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- «Avtomatychne Zvaryuvannya» (Automatic Welding), https://patonpublishinghouse.com/eng/journals/as;
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- «Tekhnichna Diahnostyka ta Neruinivnyi Kontrol» (Technical Diagnostics & Nondestructive Testing), https://patonpublishinghouse.com/eng/journals/tdnk.

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***Translated Article(s) from "Suchasna Elektrometalurhiya" (Electrometallurgy Today), No. 1, 2025.
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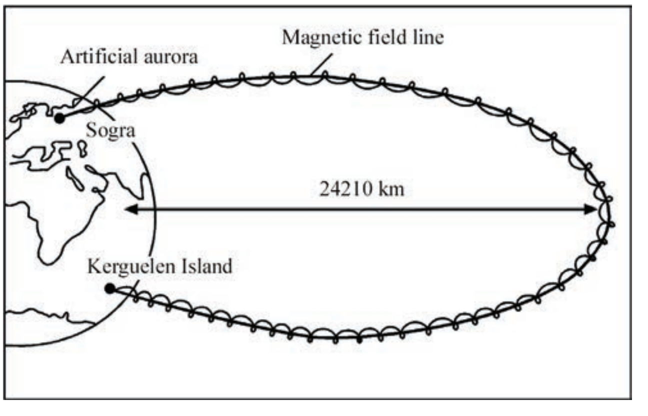
50 YEARS OF THE ARAKS EXPERIMENT: PROBING THE EARTH'S IONOSPHERE AND MAGNETOSPHERE WITH A POWERFUL ELECTRON BEAM

The early 1970s marked the beginning of active space exploration, highlighted by the successful implementation of several international research projects. These initiatives became possible during a brief period of détente in global tensions. Agreements between the USSR and the USA facilitated scientific and technical cooperation between the two opposing blocs, particularly in the field of space research. The signing of treaties limiting anti-ballistic missile systems and strategic armaments created opportunities for joint experiments in the peaceful exploration of space. Among the most notable was the historic Soviet-American "Soyuz-Apollo" mission, which involved docking and a joint manned flight of spacecraft from both superpowers. Another significant project was the Soviet-French (with USA participation) ARAKS experiment, dedicated to studying physical processes in the Earth's ionosphere, especially those associated with auroral phenomena [1–4].

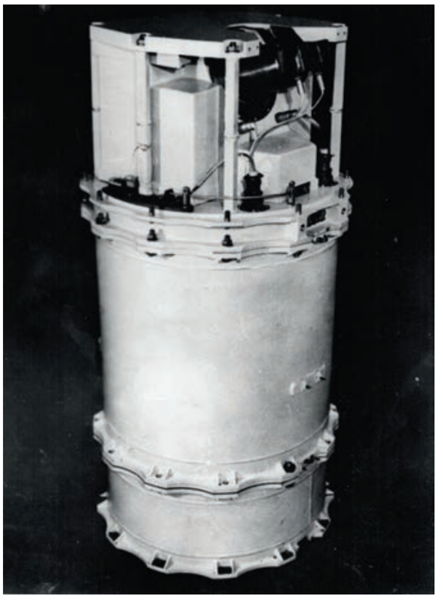
The ARAKS experiment (Artificial Radiation and Aurora at Kergelen and Sogra) pursued both scientific and practical objectives. Scientifically, it aimed to investigate the interaction of high-energy particles with the Earth's magnetic field and atmosphere, test theoretical plasma physics models, and validate hypotheses. On the practical side, the experiment sought to refine the design of powerful energy sources, systems of control, automation, and data collection under extreme space conditions. Additionally, it enabled full scale studies of supersonic flow of the Earth's rarefied ionospheric plasma around a spacecraft and the electrification of spacecraft surfaces to high potentials, which could interfere with or even damage onboard electronic equipment. A particularly intriguing aspect of the experiment was its aesthetic component, as its name suggested — the artificial creation of auroras.

The core of the experiment involved injecting an electron beam, generated by an electron beam gun (betatron), into the Earth's magnetosphere to study the dynamics of electron movement within the Earth's magnetic field and their interactions with the ionosphere. Unlike passive methods, which observe natural phenomena independent of the researcher, this experiment represented an active space study. It entailed directed intervention in the research object with controlled parameters, followed by analysis of the results, similar to experiments conducted in terrestrial laboratories. Despite numerous laboratory and passive experiments in this field, active experiments remain relatively rare in global scientific practice. Since October 1974, a series of American active experiments, such as EXCEDE [5], Echo [6–8], Spacelab 1 (1983) [9], Atlas-1 (1992) [10, 11], and Beam-PIE (2023) [12], as well as the US-Japanese Charge-2 (1985) [13] and SEPAC [14] experiments et al., have been conducted.



The active experiment ARAKS was, in fact, the first such successful study (January–February 1975) with technical characteristics of onboard equipment that were practically replicated only half a century later. The initiators of the project were Dr. I.O. Zhulyn (Institute of Terrestrial Magnetism and Atmospheric Wave Propagation, USSR) and Prof. F. Cambou (Center for the Study of Radiation in Space (CESR), Toulouse, France). The main scientific institutions involved in the project were: in France — the National Center for Space Studies (CNES), Toulouse; the Center for the Study of Radiation (CESR), Toulouse; the Ionosphere Research Group (GRI), Saint-Maur-des-Fossés; in the USSR — the Institute of Space Research, Moscow; the Institute of Terrestrial Magnetism and Atmospheric Wave Propagation, Moscow; the E.O. Paton Electric Welding Institute of the Academy of Sciences of the Ukrainian SSR, Kyiv;

the Institute of Electrodynamics of the Academy of Sciences of the Ukrainian SSR, Kyiv; the Kurchatov Institute of Atomic Energy, Moscow. The abbreviation ARAKS is phonetically similar to the name of the Araks River in Armenia, where the agreement to conduct this experiment was first reached.



