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Research Article

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A Historical Review of Research, Development, and Applications of Subsurface Radar in the Soviet Union and Russia from the 1960s to the Present

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Abstract
The article describes the history of research and development of surface-penetrating radar in the USSR, starting from the 60s and ending today in Russia and neighboring states formed after the collapse of the USSR. It reports key applications ranging from Antarctic ice and soil exploration to subsequent use in humanitarian demining, non-destructive testing and cultural heritage site surveys. The paper is under line the outstanding role played in the initial period of this technology formation by Prof. M.I. Finkelstein and his colleagues. Their research had a significant impact on the subsequent development of ground penetrating radar in modern Russia and neighboring countries.

Keywords: Microwaves (MW), Surface-Penetrating Radar, Subsurface Radar, Ground-Penetrating Radar (GPR), Non-Destructive Testing, Humanitarian Demining, History of GPR Development

1. Introduction (What is GPR?)

In radar technology, there is a special area of research that is associated with the examination of optically opaque dielectric media, but which are partially permeable to electromagnetic waves in the radio and microwave (MW) ranges from 10 MHz to 10 GHz. Such media include soil, rock, fresh and sea ice, building constructions and many structural materials and composites. In these media, electromagnetic waves are subject to attenuation, sometimes very strong, but at the same time it remains possibility to register the reflected signal from inhomogeneities located in the medium under consideration. The advantage of radar sensing of media, for example, over X-ray sensing, is the ability to examine the medium with one-way access to it. This circumstance is especially pronounced when examining soils, because in this case the Earth is a one-sided surface. Many building and engineering structures also do not allow two-way access. This makes it possible to use such radars as a means of non-destructive testing. Moreover, the level of their electromagnetic radiation is so low that there is no need to worry about the safety of operating personnel or electromagnetic compatibility with other devices.

Radars of this kind have received various names in the scientific literature: Subsurface Radar, Surface-Penetrating Radar or Ground-Penetrating Radar (GPR). The abbreviation GPR is commonly used to refer to. However, the last term is much narrower than the formers. But the scientific tradition historically favors this abbreviation. It is worth noting that in Russian-language literature the term georadar is also often used. This is due to its use in geophysical research.

2. Beginning of GPR Research in the USSR

The first experiments on the practical application of subsurface radar in the Soviet Union were undertaken in Antarctica in 1966 using the GUYUS-1M4 marine radar station developed at the end of World War II (operating frequency 214 MHz, $\lambda = 140$ cm, range determination accuracy 120 m). Two years later, this radar was installed on board the Il-14 aircraft, which made it possible to study vast areas of the continent [1]. The purpose of these studies was to measure the thickness of the ice sheet and determine the relief of the underlying continental surface. However, one of the most significant results in radar probing in Antarctica was the discovery by British scientists in 1993 of the subglacial Lake Vostok located near the Russian polar station of the same name [2].

The beginning of research in impulse subsurface radar in the USSR in 60 80s is inextricably linked with the name of an outstanding scientist, Professor Moses I. Finkelstein (1922 – 1992), who worked at the Riga Institute of Civil Aviation Engineers (RICAE), Riga, Latvia, Figure 1. In that time Latvia was a part of the Soviet Union.

Figure 1: Prof. M.I. Finkelstein (in center) and his Colleagues V.G. Glushnev and E.I. Lazarev after Receiving a Prize from the USSR Government in 1984

In the initial period, this research was associated with the need to remotely measure the thickness of sea ice from an aircraft board. The task was of paramount importance to the Soviet Union because of the need for shipping in the Arctic. Due to its importance, this way had its own name, the Northern Sea Route (NSR). These studies were successfully completed in 80s with the development of the Aquamarine airborne device. The Aquamarine subsurface radar was tested in the ice of the Arctic on NSR. However, due to the collapse of the USSR, this area of work did not receive further development.

Similar efforts were launched to develop instruments capable of measuring the thickness of freshwater ice on rivers and lakes. The relevance of these studies is related to the need to ensure the safety of transport convoys in Siberia in winter, where the road network is extremely rare, and bridges and crossings over water barriers are absent in many places. Moreover, transport often moved on the ice of frozen rivers, because the land routes were completely impassable.

