B. N. Mozhzhevelov, the Department Head of the Central Radio Laboratory (CRL), how he would have reacted to the idea of radio detection of aircraft. This question arose because the PDA intended to propose that the CRL conduct research in this direction. Mozhzhevelov recommended speaking first to Yu. K. Korovin, and then perhaps to officially apply to the Director of the CRL. At that time, Yuri K. Korovin (1907-1988) was the leader of the Decimeter Waves Group in the CLR, and was busy with two-way communications at decimeter wavelengths. His group had already developed transmitters, receivers, and measurement devices to conduct

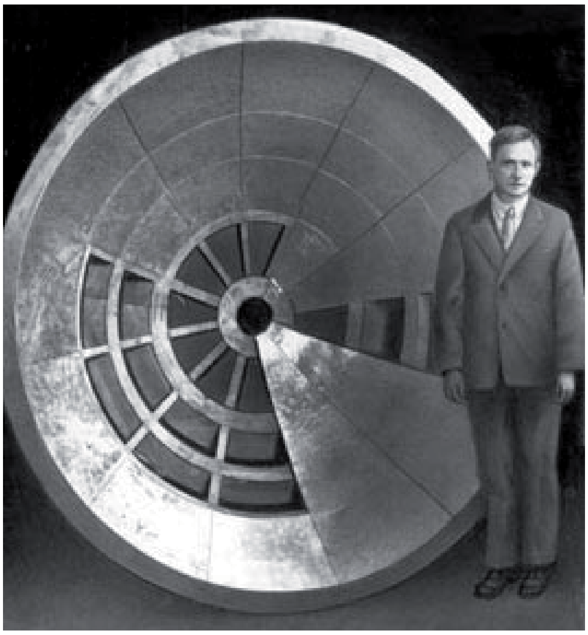


Figure 4. The original antenna designed for the first radar experiment. V. A. Tropillo is standing next to the antenna.

testing of communication range. D. N. Rumyantsev, the Director of the CRL, immediately agreed, and in October 1933, a contract was signed [4]. It was a legal document – the first in the USSR – that started research and development work as well as financing in the field of radar. Yuri Korovin (Figure 3) was assigned as leader of this work. Two-way radio equipment was allocated to carry out the experiments. This equipment was made earlier (except for the antenna) in the CRL, and used by Korovin in his investigations of the task of the Department of Communications (DC) of the Red Army (RA). The equipment contained:

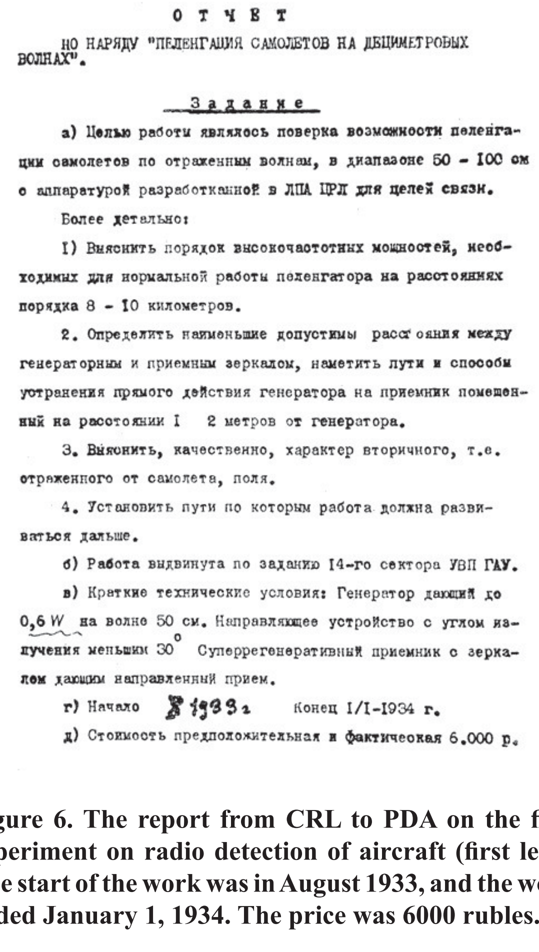
- A continuous-wave transmitter operating at a wavelength of 50 cm to 60 cm, but of very low radiating power: 0.2 W;
- A super-regenerative receiver;
- And two ground-based parabolic-reflector antennas of 2 m diameter (Figure 4).

Figure 5. Yu. A. Katsman.

Oscillating tubes for this equipment were developed in 1932-1933 by engineers of the Leningrad Electro-Technical Institute (LETI) V. I. Kalinin and Yuri A. Katsman (Figure 5), together with CRL researcher V. A. Tropillo (see Figure 4). A 1 m^2 screen of sheet brass initially served as a reflective surface to adjust the transmitter and receiver. A brash mesh of 10 m^2 was later substituted for it.

The main experiment to verify the radiowave reflections from flying aircraft was organized in Leningrad. Tests were carried out on the area of the rowing port. Radiating equipment was placed on the shore, and the receiving equipment was on sea ice at 20 m from the shore. The transmitting and receiving antennas were similar. According to the agreement with the PDA, experiments on the radio detection of the airplane were planned in December 1933. However, due to adverse weather conditions with a lack of ice thickness off the coast of the Gulf of Finland, the experiment was postponed.

Finally, on January 3, 1934, the weather improved, and the long-awaited experiment of radio detection of aircraft was carried out. During the experiment, a seaplane made several takeoffs and landings with different angles relative to the direction of radiation and reception. The reception apparatus allowed observing the Doppler effect in the form of a typical sound in the headphones when the seaplane entered into the zone of visibility.



ОТЧЕТ

НО НАРЯДУ "ПЕЛЕНГАЦИЯ САМОЛЕТОВ НА ДЕЦИМЕТРОВЫХ ВОЛНАХ".

Задание

а) Целью работы являлось поверка возможности пеленгации самолетов по отраженным волнам, в диапазоне 50 - 100 см с аппаратурой разработканной в ЛПА ЦРЛ для целей связи.

Более детально:

1) Выяснить порядок высокочастотных мощностей, необходимых для нормальной работы пеленгатора на расстояниях порядка 8 - 10 километров.

2. Определить наименьшие допустимы расстояния между генераторным и приемным зеркалом, наметить пути и способы устранения прямого действия генератора на приемник помещенный на расстоянии 1 2 метров от генератора.

3. Выяснить, качественно, характер вторичного, т.е. отраженного от самолета, поля.

4. Установить пути по которым работа должна развиваться дальше.

б) Работа выдвинута по заданию 14-го сектора УВП ГАУ.

в) Краткие технические условия: Генератор дающий до 0,6 W на волне 50 см. Направляющее устройство с углом излучения меньшим 30° Суперрегенеративный приемник с зеркалом дающим направленный прием.

г) Начало [illegible] 1933 г. Конец 1/1-1934 г.

д) Стоимость предположительная и фактическоая 6.000 р.

Figure 6. The report from CRL to PDA on the first experiment on radio detection of aircraft (first leaf). The start of the work was in August 1933, and the work ended January 1, 1934. The price was 6000 rubles.

The seaplane was detected at a distance of 600 m to 700 m at 100 m to 150 m flight altitudes. Judging by these figures, it was quite a short distance, but in essence it established the key fact of detection of the reflected signal from an aircraft. In 1935, Yu. K. Korovin got the "Author Certificate" (a kind of patent) number 2578, "Device for Radio-Detection of Aircraft Based on Using Doppler Phenomenon."

During the next several days of January, Yu. Korovin held a number of flight tests, and collected reliable enough material for further work on the development of new equipment for detecting aircraft and direction finding. In the CRL report, sent to PDA by February 14, 1934 (Figure 6), Yu. Korovin formulated the first results of his work:

1. The direction finding of aircraft was possible at a distance of 8 km to 10 km in the case of a radiating power of the order of tens of watts and a wavelength of 10 cm to 20 cm. This conclusion was based on the results obtained with a power of 0.2 W at a wavelength of 50 cm.

2. At 0.2 W power and a wavelength of 50 cm, the aircraft was detected at a distance of 600 m to 700 m.

3. Direction finding of elementary surfaces (a 25 cm diameter disc) was obtained at the same power and the same wavelength at a distance of 100 m. The experiments with elementary surfaces allowed roughly calculating the reflection effect from complex reflectors (aircraft).

4. Obtaining secondary characteristics of the field, that is, the distribution of the reflected field in space depending on the position of an aircraft in the irradiated zone, was possible at a transmitter power of the order of 4 W to 5 W at a distance of 1 km to 1.5 km. The apparatus used (0.2 W) did not allow the experimenters to carry out these measurements.

5. Use of a multilayer screen made it possible to reduce the distance between the transmitting and receiving antennas to 1 m to 2 m; at a wavelength of 50 cm and a power of 0.2 W, the shortest distance between those antennas was 8 m.

Later, Yuri Kobzarev (1905-1992), a pioneer of pulse radar, wrote in his memoirs [5]:

> January 3, 1934 in Leningrad, the radio waves reflected off the aircraft were registered using a small purpose-built device. From that day, which can be regarded as the birthday of the Soviet radar, the intensive research began.

The conclusions of the PDA in 1934 were also very optimistic. They reviewed and approved the CRL report [6]. In addition, the need was identified to boost development of radio-detection equipment, both in the CRL and in the Leningrad Electro Physics Institute (LEPI), to initiate a parallel development. The decision of the PDA provided for the desirability of speeding up the work to manufacture and test the operational prototype of the device during the same 1934.

2.2. Radio Detection in VHF Band

As was mentioned above, engineer Pavel Oshchepkov, who in 1932 served in the army, also proposed a similar idea for radio detecting aircraft. He intended to improve the air defense of the Red Army. The structure of the Air Defense Service included a series of observation posts, which were equipped with just binoculars and telephone communications to alert the Air Defense Command Points. In the Department of Air Defense, the idea of radio detection thus emerged based on the analysis of the organization of air-defense surveillance at observation posts.

The difference between the approaches to radio detection in two Red Army departments (PDA and Air Defense) might not seem too obvious. However, it was. The purpose of the PDA was application of radio-engineering methods to detect aircraft for better aiming the antiaircraft artillery, while in the Air Defense, the purpose was to alert as early as possible regarding approaching bombers.

In the second half of 1933, in his report to the People's Commissar of Defense, Pavel Oshchepkov outlined the principle of using the new means of radio detection of aircraft in the air-defense system. More detail was described in [7]. The request for assistance in the promotion of activities on radio detection of airplanes by Pavel Oshchepkov, as a representative of the Air Defense Department, was directed to academician Karpinsky, the President of the Academy of Science, who asked Abram F. Ioffe (1880-1960) for assistance. Ioffe did not work directly as a radar developer or designer, but his role was very significant.

2.3 A Short Biography of A. F. Ioffe

Abram Ioffe was born in 1880 in the town of Romny, situated in the province of Poltava (the central part of modern Ukraine). He was from a merchant family. He received higher education in the Romny specialized school from 1889-1897. His schoolmate and close friend was Stepan (Stephen) Timoshenko, the father of modern engineering mechanics. Ioffe graduated from St. Petersburg Institute of Technology. He got a PhD from Munich University, where his teacher was Wilhelm Konrad Roentgen. Ioffe then rejected the flattering offer to continue working with Roentgen, and returned to St. Petersburg. (At the end of his life, when Roentgen was seriously ill, Ioffe gave him money for X-rays and treatment).

Ioffe was a wonderful physicist in the Russian Empire and in the Soviet Union. In 1911, he determined the charge of the electron. His article was published only in 1913, a little bit later than was done by Robert Milliken, who is officially recognized as the first. Ioffe was extremely effective as an organizer of science, and was a creator of the powerful scientific school in the Soviet Union. In 1916, Ioffe organized his famous Seminar in Physics for young scientists in St. Petersburg. The participants in that seminar later became the pride of Soviet physics. He was a teacher of A. P. Alexandrov, P. L. Kapitsa, N. N. Semyonov, L. A. Artsimovich, I. K. Kikoin, Ya. I. Frenkel, I. V. Kurchatov, and many other prominent scientists.

After the October revolution of 1917, Ioffe worked on the development of science under the new conditions. He was a very influential person, and the greatest authority in physics and engineering. He was also a smart and experienced "politician," which gave him the possibility of avoiding expressing a political preference for a long time, and being useful for science and for scientists under the difficult conditions of the Soviet reality. It was even strange that, according to [54], he became a Communist Party member only in 1942, in wartime, when he was 62.

Abram Ioffe was officially Vice President of the Academy of Science (never President), but he was known as the "Principal" Academician, father of Soviet Physics, or just "papa Ioffe." In 1918, he organized the Physics and Mechanics faculty in the Polytechnic institute where engineer-physicists were prepared. In the same year, 1918, he created and headed the Physics and Engineering Department at the State Roentgenological and Radiological Institute. In 1921, this department was transformed into the entire institute of applied physics, named the Institute of Physics and Technology (IPT), later the Leningrad IPT (LIPT) of the Academy of Sciences, and A. Ioffe became the Director of the LIPT. Today, this institute in St. Petersburg is named after Abram Ioffe.

A huge number of research works done in LIPT were not signed by Ioffe, in spite of his significant contributions: Ioffe was notable for his generosity in science, and did altruistically help his pupils. It was Ioffe who asked Rutherford, the head of Cavendish Laboratory in Cambridge, to invite Piotr Kapitsa for work placement. In addition to LIPT, Ioffe headed the Agrophysics Institute since 1932. He was the initiator and very actively participated in the creation of the institutes for Physics and Technology in Kharkiv, Dnipropetrovsk, Sverdlovsk, and Tomsk. He could have been the leader of the Soviet atomic project, but he was brave enough to refuse this offer in favor of a younger scientist: Igor Kurchatov. Stalin said, "I don't know such academician," but Ioffe insisted, and Kurchatov was appointed and awarded with the title of Academician.

In the beginning of the 1950s, when the anti-Semitic campaign on the "fight against cosmopolitism" was developed in the USSR, Ioffe was fired by the institute created by him. Nevertheless, he did not capitulate: he organized a new Laboratory of Semiconductors. After Stalin's death, he became the Director of the institute created on the basis of that laboratory. Ioffe was posthumously awarded the Lenin Prize (the highest award in the post-Stalin USSR) in 1961.

However, let us go back to radar history. Abram Ioffe always quickly responded to any fresh idea [5]. Very soon, he thus invited his friend, Dmitry Rozhansky (1882-1936), as well as Alexander Chernyshov (1882-1940), Nikolay Papaleksi (1880-1947), Boris Shembel (1900-1987), Pavel Oshchepkov, et al., to the meeting organized by him on February 7, 1934. After the meeting and positive discussions, the Red Army Air Defense Department signed a contract on February 19, 1934, with LEPI [8] to study the reflection of electromagnetic waves from different surfaces, to develop radio-detection equipment, and to conduct the first experiments to detect aircraft. Based on the accumulated material, it was then planned to develop a draft of an air-reconnaissance station. Engineer Boris Shembel was appointed as the immediate supervisor of the research. It is interesting to note that B. Shembel had already started to work on radio detection according to the contract with the PDA.

Before June 1, 1934, the equipment named "Rapid" was developed. This consisted of an electromagnetic wave oscillator (4.7 m wavelength, 200 W power), a superheterodyne receiver, and a receiving antenna designed as a horizontal dipole. In June, "Rapid" was tested near Leningrad. The radiating system was installed on the roof of LEPI and oriented into the direction of the receiver; it was stable during the tests. The receiver was moved within 11 km to 50 km from the radiating system. An airplane, following its planned course, crossed the track of the electromagnetic radiation (the so-called "electromagnetic veil") at different points of the line-of-sight between the radiating and receiving equipment to determine the maximum distance at which the receiver still could reliably detect the airplane.

According to the test results of July 10-11, 1934, a record was compiled where it was indicated that the airplane was detected in all cases when it was within 3 km from the receiver at altitudes up to 1000 m. On August 9 and 10, 1934, experiments with "Rapid" were repeated. The reception apparatus was installed in the Krasnogvardeisk area (50.4 km from the transmitter), and in the Siverska station (70.6 km from the transmitter); the airplane flew at altitudes up to 5200 m. In these experiments, the beat signal from the aircraft was heard with headphones at distances of 5 km to 7 km from the receiver.

In September 1934, the LEPI presented the second release of the "Rapid" equipment: a 100 W transmitter operating at a wavelength of 4.8 m, with the antenna system radiating at 60° in azimuth and elevation, and the receiver at the central station where a recording unit registered the received signals on a tape.

The "Rapid" device served as one of the prototypes for further development of radio-detection systems at NIIIS of the Red Army and in the radio-factory industry. At this point, the Red Army Air Defense Department stopped the work with LEPI, even though it had not yet been fully completed in accordance with the terms of the contract. The reasons were not fully clear, but very soon after, the LEPI was liquidated (more details are in the next section).

3. Continuous-Wave or Pulsed Radar?

In a note dated January 4, 1934, Pavel Oschepkov wrote his principal considerations about the viability of a pulsed method of radio detection instead of the continuous-wave method. His idea was based on the fact that in order to increase the detection range, the output power should be significantly increased. In the continuous-wave method, the manufacturing of high-power oscillating tubes caused considerable difficulties, due to the prolonged heating of the electrodes. Powerful VHF tubes at that time required water cooling, and had a service life of only 50 hours. Use of these tubes was impractical, even in a half-load mode. Oshchepkov supposed that when using pulsed radiation instead of CW, the main difficulty in the production of high-power VHF oscillating tubes – that is, the high temperatures on their electrodes – would disappear. According to his calculations, the power per pulse could be 100,000 times greater than the average power for continuous radiation, and this increased the range of detection. Today it is obvious that his conclusion was wrong: in reality, in order to detect a target at great distance, one needs significant mean power in the sounding waveform for both the CW and pulse methods.

In making his calculations, Pavel Oshchepkov arrived at the idea of creating a station with 360° visibility, determining two coordinates of the target: azimuth and range. However, this idea was not used in terms of research and development at that time. The systems with 360° visibility were developed and produced in radio factories ordered by the PDA a few years later. They were used for observation and alerting in the Air Defense Service, and as systems guiding flak artillery.

Although Oshchepkov expressed the idea of a preference for the pulse method, it thus did not result in the expression of a corresponding task of the LEPI. The development was carried out on the basis of the continuous-wave method, and recording of the Doppler frequency.

Shortly after the meeting at Abram Ioffe's office (February 7, 1934), Alexander Chernyshev applied to the Military Invention Division of PCD with the first application (in the Soviet Union) for an invention in the field of radio detection: "Device for the Detection of Airplanes and Airships in Flight by Means of Electromagnetic Waves." Its essence was as follows: the radio-detection system would consist of a single continuous source of powerful electromagnetic radiation, and a large number of radio receivers located on the periphery around it. When a non-directional radiation transmitter was used, the power should be significant; in case of directed radiation, it could be much less. In the latter case, a directional antenna rotated and sequentially illuminated the horizon, or a part of it. Some experts, such as Prof. Boris Vvedensky (1893-1969), expressed serious comments on this approach, mainly because of problems caused by continuous radiation. It was noted that the use of pulsed radiation could save on average power and facilitate the fight against unwanted interference from the "direct" signal.

In accordance with the contract [8], the following performance characteristics were intended to be reached:

- Detection of aircraft in the observed area and coordinate determination at altitudes up to 10 km and at a distance of 50 km;
- Range accuracy of 2% to 5%;
- Determination of the number of airplanes (one, two, unit, troop, squadron, and more);
- Accuracy of determining the aircraft's speed up to 25 km/h.

Such LEPI obligations under the contract with the Air Defense Department demonstrated that neither LEPI nor the customer had yet imagined the complexity and scope of research and development necessary to provide such requirements.

As was mentioned above, although further experiments carried out in March 1935 with the improved equipment showed that the detection range could be significantly increased, LEPI's work in this direction was terminated by the customer. By this time, inside the Air Defense Department, the Experimental sector was created, with laboratories in Moscow and Leningrad. The orders for the development of a powerful VHF generator of continuous radiation and appropriate reception facilities were given to industry for the planned early warning system "Elektrovizor," also proposed by Oshchepkov.

In 1935, the LEPI was disbanded. Its premises, personnel, and equipment were handed over to the NII-9, or Research and Development Institute #9 (RDI-9). This was a new institute, which was organized for the development of important defense topics, including radar. Mikhail A. Bonch-Bruevich (1888-1940) was appointed as the scientific director of the new institute. He was known as the founder and leader of the former famous Nizhny Novgorod Radio Laboratory. Bonch-Bruevich knew very well the work of radio operators: "listeners" of the first World War. He believed that the most promising method was the acoustic indication of the received signals. Indeed, the ability of wireless operators to extract the necessary signals from the incredible cacophony of sounds (a mixture of signals of many stations, caused by bad selectivity of the receivers) was amazing. A strong preference for the continuous-radiation technique was therefore given in RDI-9. Actually, the work was aimed at creating radio-direction finders to replace the old acoustic system, which was combined with optical projectors (the so called “Projector-Sound”). Especially attractive (from their point of view) was a resemblance of these systems, so that operators would not even have to relearn [5].

There were many difficulties during the development of continuous-wave systems. They mostly occurred due to the proximity of the CW transmitter to the receiver, even if they were spaced apart by tens of meters. In 1934, in parallel with the work of the Boris Shembel team in LEPI, the pulse radio-detection method was also tested. The research on pulse radar was led by engineer Moisey D. Gurevich. Under his leadership, the experimental setup was based on a UHF magnetron oscillator working in pulsed mode. The oscilloscope, synchronized by the generator, was connected to the output of the receiver. The direct and reflected pulses could be simultaneously marked on the screen. However, this work was also stopped [2]. The management had continued to give priority to the CW method, especially since there had been significant advances in the creation of the transmitting and receiving UHF devices. Only after 1938, at the Leningrad Institute of Physics and Technology (LIPT), when the experiments had been conducted that demonstrated the high performance of pulse technology, did the pulsed radar method get the rights of development also in RDI-9. However, the “Projector-Sound ideology” was not completely overcome: the pulse method was viewed only as a means of allowing replacement of the optical rangefinder by a radio-rangefinder (to allow the operation of the plant under cloudy conditions). Development of a decimeter direction finder with continuous radiation continued to play a leading role in the RDI-9 institute [5].

Anyhow, at that time, a radar system with continuous radiation that could be adopted for operational use was not created. All attempts to build a CW operational prototype failed [9].

At the same time, considerable success had been achieved in the application of the pulse method in the Ukrainian Institute of Physics and Technology (UIPT). There, in 1938, a pulsed-radar system was created for anti-aircraft artillery (it was called the “Zenit”). This system operated in the 60 cm to 65 cm wavelength range [2, 10]. More details about this apparatus are in Section 5.

4. First Radars for Anti-Aircraft Artillery

In 1935-36, the RDI-9 had to create a new mobile apparatus for radio detection for anti-aircraft artillery, and thoroughly test it on the range. Based on the experimental setup of 1935, and its testing using an airplane and a simulator, the pilot plant of the RDI-9 produced a transportable two-antenna flak radio searcher, “Burya.” The name radio searcher (radioiskatel) was used for this kind of radar. This development was still carried out in the laboratory headed by Boris Shembel. The radio searcher “Burya” included:

Figure 7. The radio-searcher “Burya.”

- A magnetron oscillator at a wavelength of 24 cm to 25 cm, with a power of 6 W to 7 W continuous wave;
- A regenerative receiver and detector with direct amplification;
- Two parabolic antennas (radiating and receiving) with diameters of 2 m and beamwidths of 7° to 10°;
- A power supply (batteries and dry cells).

To facilitate the development of the radio searcher, the PDA gave to the RDI-9 a regular (acoustic) rangefinder, ST-2. The horns and acoustic transmission lines were removed, and parabolic antennas were installed at the attachment points. All the radio equipment, together with batteries, were placed on the frame and the rotating base of the ST-2 sound ranger.

During the thorough testing, the “Burya” radio searcher (Figure 7) showed a target detection range (maximum) of 10 km to 11 km, with a median error in azimuth of 3° and in elevation of 4.1°.

The performance of the radio searcher surpassed similar characteristics of the acoustic rangefinder. However, the “Burya” radio searcher did not yet fully satisfy the requirements of the anti-aircraft artillery.

During the field tests in Crimea, Boris Shembel first noticed and then systematically observed the reflection of electromagnetic waves from distant mountains (about 100 km). This indicated that radio waves of 24 cm to 25 cm

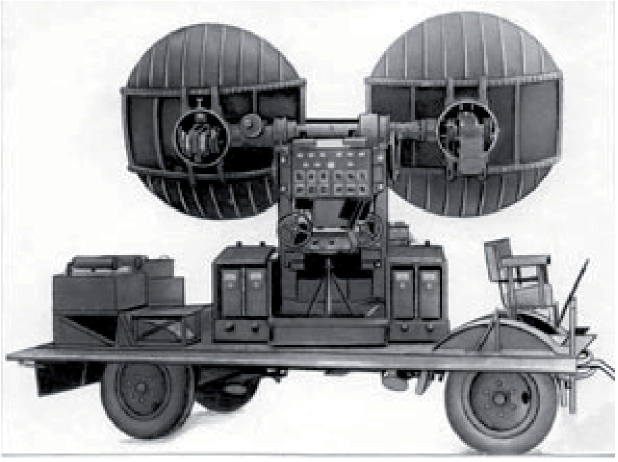


Figure 8. The radio-searcher B-2.

could be used for aircraft detection at distances much greater than those obtained at the site. This fact was very important for future developments. During observations of reflections from the mountains, the method of frequency modulation (FM) of the magnetron was used, which was introduced by Boris Shembel into the "Burya" equipment. Based on this experience, the idea of range measurement with FMCW radar was proposed by Shembel in 1937 [9].

The new radio searcher B-2 (Figure 8) had a parabolic antenna with a squinted antenna pattern and a beamwidth of 5° to 6°. To search for the aircraft, it used a conical scan within the sector of 40° to 50° in azimuth and elevation. By successively irradiating the airspace sector by sector, the radio searcher detected the airplane, and then switched to tracking by determining the angular coordinates by the equi-signal-zone method.

For further development of radio searchers, Mikhail Bonch-Bruevich suggested using the idea of a flat antenna beam, that is, a fan-shaped radiation pattern. He emphasized that flat antenna patterns were able to simultaneously solve two main tasks: to increase the reliability of detection and searching for aircraft, and to improve the accuracy of determining the coordinates. Therefore, the next system that implemented this idea was the B-3 system. Two B-3 radio searchers formed a complex, in which one unit (azimuth) was designed to search for targets in the horizontal plane, and the other unit (elevation angle) searched in the vertical plane (Figure 9). Together, they determined the target's coordinates in space-angle. Both radio searchers had antennas with flat antenna patterns (fan-shaped), with a beamwidth of 35° to 40° in one plane, and 2° to 3° in the other plane.

Both radio searchers were of identical structure and electronics, but they only differed in appearance by the fact that the antenna of the azimuth unit was horizontal, and the elevation-angle unit's antenna was vertical. The coordinates of the target were determined by the maximum audibility of the reflected signal. Later on, preference was given to a pulse radar for anti-aircraft artillery.

5. Three-Dimensional Pulse Radar Development in UIPT

Ukraine was one of the most technically advanced republics in the USSR. It formally had legal attributes of independency, such as its own constitution and the formal right to secession – which, of course, was impossible to implement, in practice. Before the collapse of the USSR in 1991, Ukrainian scientists were involved in the overall development of science and technology of the USSR. Considering the contribution to radar, one should note that the most powerful community of radio-physicists in Ukraine was in Kharkiv. The history of radar in Ukraine (and in the USSR, as well) is inseparable from the history of the creation of the community of radio-physicists in Kharkiv in the twenties of the twentieth century. That is why we shall first briefly recall the essential milestones that are relevant to radar [11-13, 53].