It should be noted that the tasks of measuring the thickness of freshwater and sea ice differ dramatically in difficulty. While freshwater ice, as demonstrated by Antarctica experiments, is virtually transparent to radio waves, sea ice, due to the saltwater lenses it contains, strongly absorbs electromagnetic radiation. Despite numerous studies in this area, a satisfactory solution for measuring sea ice thickness has yet to be found.

Another project was started by RICAE on geophysical radars for near-surface soil sounding in 1972. At that time, the fundamentals of constructing GPR systems, as well as methods for recording and processing signals for them, were developed.

The studies of M. Finkelstein and his colleagues had an exceptional influence on subsequent work in this area in the USSR and later in Russia and neighboring countries. This period was marked by publishing a lot of papers and books related to GPR in the Soviet Union [3-8]. Professor M.I. Finkelstein was also awarded the USSR State Prize for his outstanding role in research and development in the field of subsurface radars in 1984.

3. Transition from Analog to Digital Devices

The first developed GPRs in Soviet Union were extremely imperfect and required long signal processing in the laboratory. Moreover, these were rather primitive samples as if were created by radio amateur. This was largely due to the lack of small-sized devices for displaying information capable for working in the field conditions and suitable electronic components.

It should be noted that during this period, scientific and technological development in many sectors of the USSR, and not only in the field of subsurface radar, lagged behind Western advances. This was primarily due to the restrictions of the Cold War, which contributed to the Soviet Union's overall backwardness in electronics.

Given the historical nature of this review, it's worth describing the signal recording and processing used at RICAE during the initial stages of GPR research. The initial analog ground penetrating radar signal was recorded on a reel-to-reel tape recorder, which was then connected to an oscilloscope, and the radar signal was imaged on photographic film through an optical system. Further processing required wet film development and subsequent photo printing, which precluded the possibility of analyzing the data directly at the measurement site and subsequently adjusting the experimental conditions. The final result of this procedure at scanning along a complex terrain feature is shown in Figure 2 [5]. The complexity and time-consuming nature of this process also precluded its use for mass-produced industrial devices, and it was limited to experimental works performed only by enthusiastic researchers. Nevertheless, these experiments demonstrated the potential of subsurface radar technology and its practical value, and also made it possible to identify areas for its improvement.

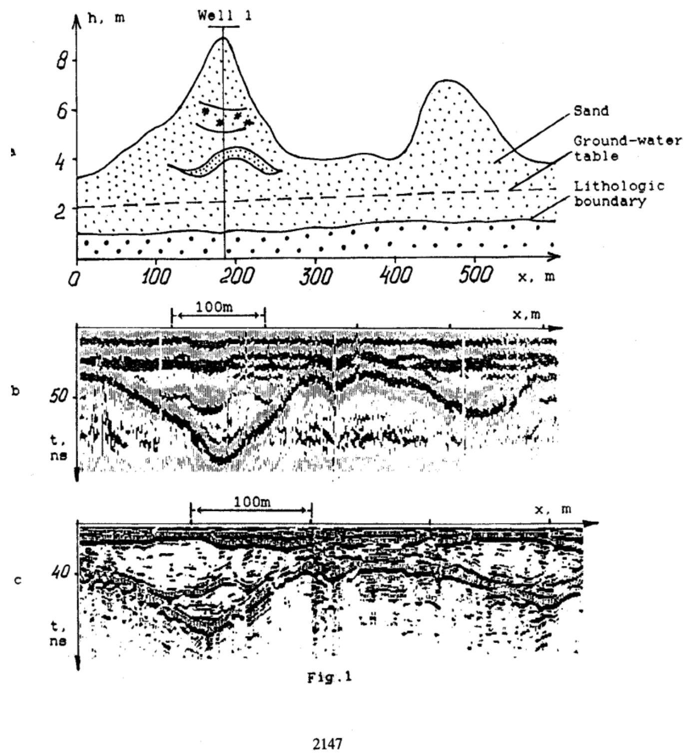

Figure 2: Experiment on Scanning along a Sandy Area with Complex Terrain [5]

An undoubted breakthrough in the early 80s was the appearance one of the first industrial subsurface radar YL-R2 created by the Japanese company OYO, Figure 3. This device, although it was still analog, made it possible to receive and display information in real time at place of measurements by built-in printers, and if it is needed to repeat measurements at once. The appearance of this device in USSR had a significant impact on the further development of the GPR technology in the country.