5.1 Kharkiv Radiophysics School

By the beginning of the twentieth century, Kharkiv was a large industrial, cultural, and scientific center, with lasting university traditions. The Kharkiv State University (KhSU) was established by imperial decree in 1804. Remarkably, KhSU 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 worldwide fame: mathematicians S. N. Bernshtein, M. V. Ostrogradsky, A. M. Lyapunov, and V. A. Steklov; biologist I. I. Mechnikov; chemist N. N. Beketov. physicists A. I. Akhiyezer, L. D. Landau, I. M. Lifshits, and K. D. Sinelnikov; chemist D. I. Mendeleev; and astronomers M. P. Barabashov and V. G. Fesenkov lectured at KhSU. The

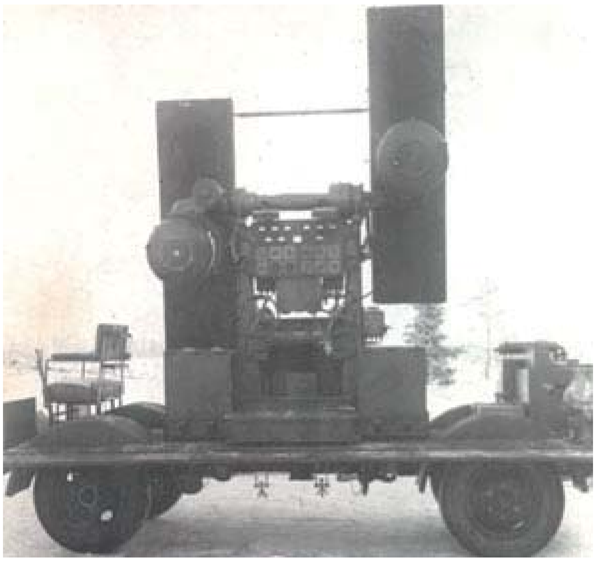


Figure 9. The radio-searcher B-3: the device for determining the elevation angle.

Figure 10. D. Rozhansky (1882-1936).

Figure 11. A. Slutskin (1891-1950).

university won a reputation as one of the most prestigious schools of higher education in the Russian Empire, and became a center of advanced science and technology. After the October revolution and bloody civil war, Kharkiv was chosen as the capital city of the Soviet Ukraine from 1919 to 1934 (at that time, Kiev was considered less politically reliable). One of the first research departments of physics in Ukraine was established in the KhSU in 1921. It was a new, independent scientific unit [12].

The department was established under the leadership of the prominent physicist, Dmitry Rozhansky [13]. Dmitry A. Rozhansky was born in Kiev, studied at the Kiev High School (the First Gymnasium), where famous writers Mikhail Bulgakov and Konstantin Paustovsky also studied, as well as the prominent aircraft designer, Igor Sikorsky. Rozhansky graduated (with an honors diploma) from the St. Petersburg University in 1904, and spent two semesters (1905/1906) in the laboratory of Prof. H. Simon in Gottingen, Germany, where he published his papers in the *Physikalische Zeitschrifft* journal. He finally defended his MS dissertation in 1908. Dmitry then worked in the Physics Department of the St. Petersburg Institute of Electrical Engineering under the leadership of Alexander S. Popov. Rozhansky moved back to Ukraine (to Kharkiv) in 1911, and in 1914, he became a Professor and Head of the Department of Physics at the KhSU. The Kharkiv period was very fruitful for Rozhansky's creativity. In 1913-1914, several of his fundamental results were achieved. In particular, in the book *Electric Rays*, he presented the physical foundations of radio engineering at the highest scientific level. At the same time, his famous book *Electric Oscillations and Waves* was published in two parts. As a recognized scientific leader, he had grouped around himself similarly minded associates, creating a supportive atmosphere and determining the topics of research.

Rozhansky was one of the first who foresaw the future of high-frequency radio engineering, and he initiated research on electromagnetic oscillations. In fact, this gave birth to the Kharkiv radiophysics community as a whole.

Research by D. A. Rozhansky (Figure 10) led to the creation of UHF magnetrons in Kharkiv [14] by his pupil, Abram A. Slutskin (Figure 11), together with Dmitry S. Shteinberg (1874-1934), who also was a follower of Rozhansky, despite his age (Figure 12). According to the reference of the great radio physicist, academician Leonid Mandelstam, these works were the most valuable in the field of electronics of that time [15]. The use of magnetrons in radar led to a revolution in this field.

In 1921, Rozhansky was invited to the famous Nizhny Novgorod Radio-Engineering Laboratory. However, in 1923, he moved to Leningrad (then Petrograd, today St.

Figure 12. D. Shteinberg (1874-1934).

Figure 13. A group of UIPT people during the visit of P. Ehrenfest to Kharkiv in 1930.

Petersburg) where, together with L. I. Mandelstam and N. D. Papaleksi, he took part in the organization and worked at CRL.

After leaving Kharkiv, Rozhansky kept in close contact with his former staff and students. He visited Kharkiv twice a year [15]. Around 1924, Abram Ioffe invited Rozhansky to the Leningrad State Physics-Technical Laboratory, organized by him, and to the Physics-Mechanical Faculty of the Leningrad Polytechnic Institute, where Rozhansky led the Department of Technical Electronics.

Rozhanky was interested in issues of short-wave propagation, and in 1925 he again came to Kharkiv. There in Kharkiv, he met Yu. B. Kobzarev who, still being a student of Kharkiv University, assisted Rozhansky during measurements of receiving signals. Later, D. Rozhansky invited the talented student to Leningrad.

Rozhansky was an honest and deeply principled man, who never did anything that could be against his conscience, and he never was afraid to express his opinion. This was not easy in the environment of increasing suspicions, spying-mania, and the approaching mass repression of the 1930s in the USSR. In the country, the fight against "enemies" was intensified that time. In Leningrad, a group of "saboteurs" was charged with mass poisoning at one of the factories, and 40 people were shot without court trials. In all institutions, meetings were organized where people usually voted unanimously, expressing the collective approval of the execution over "enemies." At such a meeting, on September 25, 1930, Rozhansky took the floor and said that he was an opponent of executions, especially without a court trial [16]. This action obviously served as a pretext to arrest Rozhansky on the night of October 4-5, 1930. Abram Ioffe immediately began to plead for his release. However, Ioffe only achieved that Rozhansky was released in nine months. Fortunately, after the prison stay, Rozhansky continued his scientific and pedagogical activity during several more years. However, his health was undermined, and he died in 1936, at the age of 48.

Prof. Rozhansky always stimulated the interest of young scientists, and promoted many of them, who later became famous. It was no accident that two of his students, Abram Slutskin in Kharkiv and Yuri Kobzarev in Leningrad (who also graduated from Kharkiv University), headed the work on the development of the first Soviet pulsed-radar systems.

Here, we have come to the principal hero of the story about the first three-coordinate pulsed radar. There is no doubt that Abram Slutskin (1891-1950) was the most remarkable man in Ukrainian radiophysics and electronics between 1925 and 1950 [11]. He played a crucial role in developing modern radio science. A. Slutskin entered the Physics-Mathematics Department of KhSU in 1910, just before Rozhansky's arrival. Rozhansky started a very interesting physical seminar, with active student participation. This determined Slutskin's ever-lasting interest in electronics. Slutskin graduated from the university in 1916. He worked there as an assistant until 1928, and then as a professor in the Physics Department. In 1928, for three weeks he worked in the laboratory of Barkhausen in Gottingen, Germany. Thanks to his brilliant results in physics and microwave electronics, he was awarded the degree of DSc in 1937, 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.

An important event in the development of the Kharkiv radiophysics community occurred in 1928, when a new research and development center named UIPT was founded. The key role in organizing this institute was played by A. Ioffe, who was then the Director of the LIPT. He persuaded the government that a certain decentralization of Soviet science was necessary, and suggested that Kharkiv was the best choice for a new institution. A. Slutskin and D. Shteinberg (1874-1934) were included among the UIPT staff, still keeping their university posts. A group of UIPT people is shown in Figure 13.

Figure 14. A. Y. Usikov.

Systematically, the scientific level of UIPT became very high. Since 1932, Lev Landau (1908-1968), the future Nobel prize winner, was assigned Head of the Theoretical Department at UIPT. Landau was only 24, but he was already a world celebrity in theoretical physics. In addition, he lectured at Kharkiv Technical University (Polytechnic Institute) [17]. In the summer of 1934, the International Conference on Theoretical Physics was held in Kharkiv. Niels Bohr and other prominent theoreticians took part in that event. At that time, such famous scientists as Paul Dirac, Paul Ehrenfest, Vladimir Fock, George Gamow, Piotr Kapitsa, George Placzek, Rudolf Peierls, and Victor Weisskopf quite often visited UIPT, and some of them stayed there for a long time.

However, we can definitely assert that Landau had no relationship to the work in the field of radar. He was greatly interested in theoretical physics, and did not work on engineering problems, especially related to military issues. In contrast, Slutskin was a physicist who was greatly interested in engineering. He foresaw major trends, especially in microwave electronics and related fields of physics. In the first half of the 1920s, he investigated vacuum tubes in a magnetic field, and got magnetron oscillations. In 1924, he had gotten L-band oscillations, and continued to work hard to conquest even higher frequencies. Actually, the development of three-dimensional pulse radar at L band (see the next subsection) in UIPT was mainly associated with his intuition and initiative, because there was no obvious reason for this choice of frequency band and exactly the pulse method. Research and development in the field of higher-frequency bands later became the scientific credo of his followers. In particular, this was true relative to Alexander Usikov (1904-1995) (Figure 14), one of the founders (1955) and the first Director of the IRE (the Institute of Radio Physics and Electronics) in Kharkiv, whose activities were focused on the development of millimeter and sub-millimeter bands. The laboratory of electromagnetic oscillations (LEMO) was created as a division of UIPT as early as in 1930, and, of course, it was led by A. Slutskin.

5.2 Creation of Effective Microwave Magnetrons in Kharkiv

Effective microwave oscillators – in particular, magnetrons – later became the key components of radar systems. UIPT was one of the first institutions where the development of effective magnetrons was done. A. Slutskin began to work on this even much earlier. In 1924, after his success in getting L-band oscillations in generators of the magnetron type – that is, reaching the most high-frequency part of the spectrum then available – he began to work hard to achieve even higher frequency bands. Slutskin investigated the mechanisms and conditions of excitation of split magnetrons, and developed a theory of a magnetron oscillator operating in the dynatron mode. According to Usikov [33], Slutskin enjoyed an extremely high reputation as initiator of a completely new method of oscillation: the split-anode magnetron. Another active member of that team, Semion Braude (1911-2003),who was only 22-25 (Figure 15) when working on magnetrons, noted [15]:

> Slutskin was my teacher, as he lectured on electrodynamics in KhSU where I studied. It was with his personal support that I was assigned to UIPT after my graduation. I have been formed as a scientist under a strong influence of him....It should be noted that he personally supervised all the research projects of his staff, and every day discussed the results obtained.

An interesting analysis of the first publications on magnetrons was written in [18]. According to [18], the first publication on magnetron oscillation was by A. W. Hull, whose papers [19, 20] appeared in 1921. Soon, A. Zachek

Figure 15. S. Y. Braude.

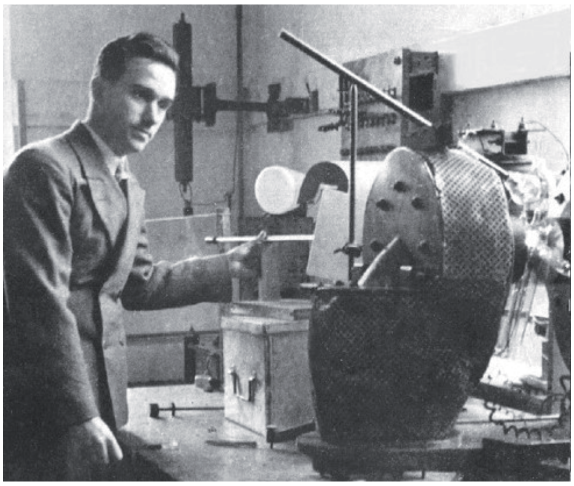


Figure 16. I. Truten.

demonstrated (in 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 [21]. E. Habann revealed (in 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 drastically increased [22]. In the same 1924 at KhSU, A. Slutskin and D. Shteinberg [18] investigated the processes occurring in electron tubes under the impact of an external field. By using the three-electrode tube, they succeeded in generating electromagnetic oscillations within the wavelength band of 40 cm to 300 cm [23]. Later, they studied the effects associated with the tube-element geometry, operation modes, and the magnetic-field strength [24]. At their request, industry manufactured diodes where the anode was made from a nonmagnetic material (tantalum) [11, 18]. By the end of 1925, these studies enabled A. Slutskin and D. Shteinberg to obtain oscillations with a wavelength of 7.3 cm. This was mentioned in the memorial paper about Slutskin [25], written by his former student Ivan Truten (1909-1990), whose picture is shown in Figure 16. Additionally, this result was stated in a book [26] with a reference to the archive materials [27]. Here, one should keep in mind that important pioneering experimental work was also published in 1928-1929 by H. Yagi [28] and K. Okabe [29], with a magnetron having a split anode in the form of two half-cylinders. It is obvious that all the works mentioned were really independently performed. From this analysis, one can conclude that there is no doubt that – together with the other researchers better known in the West – A. Slutskin and D. Shteinberg can be considered to be pioneers of the magnetron-oscillation method.

Later, many different magnetron oscillators were developed in LEMO-UIPT. In Figure 17, a magnetron with a hollow anode, water-cooled from the inside, is shown. Two half anodes were connected by tunable circuits, consisting of metal tubes for bringing in the water and carrying it away. This design, proposed by Lelyakov, later served as the basis for different modifications. Braude, Lelyakov, and Truten had developed a water-cooled magnetron in a glass case, which enabled them to achieve an output power of 5 kW to7 kW at a wavelength of 80 cm. Even higher power (up to 17 kW in the CW mode) with 55% efficiency

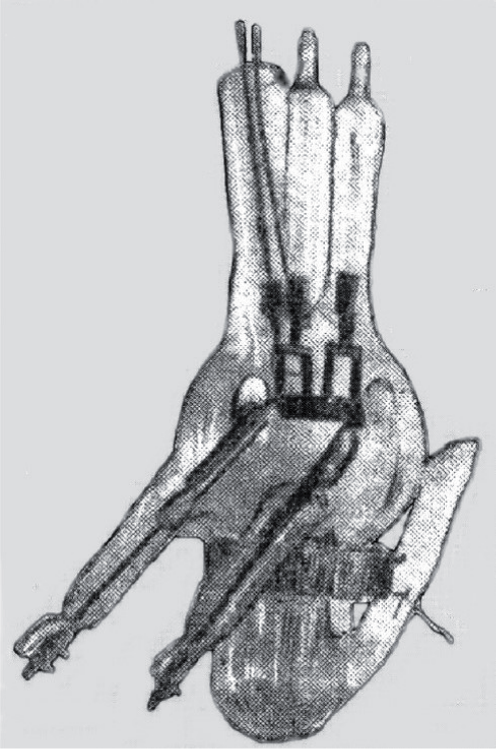


Figure 17. A magnetron with water cooling in a glass case: $P = 7$ kW, $\lambda = 80$ cm.

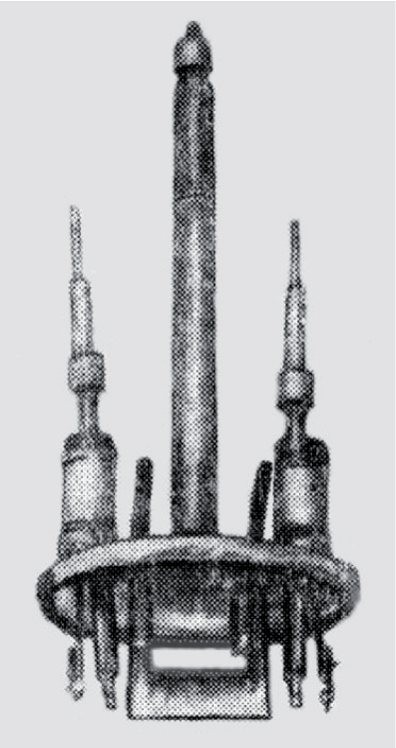


Figure 18. A magnetron in a metal case (removed): $P = 17$ kW in CW mode.

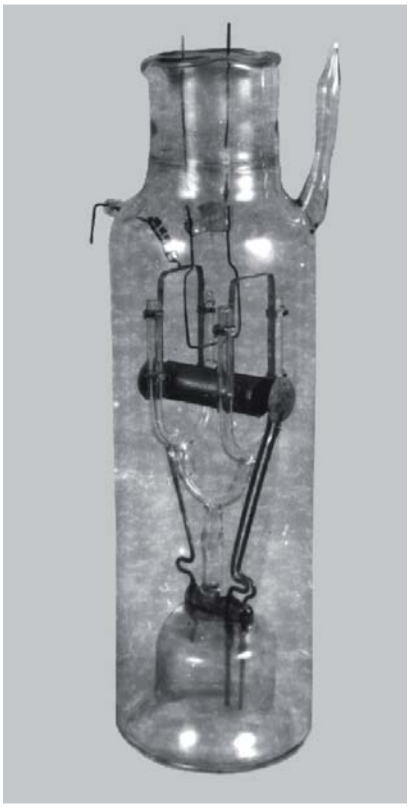


Figure 19. A pulse magnetron, $P = 60$ kW.

was achieved by Braude, in the all-metal "barrel-type" oscillator (Figure 18). Moreover, a tunable magnetron was designed, in which the frequency was tuned over a 30% band, by varying the length of the circuit extending off the metal case. These results were only published after the war, in 1946 [30].

At the same time, extensive investigations of the magnetron's power and frequency control, and the design of a pulsedmode device, were carried out. This work was led by Usikov. 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, together with colleagues [31], investigated the characteristic features of pulsed excitation in magnetrons. This work resulted in the design of high-power pulsed L-band magnetrons. At this time, a packaged un-cooled magnetron, with a linear cathode inserted in a glass case, was developed (Figure 19). It was implemented by Alexander Usikov, Ivan Truten, Iosif Vigdorchik (1910-1980), and Semion Braude. At the end of 1938, it generated pulsed power of 12 kW to 60 kW at a wavelength of 60 cm to 65 cm. Based on its own theoretical work, the UPTI thus created a series of magnetrons operating at wavelengths from 20 cm to 80 cm, with average power generation of 10 W to 100 W. More details can be found in [18].

It is worth recollecting that even earlier, the results on magnetron generators obtained by A. Slutskin were used in the CRL by Yu. Korovin's group when creating facilities for the radio detection of aircraft in 1934. Since September 1934, UPTI started to supply magnetrons of different powers and different wavelengths to the design bureau of the Red Army Air Defense.

By the end of 1936 [18], LEMO-UIPT had thus carried out a wide range of 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.

5.3 Development of the Pulsed Radar "Zenit" at UIPT

According to [2], from 1937, by decree of the PCD, the work on radio detection of aircraft for the air-defense alert service were to be the duty of the DC-RA via its body the Research, Development, and Testing Institute of Communications (RDTIC-RA): NIIIS, in Russian. Along with the problems associated with long-range surveillance for air defense, the RDTIC-RA initiated a parallel development of improved radars for anti-aircraft artillery. Having studied the state-of-the-art of the preceding developments, the experts of the RDTIC-RA concluded that they should employ the pulsed method.

The UIPT, foreseeing and following the general trend of the developments in the field of microwave radio engineering, began – earlier than other institutions – its own theoretical and experimental research in the field of generating electromagnetic waves using magnetron methods in L band, S band, and in the even shorter centimeter bands. Subsequently, these studies were a significant contribution to the development of radio-detection equipment, not only for their own needs, but also for their Leningrad and Moscow colleagues.

Further studies in this area were carried out in the LEMO at UIPT, and Abram Slutskin was the Head of the Laboratory from 1930. Based on the successful development of the generators, by the end of 1936 Slutskin launched an ambitious project on the development of the first pulse radar. This was able to determine all three coordinates of a target, while all modern (at that time) experimental systems were designed to determine only two coordinates of a target. Beginning in March 1937, in accordance with the task that was formulated by the RDTIC-RA, the UIPT officially started the design of an L-band pulse radar for anti-aircraft artillery [32]. It was tentatively named "searchlight," and had to operate at a wavelength of 60 cm to 65 cm.

In July 1937, the draft of the short-range radar for air targets (that was the name of the system for anti-aircraft artillery) was ready. It was equipped with a purposely developed magnetron of 1 kW power at a 68 cm wavelength [2].

This work, coded "Zenit," was performed under the guidance of A. Slutskin by the staff of LEMO: S. Braude,

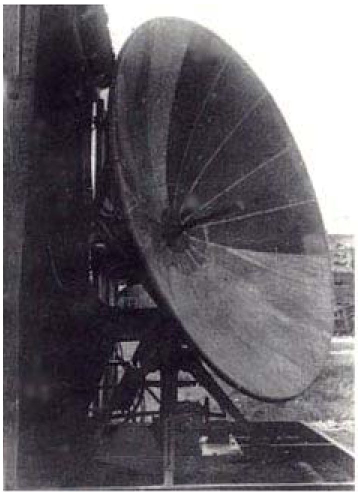


Figure 20a. The Zenit antenna.

Figure 20b. The transmitter located on the back side of the radiating reflector of the Zenit antenna.

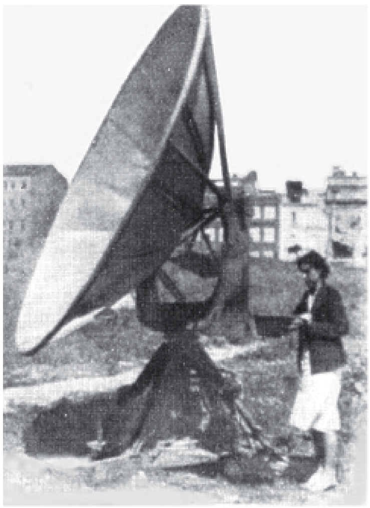


Figure 20c. Another view of the Zenit antenna.

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.

In the middle of 1938, the first test of the "Zenit" prototype was fulfilled by detecting a small airplane. Some details of this radar prototype's development were found in Usikov's archive, which has partially survived [34]. In addition, a lot of interesting facts were revealed from interviews with S. Braude, A. Usikov, and other participants in the events or their younger colleagues [11, 15, 33]. It is interesting to follow the features of the systems and its principal components.

5.3.1 Features of Radar Design

A. Usikov described this radar as a two-antenna laboratory setup, in which the reflector antennas of the transmitter and receiver were separated approximately 50 m from each other, in order to reduce jamming of the sensitive receiver due to the high-power pulses of the transmitter. Both reflectors scanned in a synchronous manner in the horizontal (0°-360°) and vertical (0°-90°) planes, thus providing a stable, parallel orientation of the antenna-pattern axes [33].

A transmitter was located on the back side of the radiating 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 focus 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.

5.3.2 Antennas

The antennas used identical all-metal parabolic reflectors, 3 m in diameter, fed by in-focus half-wave dipoles (Figure 20). A. Usikov recalled that manufacturing of the parabolic reflectors required a lot of sheet metal with a good environmental resistance. He hence he came up with the idea that it could be made of galvanized iron. This led him to a necessary but also risky action. Somebody in his team noticed that the institute buildings were equipped with rather impressive rainwater pipes, about 30 cm × 30 cm in 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 [33]. Reflector-antenna theory did not exist in the 1930s. Nevertheless, we can see that the "optimal" way to build the reflectors was found, although the performance characteristics of such antennas probably were far from optimal. The beamwidth of the amplitude radiation pattern of the antenna was about 16° in the "equatorial plane."

5.3.3 Transmitter

The development of the transmitter was led by A. Usikov, with I. Vigdorchik and P. Lelyakov participating. The transmitter was actually a magnetron source with a stabilizing resonant circuit. It was important to find a proper way for pulsed excitation of magnetrons. This led to comprehensive testing of several magnetrons, with different cathodes and anodes. 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 standard GK-3000 tubes. A relaxation-generator circuit, exploiting the TG-212 thyratron, was selected as a control device.

The first variant of the radar transmitter, in 1938, had the following parameters: wavelength, 60 cm; pulse power, 3 kW; pulse duration, 7 µs to 10 µs; magnetron voltage, 18.3 kV; pulse current, 20 A; magnetron lifetime, 50 hours. In 1940, the modernized Zenit radar used a new magnetron, with a pulse power of 10 kW to 12 kW, a wavelength of 64 cm, and a pulse duration of 10 µs to 20 µs.

5.3.4 Receiver

S. Braude, Y. Kopilovich, A. Maidanov, and I. Truten were responsible for the development of the receiver. First, they designed an original 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 airplane using 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, due to the strong dependence of the receiver's sensitivity on the magnetic field and the magnetron's emission current. That is why, along with this device, the research team had investigated a super-regenerative receiver based on the 955 type of acorn tube (a triode). This had a much higher sensitivity, and was implemented in the modernized version of the Zenit radar. Later on, to enhance the sensitivity of the receiver, I. Truten developed a superheterodyne receiver with an L-band amplifier (1940).

5.3.5 Calibration and Testing

In the summer of 1938, an experimental electromagnetic Zenit "searchlight" was assembled. 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 Kharkiv Tractor Industry [33]. 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 elevation angles 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 system. Under such conditions, a stable effect of reflection of the decimeter waves from the aircraft was observed. On this basis, the conclusion was made regarding reliable detection of the aircraft at a distance of 3 km. This result was quite appropriate for the beginning of the work [2]. It was of the same order as the first research results, obtained at CLR and LEPI (Section 2), but it was obtained using the pulse method instead than the continuous-wave method.

The test results enabled the designers to understand what should be done to improve the performance of Zenit. Satisfied with the first results, the CD-RA allocated a new project to LEMO-UIPT in May 1939. The task was to increase the radiation power and to improve the reliability. The modernized prototype radar had the following performance specifications: a wavelength of 64 cm; a pulse power of 10 kW to 12 kW; and a pulse duration of 10 µs to 20 µs [2]. It was under preparation to be transferred to industry.

In less than four months, WWII started in Western Europe. In about three weeks, it was accompanied by the Soviet campaigns against Poland, the Baltic States, and Finland. This added the zeal of military-oriented research and development work.

In September 1940, a modified Zenit radar was presented to interested customers for tests. The Department of Air Defense, the Red Navy, the PDA-PCD, the RDTIC-RA, and others were among them. Investigation of detection possibility and coordinate determination was done on a single airplane and on a group of airplanes. S. Braude was an eyewitness of this test. In his interview [11, 15], he recalled:

The mission of a bomber was to execute several turns on the flight course. First it 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 circle, the pilot turned to the opposite side, as he did not seriously consider the experiments and hoped that this deviation, in the clouds, would not be detected. He was deeply impressed that his unplanned maneuver was recorded at the ground-based station. From that moment, he became an active zealot of radar and played an important role in the fate of the Zenit project.

The final report on the test results (1940) [34] confirmed the following. The device was able to determine the three-dimensional position of a single aircraft at various heights. The range of the reliable detection and three-dimensional target-position determination at altitudes of 4000 m to 7000 m was 6 km to 25 km. At ranges of 25 km to 35 km, the detection was less reliable. Two tests were done to estimate a relative measurement accuracy. Comparisons of the airplane altitudes determined by the Zenit radar with the barograph indications revealed an average difference 8.9% in the first test, and 5.2% in the second test.

The times required to determine the target coordinates were as follows:

a. two coordinates, elevation and range: 13 sec;
b. two coordinates, azimuth and range: 17 sec;
c. three coordinates, elevation, azimuth, and range: 38 sec.

Interesting conclusions were drawn from the observations of squadrons with the Zenit radar. A group of airplanes was reliably detected at heights of 3000 m and 4000 m in the specified space sector. If a squadron was flying in tight order, the oscilloscope indicated the beating of 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. 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. Even some results concerning target resolution were obtained [34].

The generalized basic results of those tests according to [2] showed the maximum range of reliable detection of a single SB-type airplane was 25 km, and of a group of planes was 30 km. The measurement accuracy was 1 km on range, 3° to 4° degrees in azimuth, 1° to 2° degrees in elevation angle, and 10% in height.

Estimating the overall results of the Zenit tests, the state commission officially asserted [2] that the Ukrainian Institute of Physics and Technology (UIPT) had designed the first experimental setup that enabled locating a flying airplane in three coordinates (distance, azimuth, and elevation). Later, General Lobanov [2] wrote that it was a great success for the young UIPT team. Compared with the experimental radio searchers "Burya" and B-2, developed at RDI-9, the Zenit prototype had considerable advantages for the detection range, and the ability to determine all three coordinates that are necessary for shooting air-defense artillery, which was a very important quality in that time. Neither the British Chain Home nor the German Freya (which were perhaps the most advanced radar systems in Western Europe) could estimate both target azimuth and elevation angle along with target range.

However, due to some shortcomings of the Zenit prototype, the UIPT was forced to continue the work on its improvement. The first drawback was the inability to continuously determine the coordinates of the airplane and to enter them into the antiaircraft director in preparing data for anti-aircraft firing. Zenit could periodically determine target coordinates: as mentioned above, for the evaluation of all three coordinates, 38 seconds were required.

The second drawback was the difficulty in target search due to the narrow antenna pattern, similarly to radio searchers Burya and B-2, developed by RDI-9.

The third drawback was the presence of a dead zone of radius 6 km, within which anti-aircraft artillery could not fire. Meanwhile, this area was the most effective in shooting with guns of 85 mm caliber.