Figure 3: Ground-Penetrating Radar YL-R2 Produced by OYO Corporation, Japan

In the 80s, digital signal processing using analog-to-digital converters began to be introduced in the USSR. This literally revolutionized the entire field of GPR, making it possible to create instruments with real-time information display.

Considering that, at the same time, electronic components made it possible to generate and record shorter and shorter pulses, which led to a reduction in the size of antennas and an improvement in spatial resolution. In the USSR, as well as throughout the world, interest arose in the use of GPR to detect underground mines not only for military but and humanitarian goal.

4. Experiments on Recording MW Images of Subsurface Mines

Military conflicts all over the world are characterized by widespread use of both antipersonnel and antitank mines. Since the 1960s, a significant proportion of deployed mines had plastic casings, and some had almost no metal parts, making them difficult to detect by metal detectors that were main instrument of sappers. The main threat of the widespread occurrence of mines is not so much for the warring parties, who usually have the means and experience to deal with them, but for the civilians during and especially after the end of the conflict.

This required the development of new effective demining tools that would reduce the cost of these works, increase their productivity, and also reduce losses among sappers. A major problem encountered in mine clearance is the high rate of false alarms when using standard mine clearance tools, such as metal detectors. This is due to the fact that the battlefield, as a rule, contains a large number of metal objects: fragments of mines and shells, bullets and many other objects, including metal garbage in populated areas.

One of the ways to reduce the level of false alarms against the background of reflections from soil inhomogeneities and third-party objects could the ability to see the shape of an underground object. In the late 80s, the Remote Sensing Laboratory, Moscow (https://www.rslab.ru/english/) proposed the use of subsurface radar technologies to obtain microwave images of mines in the soil in the survey plane of the earth's surface. An experimental set-up for recording such images was designed by Laboratory staff, Figure 4.

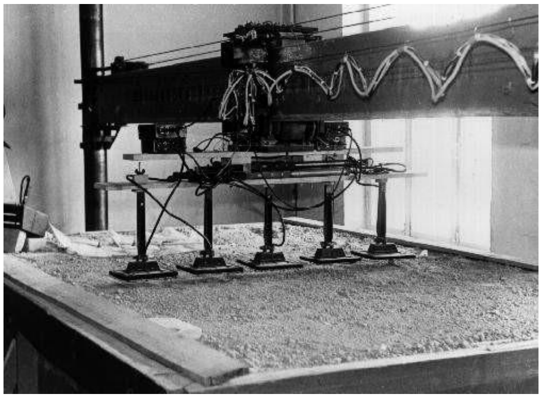

Figure 4: Experimental Setup Designed for Recording MW Images of Subsurface Mines

The setup had line array of a few of sensitive elements with operational frequency of 600 MHz moving over the sand box. Italian and Soviet anti-tank mines in plastic and metal casings were used as search objects. An Italian plastic-body mine is shown in Figure 5.

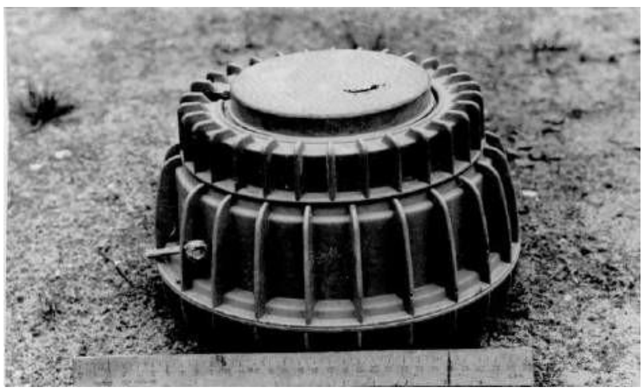

Figure 5: Italian TC-6.1 Plastic-Body Antitank Mine

One such recorded radar image is shown in Figure 6. There are two antitank mines (metal and plastic bodies) in centre of trial mine field, a piece of metal pipe in the left, metal plate in the right bottom corner and a brick in the right top corner.