Finally, it was stated that the three-coordinate Zenit prototype couldn't yet serve as a basis for the industrial production. The Committee recommended that UIPT finalize the design of the station to improve the reliability of aircraft detection and accuracy of height determination, and provide continuous determination of the coordinates.

Having limited funds and production capacity, the Ukrainian Institute met with considerable difficulty in manufacturing this device [2]. Under such conditions, the fact that a group of able young scientists at UIPT not only succeeded to make the theoretical calculations and experiments necessary for developing a laboratory version of the Zenit pulse radar, but had managed to produce the radar setup on its own, was credited to the efforts and enthusiasm of the team.

In [11], a comment was made that helped better understand the situation at UIPT in that time. Along with the technical problems mentioned, the working conditions at LEMO were certainly inadequate in 1935-1938, because of the general atmosphere at UIPT during the years of Stalin's terror. At that time, the UIPT, a leading research center, was literally smashed by a series of severe repressions, with Lev Landau being the main target [26].

United by a common goal, Slutskin's people kept perfectly friendly relations, despite sharp discussions [15]. However, the climate in the institute was not favorable for healthy working conditions. 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 to the collective.

In addition, some of the leading scientists – first of all, the theoreticians – displayed neglect towards the radiophysics research, considering it second-rate physics. The gap became even deeper when UIPT started working on defense projects, which dominated in research and development carried out by LEMO. The Ukrainian historians of science Y. Pavlenko, Y. Ranyuk, and Y. Khramov wrote [26] that exactly the latter point was at the very core of the conflict at UIPT.

When the defense-oriented research was started at UIPT, most scientific leaders of the institute who normally determined the science policy were not involved into the new defense themes. The reason was not fully clear. Somebody could refuse to participate in the military projects, feeling that this would inevitably limit the freedom of research. It could also have been possible that they were not allowed to do so by the then-director of the institute or by the NKVD/KGB. Meantime, military projects had preference; moreover, the scientists involved were paid greater salaries. This resulted in splitting the institute into two conflicting groups, each of which had its sympathizers beyond the institute. In accordance with [35], part of the UIPT scientists, including Landau, proposed to separate LEMO from the UIPT. 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, while the less-fortunate fields of genetics and cybernetics (computer science) were crushed [36]. In this connection, from the view of the story on Ukrainian radar development, the most important point is that Lev Landau, the indisputable informal scientific leader of UIPT, who was really a very bright personality, did not stay away from this internal conflict. All who left their opinion in any form [35], including the NKVD informers whose observations were summarized in the voluminous file on Landau in the KGB [37], agreed that Landau's attitude toward the radar project at LEMO (and so personally toward A. Slutskin) was negative. Although this was his general attitude toward the military research in the USSR throughout all of his life, he later never openly expressed it [37], and 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 "Trotskyist-sabotage group" accused of "trying to spoil defense works in UIPT" [26]. Landau then escaped to Moscow, to work in the Institute of Physical Problems of Piotr Kapitsa. Nevertheless, 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 used military nuclear-program research as a shield against the persecutions [36].

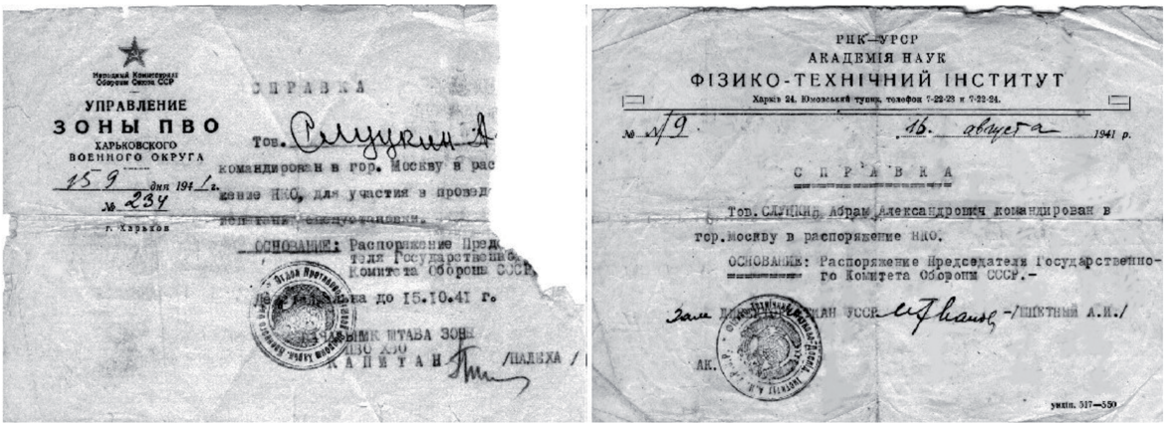
Working on overcoming the indicated drawbacks, UIPT also tried to increase the energetic potential of the Zenit setup to increase the detection range. In 1939-1940, the situation inside UIPT became somewhat more favorable for LEMO. The work schedule of the laboratory for 1941 foresaw solving the problems around the improvement of Zenit, and the development of a single-reflector pulse radar, Rubin.

However, the beginning of the war on the territory of the USSR infringed on these plans. It is well known that Moscow experienced its first air raid on the night of July 22, 1941. Under these circumstances, the DC-RA offered to check the feasibility of using the Zenit system in combat situations for the air defense of Moscow [2]. Even before, at the very beginning of the war, the pilot who took part in the 1938 tests of Zenit in Kharkiv wrote a letter to Stalin, and urged him to deploy this promising detection system [11]. On August 16, the LEMO staff members S. Braude, A. Chuhakov, L. Kitaevsky, Y. Kopilovich, A. Maidanov, A. Slutskin, A. Terpilo, I. Truten, A. Usikov, and I. Vigdorchik were sent to Moscow, and added 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 21. They played the role of identification, guaranteeing a safe passage to Moscow [11].

Braude [15] told about an occurrence that happened during their work in Mytishchi. A group of soldiers were assigned to the radar team. The moral atmosphere at the beginning was full of tension. Of course, people did not have any understanding of the radio-detection principle, and groups of healthy men staying in the rear could be considered to be escaping from military service. The situation changed when the team succeeded 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 antiaircraft artillery.

In September 1941, after further testing, the commission, chaired by the deputy commander of the air defense corps, Colonel Makeev, noted [2]:

- 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;



Народный Комиссариат
Обороны Союза ССР

УПРАВЛЕНИЕ
ЗОНЫ ПВО
ХАРЬКОВСКОГО
ВОЕННОГО ОКРУГА
15 9 дня 1941 г.
№ 234
г. Харьков

СПРАВКА

Тов. Слуцкин А.
командирован в гор. Москву в рас
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ОСНОВАНИЕ: Распоряжение Пред
теля Государственно
Комитета Обороны СССР

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РНК—УРСР
АКАДЕМІЯ НАУК
ФІЗИКО-ТЕХНІЧНИЙ ІНСТИТУТ
Харків 24. Юмовський тупик, телефон 7-22-23 и 7-22-24.

№ 9 16. августа 1941 р.

СПРАВКА

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

ОСНОВАНИЕ: Распоряжение Председателя Государственного Комитета Обороны СССР.-

Зам [illegible] АН УССР -/ШИКТНЫЙ А.И./

АК.

укліт. 517—550

Figure 21. The certificates given to A. A. Slutskin in 1941 for the journey to Moscow and participation in the tests of "Zenit" in combat conditions.

- 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 (see Section 7). Further modifications could be developed only under laboratory conditions. However, such work was not possible at that time, neither in Moscow nor in Kharkiv. 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 its way to central Asia. As is known, in the summer of 1941, the situation on the Soviet-German front dramatically developed. In the first days, the cities of Riga and Minsk were lost, and rather soon, the German tank armies were threatening Moscow. The more-successful defense of Soviet troops in the Kiev direction put a serious strategic problem to the German commanders. On August 23, 1941, at a meeting in the headquarters of the "Center" group of armies, Hitler rejected a proposal by General Guderian to concentrate all the forces for an offensive on Moscow, and decided to attack East Ukraine from the north. Kharkiv, which is located to the east behind Kiev, was in the mainstream of the new German offensive. After the fall of Kiev, at the end of September, the fate of Kharkiv was determined, and on October 24, the Red Army left it. However, much earlier, in July 1941, the State Defense Committee had decided to evacuate the heavy industries of Kharkiv to the east. Obviously, the 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"

In 1939-1940, along with designing the Zenit radar, LEMOUIPT performed three research and development projects for the CD-RA: "Generator and Receiver Operating in cm-Band," "Application of the Independent Excitation Principle for Generating Frequency-Stable dm-Band Pulses," and "Design of a High-Power Pulse Source at dm-Band Stabilized by a Resonant Circuit" [2]. The results of these studies, as well as the experience accumulated during development and testing the Zenit radar, enabled LEMO to proceed with the design of the "Rubin" radar in 1941. This system had to have increased target-detection range and improved accuracy of target location. Nevertheless, perhaps the most interesting aspect was the development of the single-antenna system for both transmitting and receiving. Unfortunately, the rapid approach of the front line forced LEMO of UIPT to stop working as early as in July 1941, and to pack the equipment for a long trip. The final destination for the UIPT was Almaty, Kazakhstan; except for LEMO, which was evacuated to the city of Bukhara, Uzbekistan, over 3500 km away from Kharkiv, and 1500 km from Almaty. Located in the heart of Central Asia, Bukhara city had a glorious past. Before 1920, it was the capital of the Emirate of Bukhara, a multi-national Muslim country that was under the protectorate of the Russian Empire.

In fact, the separation of the radiophysics laboratories of UIPT that was proposed by "pure physicists" in 1937 was thus done by the war: the LEMO was separated from the

Figure 22. The group from UIPT and RDTIC-RA in Bukhara, February 23, 1942.

other departments of UIPT. After WW II, UIPT returned to Kharkiv, and all its laboratories were again working together. Here, history took a curious twist [11]: 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 enjoyed the benefits of working on extremely important defense topics, except for two radiophysics 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 mmwave plasma-diagnostics technologies for Tokamak fusion machines, it was decided to separate these departments from UIPT, and to establish a new institute, the IRE. It is worth noting that Slutskin was against this separation, which was approved only after his sudden death in 1950.

However, let us go back to Bukhara of 1942. The work on the Rubin project was resumed there, in collaboration with the RDTIC-RA, which was also evacuated to Bukhara (Figure 22). 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 Kharkiv. In place of Lelyakov, L. Kitayevsky joined the project as a radio engineer.

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 in the design. The pulsed power of the magnetron was increased up to 15 kW. The improved receiver was essentially a wideband superheterodyne, with double frequency conversion. It had a high-frequency part (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 a truck. 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 providing the operation of a radar with a single antenna and also protecting the receiver from the impact of a high-power source pulse. This was done by employing a gas discharger, which 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 provided.

Figure 23. The antenna unit of the single-antenna radar "Rubin."

S. Braude recalled [15] that I. Truten was an innovator with extraordinary capabilities. A fundamental approach was always present in his research, and was especially brightly displayed later, when he guided the work of developing the mm-band magnetrons in the 1950s and 1960s at IRE, enjoying huge respect among the staff.

The antenna of the Rubin was designed as a paraboloid of revolution, 3 m diameter, with transmitter and receiver dipoles located in the focus (Figure 23). The dish was deployable, and consisted of six removable segments, made from 2-mm diameter wire. As recalled by Usikov [33], the wind loading was really strong for such large-size reflectors. Hence, it was clearly necessary to resort to a mesh-antenna design. These were made from wires stretched on the ribs, and soldered with a spacing of 20 mm × 20 mm. All this was handmade by the team members.

The beamwidth of the antenna pattern's main lobe (at the halfamplitude 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 housed in a hermetically sealed case on the back of the reflector. Rotation of the antenna in the vertical (0° to 90°) and horizontal (0° to 400°) planes was remotely controlled. These data, together with the terminology, were based on the memories of those who heard them from the designers, because there is no technical documentation available about Rubin and its antennas, or about the Zenit system.

All of the Rubin equipment (Figure 24) was placed on two cars: one for the power supply (a ZIS-6 truck), and another one for the electronics (a GAZ-3A truck). On the first car, the antenna system was installed on special rails.

Figure 24. The full set of the Rubin system.

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. That consisted of a three-phase generator (PNT-100) and a petrol engine (L-12). The modulator unit and the oscilloscope display, together with the antenna's remote-control system, were located on the electronics vehicle. The deployment and setting-up of the Rubin radar took about three hours.

In 1943, Rubin was transported to Moscow, where it was tested until November. In early 1944, the DC-RA sent the Rubin radar to a polar port and naval base in Murmansk, according to the agreement with the Red Navy Command. From February 1 until March 31, 1944, tests of the radar were performed there, led by Usikov. The place for the deployment of the radar 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 were the data regarding detecting airplanes and ships found in Usikov's archive [34].

6.1 Aircraft Location Tests

The tests were normally carried out to detect occasional airplanes.

To verify the accuracy of target location, a Hawker Hurricane once made a purposeful flight along the specified route. When flying over the sea, it was first detected at a distance of 60 km. Determination of the airplane's position at a distance of 40 km was reliable. During the tests, the Rubin system was able to detect the airplanes many times, which flew at very low altitudes (30 m to 50 m).

The average errors of estimating coordinates were up to 120 m in range, and no more than 0.8° in azimuth and elevation. The time required to measure any of angular coordinates never exceeded seven seconds.

6.2 Ship Location Tests

It should be noted that the area of testing was a relatively small, open space, and the rocky coast was 5 km from the radar. It was rather complicated to make tests under such conditions. Despite this, the tests showed that:

- "Rubin" detected all types of ships – cruisers, destroyers, transport ships, surfaced submarines, motor boats, and even wooden boats – at distances from 500 m to the limit of available range, that is, about 5000 m.
- The amplitude of the reflected signal was dependent on the type and size of the ship.
- The amplitudes of the reflected signals were not stable: they changed in time, with the fluctuation frequency depending on the vessel's size and speed.
- The average errors in the accuracy of determining the coordinates of targets were not more than 120 m in distance and 0.8° in azimuth.

Usikov was always proud of this achievement, and claimed that their team, led by Slutskin, received the best results in radar in the USSR at that time. Up to the end of the war, Rubin worked in the polar sector of the Soviet-German front for air and naval surveillance. Nevertheless, this unique and promising radar system was never launched into mass production. We do not have a clear explanation of that fact.

7. Observation of the Atmospheric-Duct Effect in Bukhara

During the work in Bukhara, LEMO scientists saw a mysterious phenomenon, which had never been previously reported. In the notes by Usikov [33], it was described the following way.

At a time when the tests of the new Rubin radar were in full swing, the specific effect of intensive repetitive noise practically spoiled all the work. It was manifested in the form of unusually strong reflections of the type of terrain objects, but at all ranges within a radius of 180 km. It was a kind of "blindness" of the radar, which suppressed the radar signals, reflected not only from the aircraft but also from local objects that acted as landmarks.

Powerful interfering reflections were observed in May to July 1942 by Usikov, Truten, and Vigdorchik. The reflections occurred at different times, usually in the afternoon, and their origin was difficult to understand. Scanning the antenna beam within the sector of 90° in azimuth and 70° in elevation was practically useless. These difficulties often even forced the researchers to cancel the planned tests.

This phenomenon had never been observed, either in Kharkiv nor in Moscow, but was manifested in Bukhara. Usikov and his colleagues therefore named it the "Bukhara effect." They guessed that the nature of this phenomenon might be due to extreme weather conditions, typical for the sandy desert terrain in the vicinity of Bukhara. More specifically, they concluded that the effect of Bukhara was caused by a sharp decreasing natural attenuation of decimeter waves propagating over the deserts of Kyzyl Kum and Kara-Kum. This made it possible to observe strong radar reflections from the local objects, located on the all way from radar to the Aktau mountain, 150 km to 180 km northeast of Bukhara. The inability to avoid these reflections by rotating the antenna was attributed to a multi-lobe directional pattern [33, 38]. Recall that the first description of the surface-waveguide propagation effect (an atmospheric duct) was given in 1946 [39]. Inside the natural channel (duct), the electromagnetic field propagates as a cylindrical wave, instead of as a spherical wave in free space, although other mechanisms exist.

As a result, the maximum range of the L-band radar under the special circumstances could exceed the range in free space by 15 times or more [40]. Normally, the ducting effect was observed over the sea. According to [41], the long-distance record was 1700 miles, between India and Arabia.

These observations and the discovery later led S. Braude to new results and the creation of the over-the-horizon radar in Kharkiv, after the war. The work on the over-the-horizon radar was started there, using decameter and hectometer waves. The work was successfully continued at home, after Kharkiv was liberated in 1943.

In 1952, S. Ya. Braude et al. were awarded the State Prize (then, the Stalin Prize) for this work [32].

8. Radar for Long-Range Detection

8.1 The First Work in LIPT

In the summer of 1935 A. F. Ioffe (Figure 25), the director of LIPT, organized a special laboratory for work on the problem of aircraft detection at his institute. D. Rozhansky, who earlier worked in Kharkiv, was assigned to be head of the laboratory. The reader will remember that in Kharkiv, Rozhansky met Yuri Kobzarev, a student of KhSU who assisted him with measurements; Kobzarev was then invited to Leningrad as his assistant. Rozhansky also invited V. I. Bunimovich, another of his pupils from Kharkiv (UIPT), to join his lab [53]. Bunimovich (together with his teacher) developed the basics of the hollow resonators that were important elements of radar transmitting devices. Later, Kobzarev recalled [5] that at the beginning of the work in Leningrad, Joffe invited him to his office, and directly said that the main task of the laboratory staff was creating pulse technology for radio detection.

When Kobzarev arrived at the laboratory, two young people – N. Chernetsov and P. Pogorelko – already worked there. They both were students engaged in degree theses under the supervision of Rozhansky. Chernetsov was engaged in the design of broadband IF amplifiers, and Pogorelko was engaged in the design of a reference oscillator to calibrate the receiver. The issues of antenna-feed device development, plus creating an input converter and an output device (later, the oscilloscope electronic device), became the basic tasks of Kobzarev (Figure 26).

It was necessary in the short term (by the fall of 1935) to produce equipment that would allow obtaining

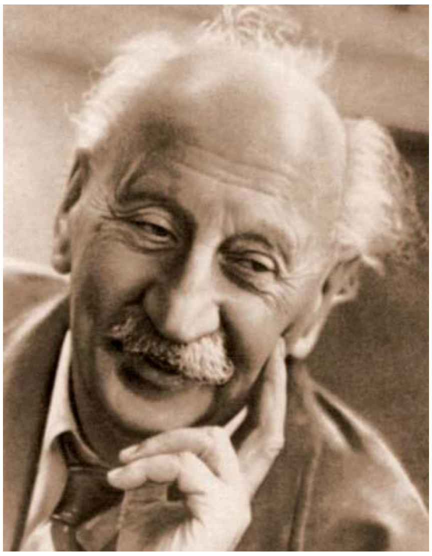

Figure 25. Abram F. Ioffe.

Figure 26. Yuri B. Kobzarev.

Figure 27. A. Maleyev (laboratory assistant), Yu. Kobzarev, P. Pogorelko, and N. Chernetsov (1937).

quantitative characteristics of the reflection of radio waves by aircraft in the real world. The first experiments were carried on with a continuous-wave transmitter.

Although the basic equipment was developed in Leningrad, the test was planned in the suburb of Moscow. In the laboratory of P. Oshchepkov in Moscow, the transmitter was developed, operating in continuous-wave mode with a carrier wavelength of 3 m to 4 m, modulated by a 1 kHz oscillation. In the winter of 1935, the equipment was brought to Moscow, where the first major test was held. During this test, Kobzarev wrote [5] that a lot of valuable material for further work was obtained.

Oshchepkov's transmitter was located in the building, while the antenna was installed on the roof. The receiver was of the superheterodyne type, and had a wide bandwidth (because it was supposed to be used for receiving pulses). The detected signals from the IF output of the receiver were used to excite the oscillating circuit of high Q, tuned to the transmitter's modulation frequency.

The set of equipment also included a reference oscillator, developed by Pogorelko, which was used to test and calibrate the receiver. Both devices were powered by batteries, and could easily be transported from place to place.

The receiver was installed at various points in the area of the airfield near Moscow. An airplane flew around it in circular paths of different radii and at different heights. The signals reflected from the airplane were manually read and recorded.

The radiating and receiving devices in this system were located along a line parallel to the border being defended. The intersection of this line by the airplane could be reliably recorded. Such a system was later developed, and in September 1939, put into service under the name "RUS-1."

This was operated in 1940 on the Karelian Isthmus, during the Soviet-Finnish war. However, there were difficulties with the determination of an airplane's identification, and during the German-Soviet war, the system "RUS-1" was relocated to a less-critical part of the border, in the Caucasus and in the Far East. It was later replaced by the pulsed radar "RUS-2" and "Redut," which had incomparably better quality.

By the end of 1936, the preparatory work for testing the pulse method itself was completed in LIPT. At this time, the leader of this work, Prof. Rozhansky, passed away. Management was transferred to Yu. Kobzarev.

8.2 The First Tests of the Pulse Method

The beginning of tests was delayed due to difficulties with transmitter development in the labs at the Experimental Sector of the Air Defense Department, where the person responsible was Pavel Oshchepkov. Finally, in March 1937, the lab staff from LIPT (four persons) arrived in Moscow. In Figure 27, one can see all of the young LIPT team on the range of the Experimental Sector in April 1937. Fortunately, we have some details of the events and features of the equipment from the memories of the principal participant [5].

After checking their equipment, they waited until the powerful transmitter, installed in Moscow, would operate. However, they could not receive a signal from that transmitter: the task of control by the powerful pulse generator had not been resolved in Moscow. Nevertheless, the desire to carry out the planned experiments was so great that a small team created its own experimental setup for radio detection.

They used the reference oscillator added by a control oscilloscope, and a modulator that converted the continuous radiation into RF pulses. Such a pulse modulator with the reference oscillator operated as a master oscillator. They hastily constructed an amplifier circuit for the RF pulses. The amplified pulses were applied to the grids of VHF vacuum tubes, which were controlled by these pulses. Such a pulse generator was a low-power transmitter (about 1 kW pulse power), but worked quite stably.

The pulse-repetition frequency was about 1 kHz, and the receiving oscilloscope device was designed for exactly the same frequency. It had a CRT at the output, and the voltage from the last oscillation circuit of the IF amplifier was applied directly to the deflecting plates of the CRT.

Because of the low radiated power, the maximum range of such an experimental setup was rather small. Nevertheless, the observations of the RF pulses reflected from the airplane, implemented with the help of this

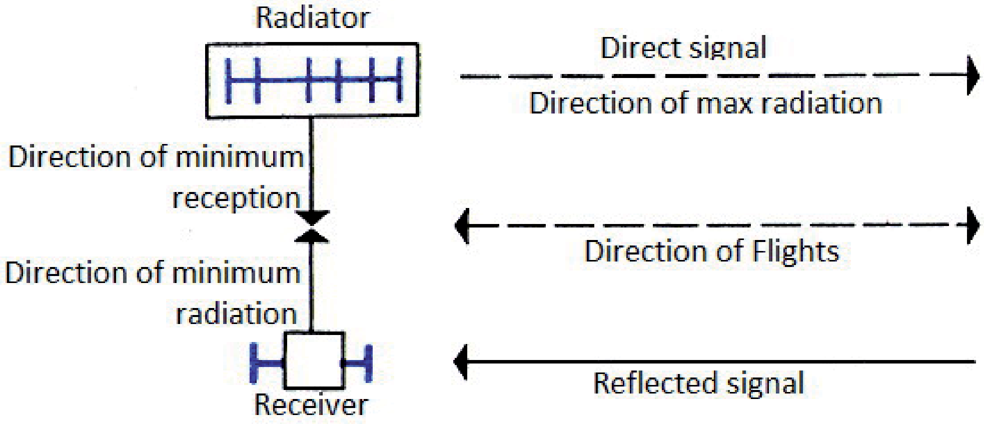

Figure 28. The layout of the experiment done by Yu. Kobzarev and his team in 1937 [5].

equipment, had a decisive influence on the entire course of further work.

From a modern viewpoint, this setup was equipped with a rather strange display. The oscilloscope's sweep was a helical curve. The beam-deflection voltage in the horizontal plane from a special low-frequency circuit was applied directly to the plates, and the beam deflection in the vertical direction was produced by the action of the magnetic field of coils in the same circuit. The damped oscillations of that circuit were excited by a special device that operated synchronously with the sounding pulses, but a little bit earlier. This was done in order that the beginning of the sounding pulse and the start the reflected pulse could be clearly marked on the sweep (helical curve). Knowing the oscillation frequency of the sweeping circuit, it was possible to measure the angular distance between the beginning of the two pulses with good accuracy. The measured angular distance was proportional to the time delay of the reflected pulse, and the distance to the target (airplane) was therefore determined.

The receiving device was mounted in a small metal cabin, and the antenna was installed on the roof of the cabin. The cabin could rotate around a vertical axis. The antenna system consisted of two half-wave dipoles, coupled by a coaxial feeder with the input of the receiver circuit. A special device allowed adjusting the degree of coupling between the receiver and each dipole. The relative position of the half-wave dipoles, the direction to the transmitter, and the direction of the airplane's route created the conditions for mutual compensation (in the input circuit of the receiver) of signals coming from the transmitter to the dipoles, and adding the signals reflected from the airplane. The arrangement of the equipment in the experiments (in 1937) is illustrated in Figure 28. In this figure, the transmitting antenna consisted of six half-wave dipoles, and the receiving antenna consisted of two dipoles spaced by a distance equal to the wavelength. The distance between transmitting and receiving equipment was very large.

The first flight was on April 15, 1937. Yu. Kobzarev recalled: "Our excitement was very great; but we were lucky." The reflected signals were surely observed at those parts of the sweep that were not occupied by "local objects." It was recorded in the photographs in the form of short breaks of the helical sweep. A photograph of the screen that indicated the reflected pulse is shown in Figure 29. The angular distance between the beginning of the sounding pulse and the reflected pulse determined the range to the airplane. In the case given, it was 12.5 km. The altitude of the aircraft was given in advance, and in this particular case, it was 500 m.

Upon completion of work at the range, it was decided to help the Experimental Sector in the development of a powerful modulator for the transmitter, based on vacuum tubes. By the end of 1937, it was decided to finalize the one-point radar (monostatic system) with a detection range of at least 50 km. The LIPT and Air Defense Department

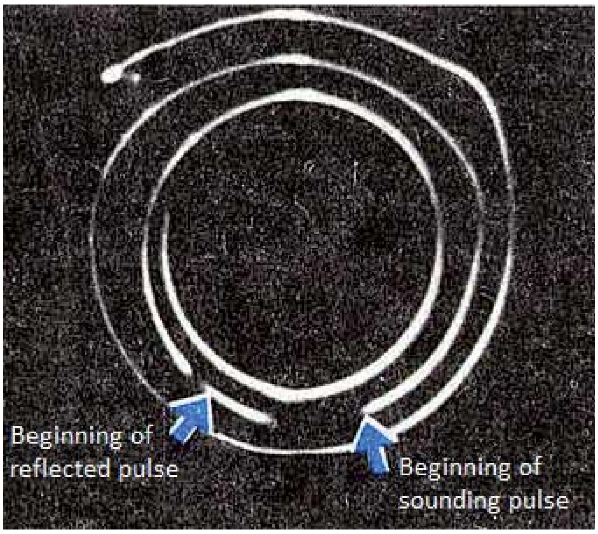

Figure 29. A photograph of the screen during an experiment in 1937 [5].

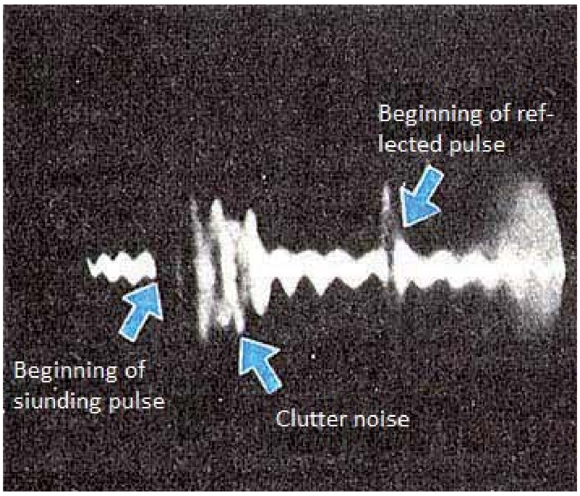

Figure 30. A photograph of the oscilloscope screen in the experiments of 1938 [5].

Figure 31. A. B. Slepushkin.

made a relevant contract, but the circumstances suddenly changed. In the summer of 1937, the Experimental Sector was eliminated. All its equipment and all the cases were handed over to the RDTIC-RA (NIIIS), subordinated to the DC-RA of PCD.