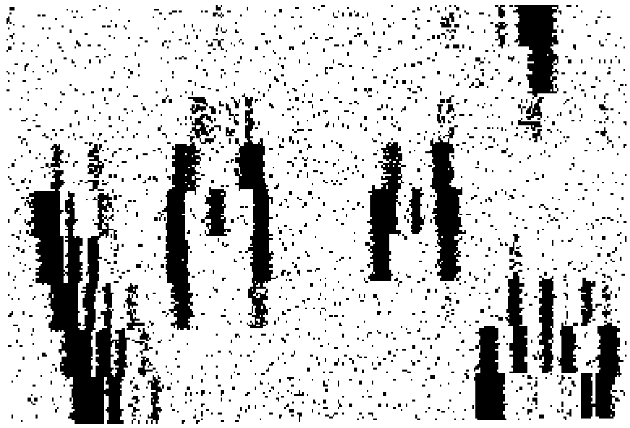

Figure 6: MW Image of Two Mines (center), a Metal Pipe (left), a Brick (upper right corner), and a Metal Plate (lower right corner)

The image was recorded in 1990. Apparently, this was for the first time in the world. It took a long time to obtain the necessary permissions to publish these results at the international humanitarian demining conferences MD'98 in Edinburgh, UK [9]. The report at the MD'98 conference was soon republished in the journal IEEE Aerospace and Electronic Systems Magazine [10].

In the Soviet Union, the possibilities for international scientific cooperation were strictly limited not only for political reasons, but also for reasons of secrecy. These restrictions have largely been lifted in modern Russia. Considering that the task of humanitarian demining is international in nature, the Laboratory staff was able to quickly establish contacts with scientists from USA, Italy, Japan and the UK and began joint research in this area [11-14]. Contacts with Italian colleagues from proved particularly fruitful [13,15]. This cooperation was not limited to this field, but also continued in other areas: non-destructive testing of materials and structures [30,31], surveying of cultural heritage sites, remote diagnostics of people in the microwave range, and other areas [16-18].

The research was supported by international western funds from ISTC, NATO, EU COST Action and also Russian scientific funds (RFBR and RSF). International scientific cooperation and grant support have had a beneficial effect on the development of subsurface radar technology in Russia. Russian scientists took an active part in international GPR and IWAGPR conferences, gave presentations and served on the organizing committees of these conferences.

5. Research and Designing of Holographic Subsurface Radars

Another research direction, which began to develop by the Remote Sensing Laboratory in the middle of 90s, was the creation of holographic subsurface radars designed to examine building structures [19,20] and for non-destructive testing of composite materials that used in the aerospace industry [21,30,31]. For these purposes, small-sized multifrequency holographic subsurface radar RASCAN was created, Figure 7. Thanks to its high spatial resolution, simple design, and low cost, this device enjoyed commercial success not only in Russia, but also abroad, from Australia to the United States

Figure 7: Holographic Subsurface Radar RASCAN Designed in the Remote Sensing Laboratory, Moscow

One of the landmark events associated with this research was participation in the summer exhibition of the Royal Society of London in 2010. As part of a joint international project related to humanitarian demining, RASCAN holographic subsurface radar was presented. Her Majesty Queen Elizabeth II of England visited the laboratory's exposition to get acquainted with this new Russian technology, Figure 8.

Figure 8: Queen of England Elizabeth II to Get Acquainted with the Russian Subsurface Radar Technology

Holographic subsurface radars are designed to survey shallow depths that are sufficient for many technological applications in the field of non-destructive testing of dielectric materials and structures [22]. Their advantage is high resolution in the sounding plane, which is especially important, for example, for examining works of art [23].

However, since the 90s, impulse subsurface radars have been considered the main stream of GPR development. Due to their design features, they are able to achieve the maximum penetration depth into lossy media [5,29].

6. GPR Production in Russia

The main manufacturer of impulse subsurface radars in Russia is the LOGIS-GEOTECH Group of Companies, Zhukovsky, Moscow region (https://geotechru.com). The company was established goes back to 1989 when the leading designers of the V.V. Tikhomirov Scientific Research Institute of Instrument Design (NIIP) at the defense industry conversion were reoriented to development and manufacture of advanced geophysical equipment on the basis of the accumulated scientific and technical potential. In 1992 the NIIP management and the key staff members founded the LOGIS Company (Ramenskoye, Moscow region), which commenced series production of GPR and seismic equipment while keeping the development of explosives detectors.