P. Oschepkov was arrested. He received 10 years in the Gulag. When his term ended and he was released, he never returned to the subject of radar, although he later became a professor and doctor of technical sciences in another field. In his memoir book [1], the second edition of which was published in 1976, he was allowed to write only the following: “In 1937 I moved away from the work on the radar, and to write its further history is not my business.”

The LIPT was told to bring the work to the end on their own. Additional work and responsibility to develop a high-power transmitter led to an overload of the team, and to the delay of the entire work. Nevertheless, by the end of 1937, the development of the modulator for the powerful transmitter was nearly completed, but the generator operated with irregularities. Furthermore, it was necessary to fabricate apparatus that could be transported without damage, and to solve the problem of transmitting high-frequency pulses of high power from a closed space to an outdoor antenna in any weather. The final solution to all these issues was only completed in the summer of 1938.

The equipment was manufactured, transported to Moscow, and installed in two buildings spaced approximately 1 km apart. The buildings belonged to RDTIC-RA. One of the buildings was located on a hill, and had a small add-on to the top floor: a 4 m × 4 m room, with access to a small platform on the roof. Another building was located in a valley. The receiver and display device were located in the superstructure of the first building. The receiver was coupled with the antenna installed on the roof. The transmitting unit and a similar antenna were located in the second building.

When designing the transmitter, it was necessary to decide whether to keep a high repetition rate (about 1 kHz), on which work was carried out in 1937, or to be satisfied with a much lower frequency: the frequency of the power network (50 Hz). They used 50 Hz, in spite of the obvious disadvantage, just because it was much simpler and easy to do. Another change was made in the display, with the sweep made linear, not helical, as in the previous version. A picture of the oscilloscope’s screen in the experiments of 1938 is shown in Figure 30. The line of the sweep was made to be a wavy line, to simplify measuring the range of the target (in the case shown, the range was 30 km).

8.3 Involvement of Industry

According to [5], having received the message about the outcome of the tests, Joffe tried in every possible way to speed up the difficult issue of bringing the radio industry to radio-detection system design and production. The path from laboratory setup to industrial design (and even the

Figure 32. S. P. Rabinovich.

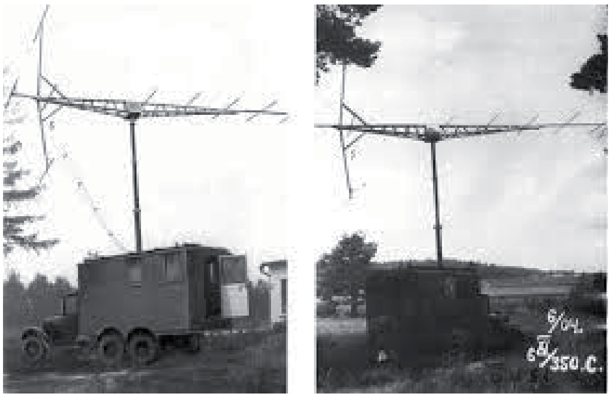

Figure 33. The two-antenna radio-detection system "Redut."

transportable system, as was required by NIIIS) was not easy. The radio plant did not give up taking on this task, but they set an unacceptable cost for the first prototype and for the duration of its manufacture. Therefore, NIIIS decided to make a transportable prototype on their own, using the existing equipment of LIPT. They nevertheless continued the search for a contractor from industry. Finally, an acceptable contractor was found (the R&D Institute of Radio-Industry). In April 1939, the Defense Committee of the Government made a decision about the development (with the participation of employees of LIPT) of two sets of transportable stations for the radio detection of airplanes. The work was headed by A. B. Slepushkin (Figure 31). L.V. Leonov was engaged in transmitter development, S. P. Rabinovich (Figure 32) in the oscilloscope indicator, and V. V. Tikhomirov (1912-1985) in the receiver.

As a result of these efforts, in 1939, the NIIIS created a prototype with two antennas. It was named "Redut" (Figure 33). The units and other equipment of LIPT were used in the Redut system. It was a transportable prototype, consisting of two automotive vans with the equipment inside, and antennas on the roofs. This made it possible to conduct comprehensive testing of the system, in particular, to determine the dependence of the range of its functioning on the height of the airplane. The testing was held in the autumn of 1939, in the region of Sebastopol, Crimea. Kobzarev took part in those tests. During the tests, it was demonstrated that an aircraft located at 150 km from the Redut was detected. It became clear that exactly this detection range (150 km) was reasonable as a requirement for future industrial sets. Shortly after the Redut was tested in Sebastopol, the USSR started the war against Finland. Because of this, at the initiative of A. Joffe, the Redut prototype was installed on the Karelian Isthmus, and during the war it was used in military operations.

At the beginning of 1940, two operational systems were manufactured by the R&D Institute of Radio-Industry. The system consisted of two cabins spaced by 300 m, which could synchronously rotate (Figure 34). One of the cabins had a transmitter installed in inside, and the other one carried the receiver. A more-detailed description was given in [2]. The composition of each system (station) included:

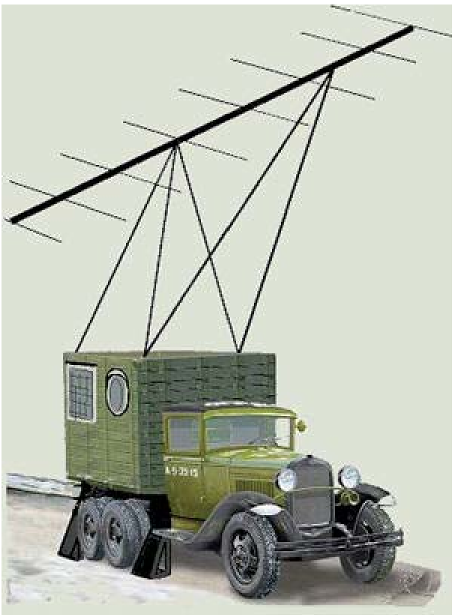

Figure 34. The Redut system, with rotating cabin.

- A generator (50 kW at a wavelength of 4 m) mounted inside the cabin, which rotated on the chassis of a ZIS-6 truck.
- Receiving equipment and a display with a sweep on the CRT screen with a length of 150 mm to 180 mm, designed for a detection range of 100 km, in the similarly rotating cabin on the second car, a GAZ-3A truck.
- Two Yagi antennas, rigidly reinforced at each of the cabins with synchronous rotation. The antenna had five directors, one active dipole, and a reflector.
- A power unit of 30 kW to 40 kW power, mounted on the GAZ-3A car (the third car of the station).

In July 26, 1940 this "station" was put into service under the name "RUS-2."

After the first two samples, ten more sets of the same station were fabricated. The operational work with them was extremely difficult, due to the continuous rotation of the cabin, and work on improving the station continued at a rapid pace. In particular, a high-frequency current collector was developed: a device that allowed the antenna to rotate while the equipment, located in the cabin, remained stationary (Figure 35). The modulation scheme was also improved.

8.4 Stationary Radar System

During the USSR-Finland war (the Winter War), it was decided to build a large fixed radar system in front of Leningrad, with increased operating range, for the air defense. The construction of this system was carried out extremely rapidly. The radar system consisted of two 20 m towers, separated by 100 m, on the bank of the lake. The towers were booths, with antennas on the roofs. One

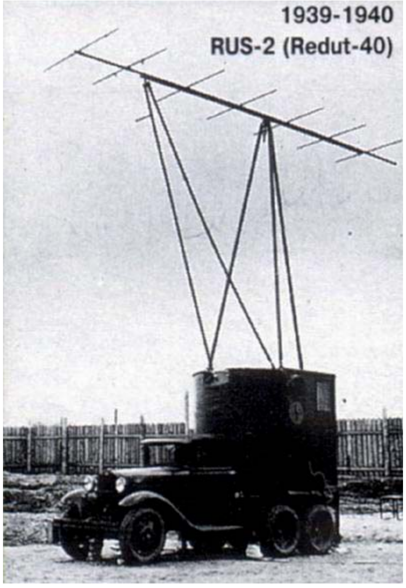

Figure 35. The modified RUS-2 radar station.

booth housed the generator, while the other booth housed a receiving device and oscilloscope. The antennas were connected by a steel cable, and could be synchronously rotated within a sector of 270°. A house with a room for the modulator, the control oscilloscope, and lounges for staff was built next to the tower with a generator.

After the Winter War, the stationary radar station was used by LIPT for further research. One of the works carried out at the station was testing under real conditions the ways proposed by P. Pogorelko to combine the transmitting and receiving antennas. Reception was conducted both on the transmitting antenna and on the "native" antenna in the receiving-antenna tower. The tests, carried out in July 1940, showed that the signal from the aircraft appeared and disappeared on both screens at the same time, which proved the possibility of creating a radar with a single antenna, with the same range.

Shortly before World War II came to the territory of the USSR (June 22, 1941), the government issued a decree, awarding the USSR State Prize (Stalin Prize) to a group of outstanding scientific works and inventions. The staff of the LIPT laboratory, who created the pulse radar system (Yu. Kobzarev, P. Pogorelko, and N. Chernetsov) were among the awardees. In his memoir, Kobzarev noted: "It is regrettable that the initiator of the work, P. K. Oschepkov, was not included into the team of awardees." He was already in the Gulag in that time.

9. Airborne Radar Systems

Another work of the R&D Institute of Radio-Industry, done in the pre-war and war years, also deserves to be commented on: the creation of the airborne radar, providing the possibility of guidance to fighters at night. Moreover, radar stations for detection of aircraft from ships of the Navy were developed and found wide application, but will not discussed be discussed in this paper.

The idea of using radar in fighter aircraft appeared in 1939. This question was debated in the Research Institute of Air Force in 1939-1940. Once upon a time, in 1939, observing the operation of the Redut radar during the war with Finland, the chief of the group of the special services department of the Air Force Institute, General S. A. Danilin, conceived the idea of using radar principles onboard of night combat aircraft. Danilin discussed it with the leading engineers of his departments. The panelists proposed various ideas for creating devices for night combat. Some proposed to use infrared equipment, others proposed acoustic equipment with a piezo-crystal receiver, while a third (engineer E. S. Shtein) suggested the use of radio detection. Danilin warmly supported the last proposal, which called for the creation of equipment similar to Redut. It was this ground-based station that became a prototype of an onboard radio detection device for the Air Force [42].

The goal was to identify fighter-bombers at night and under cloud conditions to create a means of night fighting. Initially, the frequency band of 15 cm to 16 cm was proposed, based on a klystron transmitter in pulsed mode [43]. The difficulty was in placing the equipment on the aircraft, as the mass of this equipment in those years (together with power supplies) reached 500 kg. Another problem was the combination of simultaneous control of the aircraft and radar system. In practice, a fighter pilot could not simultaneously fly a plane, search (with radar) for the enemy, and fire upon the enemy.

It was decided to install radars not on a single-pilot aircraft, but on the two-seater plane: the Pe-2 dive-bomber. The team of designers was led by V. V. Tikhomirov (Figure 36), and included R. S. Budanov, A. A. Fin, A. R. Volpert (1908-1988), and I. I. Volman (all from RDI Radio-

Figure 36. V. V. Tikhomirov.

Industry). Initial tactical and technical requirements for the first onboard radar at that time were pretty primitive:

- Detection range (by plane): 4 km to 5 km
- Zone of detection in azimuth: 120°
- Detection zone in elevation angle: 45°

9.1 Gneiss

According to these requirements, a mock-board radar, "Gneiss-1," was created. Due to a lack of the necessary klystrons, meter waves were subsequently used. The new version was called "Gneiss-2" (Figure 37). It was officially taken into service in 1943, but they really started using these radars even earlier, in 1942, at Stalingrad. The principal parameters of Gneiss-2 were :

- Carrier frequency: 200 MHz
- PRF: 900 Hz
- Pulse duration: 2 μs to 2.5 μs
- Max range: 3.5 km
- Pulse power: 10 kW
- Azimuth error: ±5°

The next airborne radar developed was "Gneiss-5" (1944). The maximum range of airplane detection was 7 km. It was a step forward: it used new devices and had higher reliability. In 1945, airborne radars were also commissioned to detect surface ships, and these were developed based on Gneiss: "Gneiss-2M" and "Gneiss-5M." They used the new antennas that allowed detecting both air and surface targets. The range of "Gneiss-5M" on ships was 10.5 km to 36 km, depending on the tonnage of the ship, and the coast-detection range was 60 km.

At the end of the war, the first panoramic radar was created. It was designed as a radar bombing sight, and also for navigation purposes. These radars became the prototypes for the navigation radar of civil aviation: RLV-DL, BPR-4G, ROS-1. These were followed by the airborne radar of the second generation, the meteorological and navigation radars. The first of these was "Groza" (Thunderstorm), developed in Leningrad in the early 1960s. For many years, it was produced in Kiev at the "Communist" plant. The development of new weather radars and their production was subsequently fully transferred to Kiev, where the new family of "Groza-M" radars was created. The next step was the development of radars with digital signal processing and color television images, the first of which was MNRLS-85, established in Kiev (the chief designer of which was Volodymyr Belkin).

10. Identification Friend or Foe

All radio-detection systems mentioned above were in fact autonomous primary radars. The history of secondary radars (i.e., systems consisting of interrogators and transponders) also began during World War II. After solving the problem of long-range detection of aircraft and equipping air defense with radars, an additional task emerged. Not only was detection of an aircraft important, it was also necessary to determine the identity of the detected airplane: either "friend or foe."

In May 1940, DC-RA and LIPT signed a contract for the development of the airplane responder, which had to work with the ground-based radar "Redut." Kobzarev recovered the stationary radar that was built on the outskirts of Leningrad, to be used by LIPT for further research. In particular, the experiments were carried out to establish a system for recognition of own aircraft. Based on the study of the scattering of radio waves by planes and estimates of the radar cross section, it was supposed that by placing a half-wave dipole on the airplane, and connecting it at the middle in a pre-determined order, one could cause a change in the magnitude of the reflected signal in the same order. Experiments carried out to implement the idea of such a "passive identification device" failed.

A group of experts of LIPT – N. Alekseyev, D. Malyarov, and Yu. Korovin, reinforced by S. Braude from UIPT (Kharkiv) – then [2] developed an "active responder." This was, a device that generated and emitted a pulse in response to the sounding waveform that came to the airplane equipped with such an active responder. It was a kind of a regenerative receiver. This device was successfully tested in the last pre-war days.