Active development of the LOGIS Company and expansion of its activity resulted in opening of a new direction, i.e. engineering surveys with geophysical equipment system. The company was transformed into the Geotech Group of Companies which enveloped the Scientific and Production Center of GPR Technologies (GEOTECH Company). GEOTECH works not only for promotion of geophysical equipment, but it also develops and practices new techniques of engineering surveys as well as performs integrated geophysical research for different sectors of the national economy.

During the last years the significance of geophysical surveys has been steadily growing in Russia. To date the devices and services of the GEOTECH Group of Companies are widely popular in railways, roadways, oil and gas industry, construction activity and many other sectors of national and foreign industries.

The last GPR produced by GEOTECH is the OKO-3 device. It is a portable lightweight low-prices system designed for non-destructive environmental monitoring. The OKO-3 GPR includes the control unit and antennas in a few frequency bands. All antennas are interchangeable and meet the needs of a broad range of applications. The main merit of the LOGIS-GEOTEC company is that it satisfied main needs of the Russian market for GPR, which in their consumer properties are not inferior to foreign analogues, but are significantly cheaper. GEOTEC company employees also make a certain contribution with their scientific research to expanding the GPR application areas [24,25].

Another well-known manufacturer of subsurface radars in Russia is the Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of Russian Academy of Science (IZMIRAN). The development of ground penetrating radars began at IZMIRAN in the early 90s and was initiated by participation in the Mars-94 space project, which involved the flight and landing of a Russian interplanetary automatic station on the surface of Mars. Unfortunately, the project could not be completed, since the station was unable to leave the orbit around the Earth. Subsequently, developments and research were reoriented to more "earthly" projects. The Loza and Grot series of ground-penetrating radars created at IZMIRAN belong to the class of geophysical devices for studying the soil structure at depths ranging from a few to hundreds of meters depending on the model of the device, the antenna used and the parameters of the probed soil (https://www.georadargrot.com/eng/index). Their distinctive features are: the use of a powerful transmitter and the registration of the signal in its own frequency spectrum, without stroboscopic conversion of the signal to the low-frequency range, which allows eliminating most operations on the signal that lead to unwanted noises [26,27]. The main area of application of these GPR is exploration of mineral deposits in desert or low-water areas.

7. Production GPR in Latvia

Direct heir to research and development carried out in the 60-80s under the leadership of Prof. M.I. Finkelstein is company Radar Systems, Inc. (https://www.radsys.lv/en/about-company) created by his students and followers in Riga, Latvia.

This company was established in 1989 on the basis of Aviation Subsurface Radiolocation Problem Laboratory (ASRPL) at RICAE, to become ASRPL's legal successor in research and development for GPR techniques, hardware and software used to solve tasks of nondestructive environmental monitoring, engineering geological surveys, thickness measurements of sea and fresh water ice, etc.

These studies were crowned with development of a number of GPR series ZOND, LOUCH, PROFILE and PYTHON. The latter is a land analogue of the space radar used for subsurface soil sounding of Mars (Project Mars-96, Russia) and designed by Radar Systems, Inc. researchers in close cooperation with their colleagues from National Space Agency of France (CNES) and Service d'Aeronomie Institute (France). Currently, one type of subsurface radars is manufactured in lots, namely Zond-12 that consists from versatile and multifunctional control unit and set of antennae for various frequency ranges, Figure 9. The company is also actively conducting research work [28].

Figure 9: ZOND-12 GPR with 500 MHz Antenna

8. Ukrainian GPR Manufacturer

Transient Technologies LLC (https//viy.ua), Kiev is a leading Ukrainian developer and manufacturer of GPR equipment. Company's engineers are carrying out the research and development in the field of ultra-wide band technologies since 1998.

Transient Technologies' progressive manufacturing and the vast technical experience of the staff both ensure in many cases the best solutions for searching for underground items and nondestructive subsurface inspection considering all the most exacting demands of the customers. More than 15 countries provide distribution and ensure full technical support of GPR products of Transient Technologies LLC. Innovative technologies being used in designing of GPR equipment and its reliability allowed company products to become the best Ukrainian producer with recognizable brand among worlds' leading GPR manufacturers and to create such excellent Ground Penetrating Radars as VIY®3 series.

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