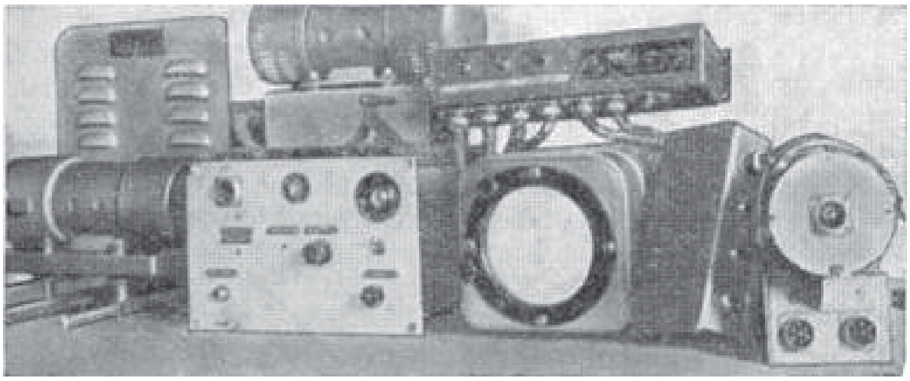

Figure 37. The complete set of Gneiss-2.

In 1942, the contract was signed with one of the radio-industry factories, and mass production of "friend or foe" devices began in 1943. This was an example of a very tight schedule for the development and batch production of airborne radio-electronic equipment.

The principle of this identification was the fact that an impulse, visible on the screen of a ground-based display near the reflected radar signal, was supplied as a recognition signal. That is, own airplanes equipped with the responder were displayed as a dual mark. The weight of such a device was 3.5 kg, the power consumption was up to 100 W, and the wavelength was 4 m to 4.3 m.

Such responders could be considered the prototypes of modern aircraft transponders, widely used in air traffic control (ATC) systems. These allow the air traffic controller to automatically receive additional information about aircraft that are in the service area.

11. Compression of RF Wideband Pulses

11.1 Establishment of ARTA

After the war, in 1946, the Artillery Radio-Technical Academy (ARTA) was established in Kharkiv. It later became the most powerful radar school in the Soviet Union. One of the most important tasks in the early years of pulse radar was the problem of clutter elimination. The principle of moving-target indication (MTI) with a delay-line canceller was already known. At the end of the 1940s, Yakov D. Shirman (1919-2019) (Figure 38), then a young teacher at ARTA, tried to more deeply understand the issues of MTI in his lectures for the students [44]. This perhaps helped him suggest the transition from a single delay-line canceller to double- and multiple-delay-line cancellers. In 1951, he obtained patent No. 13855, USSR, Ministry of Defense (Figure 39) on an MTI system with a multiple-delay-line canceller. The effectiveness of the MTI system was significantly improved. This invention was very quickly implemented in the P-12 radar system, and a little later, in the anti-missile system C-75, and in many other radars [44, 45].

Figure 38. Yakov D. Shirman (circa 1950).

Министерство Обороны Союза ССР
(министерство или ведомство)

АВТОРСКОЕ СВИДЕТЕЛЬСТВО
№ 13855

Настоящее авторское свидетельство выдано
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на изобретение "СФ"

в соответствии с приложенным описанием по заявке № 12836/ 429030
с приоритетом от 31 декабря 1951г.

Заместитель министра
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Зарегистрировано в Государственном реестре изобретений Союза ССР 4 декабря 1953 г.

Действие авторского свидетельства распространяется на всю территорию Союза ССР.

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Госплане
Москва, 8 декабря 1953 г.

Московская печатная ф-ка „Гознак". 1951. Зак. 5815.

Figure 39. Patent No. 13855 (Ministry of Defense, 1951).

11.2 The Problem of Improving Range Resolution

A contradiction arose between the tasks of increasing the range of operation and the range resolution. This seemed very serious in the 1950s. At that time, rectangular RF pulses without intra-pulse modulation were used in pulse radars. To increase the range of the radar it was necessary to increase the energy of the sounding pulse. To do this, the pulse duration had to be increased, the peak power always being limited. In turn, increasing the duration of such an RF pulse led to a degradation of the range resolution: both a theoretical and a practical problem. Ya. Shirman proposed two solutions in 1955 [46, 47] as simple approaches to increasing range resolution in a secondary receiving channel. In both cases, a long RF pulse was converted with the help of linear circuits into two short pulses. In addition, a pair of long pulses was converted , according to the superposition principle into two pairs of non-overlapping short pulses that were actually wideband. It was a radar with a two-channel receiver, where one channel was for long range, and a secondary channel was for high resolution. This approach was confirmed by laboratory and live experiments [45]. However, the thought that then appeared in the scientist's mind was that perhaps it would be better to directly radiate wideband sounding pulses, in order to simultaneously solve both tasks with the help of a single matched receiving channel: to reach increasing resolution without loss in range. Simultaneously, a theoretical problem was important: how to modernize the Woodward theory of time-frequency resolution in order to cover the described results of time super-resolution? It was really important to understand this matter, because it could open up the opportunity to also assess the prospects of angular super-resolution.

Yakov D. Shirman was an ambitious scientist, but also a very modest and extremely honest person. He also paid attention to the history of radar. In his papers and personal conversations, he indicated some predecessors whose lectures, talks, or work contained some ideas that could be related to his achievements. He personally prepared and supervised 20 Doctors of Science and 45 PhD holders in radar-related fields. He created an exclusively strong team of researchers. Of course, his pupils made great contributions to developing his research and development work. Unfortunately, it is impossible to mention many names in this paper. However, the paper written by Shirman himself, together with his pupils [45], contained a lot of references.

11.3 Compression of RF Wideband Pulses

Single-channel matched filtering was first proposed by Ya. D. Shirman for random phase-shift-keyed signals in 1955 [45]. He then developed it for deterministic linear frequency-modulated (LFM) signals in July 1956 [48]. The latter invention described a method of increasing radar range resolution using frequency-modulated sounding pulses, and the device to implement this method. In the device, to compress the duration of receiving (reflected) pulses, the receiver included a compression filter (for example) at intermediate frequency. This filter was implemented as a tapped delay line with continuous or discrete tapping, and capacitive, inductive, or conductive coupling with the delay line. In 1956, the principle of compression of linear frequency-modulated pulses was checked in the experiment done by Shirman's pupils, B. V. Naydenov, V. N. Manzhos, and Z. A. Vainoris. They designed a matched filter based on a spiral delay line. It was implemented as a dielectric rod, and located in a glass tube. Discrete capacitive pickups were arranged. The distances between them were different. They were proportional to the changing semi-period of the pulse-response characteristics (Figure 40)

The initial FM pulse, with a duration $\tau = 5$ µs and a frequency deviation of 4 MHz (±2 MHz) at a mean frequency of 3 MHz, was applied to the input of such a matched filter (MF). At the output of the matched filter, the pulse was compressed six to 10 times in time, as was clearly seen from the oscillograms. However, it had the level of remaining (sidelobes) considerably higher than the calculation, due to the absence of careful coordination of the filter's pulse response with the signal's shape.

The results were discussed with leading experts and caused great interest. Despite the doubts of some of the experts, this approach immediately received intensive development.

In the summer of 1959, based on the P-12 Radar System, the prototype of the VHF-band radar with linear-frequency-modulated pulse compression was created and tested in the modes of aircraft and missile detection, under the leadership of Ya. D. Shirman (Figure 41). The sounding pulse duration was 6 µs at a spectrum width of 5 MHz. After processing, the pulse duration was decreased 30 times and the range resolution was correspondingly improved, without a practical decrease in the range of operation. At the end of 1959, on the same basis, a new version of the radar prototype was created, with a pulse duration of 100 µs at the same average pulse power. As a result of the coherent processing of the received signal, the range of operation was increased two times, while maintaining the same range resolution [44, 45].

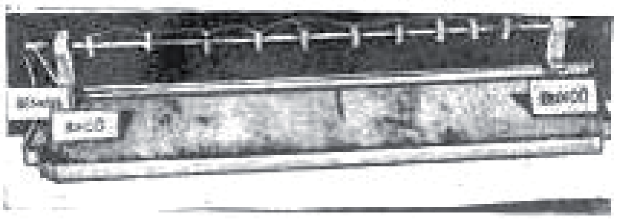

Figure 40a. The matched filter.

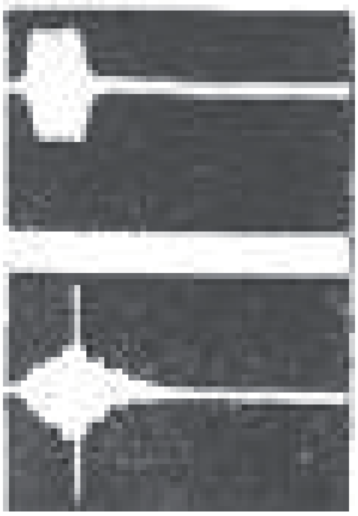

Figure 40b. The result of the pulse compression in 1956.

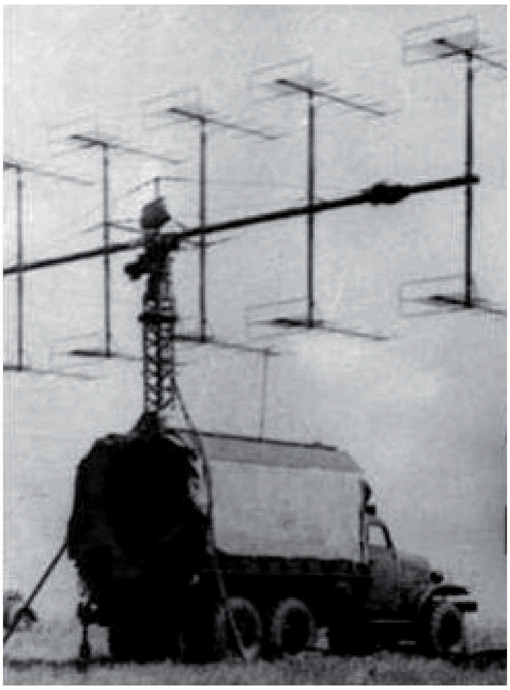

Figure 41. The P-12 radar system, where the first pulse compression was implemented.

The theory of pulse-compression filters with discrete irregular tapping was later described in a book [49]. It was developed based on the theory of pulse communications published much earlier by Shirman (1946). Compression filters were practically implemented using electrical (V. N. Manzhos, Yu. A. Koval, N. M. Ivakhnenko) or ultrasonic (V. V. Trubnikov) delay lines. The phenomenon of dispersion in delay lines was used; weighted processing was applied to minimize the sidelobe level of compressed pulses. Compression filters were also developed and built for processing phase-shift-keyed impulse signals.

The invention of wideband-pulse compression by matched filtering was one of the most significant contributions to radar theory and technique after WW II. It was independently done in Ukraine (then a part of the USSR), and practically at the same time as in the USA (Charles Cook, 1955, published in 1968 [50]). Shirman did it in a much more sophisticated and effective way.

Figure 42a. D. Tsursky and V. Almazov, together with Ya. Shirman (in the middle), shown tuning the compressing filter.

11.4 The First Super-Wideband Radar

Widening the bandwidth of the sounding waveform up to 100 times relative to then-existing radar systems made it possible to significantly improve both the range resolution and the accuracy of range measurement with matched signal processing. The first full-scale live experiment of the surveillance of aircraft with a super-wideband linear-frequency-modulated-pulse radar were made during 1962-64, using the S-band radar PRV-10 [32, 44]. A unique (for those times) compression filter for linear-frequency-modulated pulses of 2 μs at a bandwidth of 72 MHz, based on a coaxial cable, was developed by V. B. Almazov and D. A. Tsursky, who were students of Prof. Shirman (Figure 42).

Experiments with such a radar showed a range of airplane detection up to 110 km. An actual range resolution in the automatic lock-in mode of 3.0 m to 4.5 m at 65 km. This provided resolution even of elements of a target in the air, and observation of the range image (profile) of a target.

The Pioneer Award Committee of the IEEE Aerospace and Electronic Systems Society named Yakov D. Shirman as the recipient of the Pioneer Award, with the following citation: "For the independent discovery of matched filtering, adaptive filtering, and high-resolution pulse compression for an entire generation of Russian and Ukrainian radars." Formal presentation was made at the International Radar Conference, Bordeaux, France on October 2009. Six months later, Yakov Shirman passed away in the 91st year of his life.

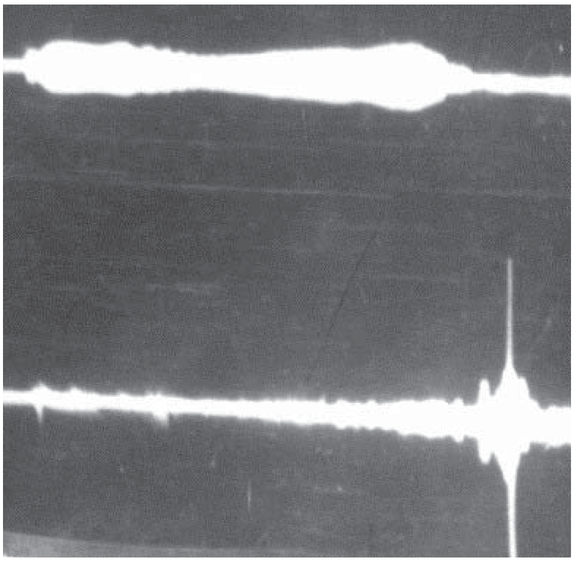

Figure 42b. The compression ratio was 144 in 1961.

12. Conclusions

In spite of the very fair general opinion of science as an international field of human activity, the development of modern radar in different countries was independent, and covered by a curtain of secrecy, because of obvious military applications.

Soviet radar achievements were disclosed later than those in western countries. Inside the USSR, the achievements in the R&D field obtained in Ukrainian institutions were never considered as such, because it was a single state, while in sports and culture there were quite official parades and competitions between the "Socialist Republics." This paper has clarified the valuable contributions of Soviet and Ukrainian engineers and scientists to the early developments in the field of radio detection, or radar. These contributions were really significant and independent, and many aspects of the radio detection of airplanes were developed at least not later than in other countries. The complicated history of microwave and radar technology in the Soviet Union – in particular, of the significant Ukrainian contribution – was a good basis for the modern scientific and technological achievements [51, 52].

13. Acknowledgment

The author is very grateful to Profs. Alexander I. Nosich and David I. Lekhovitskyi for numerous discussions of various issues of the complicated history of radar.

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