According to the experiment plan, it was necessary to select a pair of magnetically conjugate points, launch a rocket along a ballistic trajectory, generate a beta-particle (electron) beam at one of the points, and record the expected physical effects using ground-based, airborne, and space-based instruments.

As magnetically conjugate points on land, a unique pair was chosen — on Kerguelen Island (France, Southern part of the Indian Ocean) and near the settlement of Sogra (Arkhangelsk Region, USSR). Both points were located on land and positioned at high latitudes in different hemispheres, separated by a distance of more than 12600 km.

The electron beam, generated by an accelerator in the Kerguelen area, was expected to propagate along the magnetic field line northward, and upon entering the dense atmospheric layers in the Arkhangelsk region, act as a "disturbance" in the environment. Part of the plasma, reflected in the Northern Hemisphere, was supposed to return to the launch site, practically retracing its initial trajectory.

The launch of the experimental equipment was carried out using the French "Eridan" rocket, whose final stage contained two interacting experimental systems: an electron beam gun, devices for indirect potential change, particle flux detectors, and a detachable cone that was ejected at a speed of 40 m/s from the rocket's main body. This cone housed antennas designed to detect radio waves generated by the electron beam as it interacted with the ionosphere.

Ground-based measurement stations were established for the experiment. Optical and radar measurements in the Northern Hemisphere at the magnetically conjugate point to Kerguelen Island, as well as extremely low and extremely high-frequency measurements at both locations, were of particular importance. Additionally, just before the launch of the "Eridan" rocket, X-ray detectors were deployed by parachute at an altitude of ~80 km above Kerguelen Island. These detectors had been delivered there by the "Areas" rocket. The X-ray experiment was conducted by the University of Houston (USA).

The experience in developing electron beam equipment placed on rockets and satellites allowed the E.O. Paton Electric Welding Institute (PWI) and the Institute of Electrodynamics (IED) to create an electron accelerator for ARAKS with record-breaking characteristics. The project curator at PWI was D.A. Dudko. The main leadership for specific research directions was carried out by: O.K. Nazarenko — electron beam gun; V. D. Shelyagin — high-voltage power source; Yu.M. Lankin — electronics and automation; V.E. Paton — structural design.

According to its main technological parameters, the accelerator (betatron) of the ARAKS apparatus was analogous to one of the best industrial electron beam welding systems of that time — the U-250A with the U-530 gun. It provided a beam power of 15 kW, operated in a pulsed mode, and allowed electron beam deflection at angles of up to ±90°. The size and weight characteristics and reliability of the accelerator exceeded those of any known ground-based equipment at that time. For instance, the weight of the ARAKS accelerator, excluding the battery, was 120 kg, and its volume was 0.2 m^3, which was 17 times lighter and 20 times more compact than the U-250A, which was built using electron tubes.

This achievement was made possible thanks to the high level of expertise of the employees of the PWI and their experience in developing and practically utilizing high-power electron beam equipment and technologies in studies of vacuum welding, remelting, surfacing, and other processes [15, 16]. Notably, the "Vulkan" welding system was successfully tested in space during the world's first space welding experiment aboard the "Soyuz-6" spacecraft on October 16, 1969. In the ARAKS experiment, a specially developed high-power inverter transistor power supply for the electron beam gun was used, along with a high-voltage sectional rectifier on semiconductor diodes and control and automatic regulation systems based on transistors and integrated circuits, which had just begun to emerge at that time.

Moreover, the ARAKS accelerator met all the requirements for space equipment, including operational temperature range, vibration and shock resistance, level of generated radio interference, reliability, and more, as confirmed by numerous ground-based tests conducted in the USSR and France.

The ARAKS accelerator, created in the early 1970s, was far ahead of its time. Inverter power supplies on transistors with similar characteristics for electron beam welding only appeared at the very beginning of the new millennium. For space applications, however, accelerators with similar characteristics were successfully developed only in 2023, for example, within the Beam-PIE project.

After completing all ground tests in October 1974, part of the Soviet expedition under the ARAKS program departed by plane from Moscow, with stops in Dar es Salaam (Tanzania), Antananarivo (Madagascar), and Saint-Denis (Réunion, France). From there, together with members of the French expedition who joined them, they set sail on October 30 aboard the "Anichkov" motor ship, which carried all the scientific equipment. They arrived on Kerguelen Island on November 4.

The expedition team included employees of the PWI Yu.M. Lankin, Ye.M. Baishtruk, V.K. Mokhnach, and Yu.V. Neporozhniy, as well as employee IED, H.F. Pazeyev. It is important to note that the distance to Kerguelen Island from the nearest continental landmass (Antarctica) is about two thousand kilometers, while the distance from the African continent exceeds three thousand kilometers.

Such remoteness and the availability of only sea transportation imposed strict requirements on organizational aspects, equipment reliability, and demanded thorough and meticulously planned expedition logistics, along with well-coordinated actions of all team members.

Three months were spent on the installation, assembly, adjustment, and testing of the entire ARAKS equipment complex. Finally, on January 26, 1975, when favorable weather conditions simultaneously formed over Kerguelen Island and the Arkhangelsk region, the first launch of the "Eridan" rocket under the ARAKS program took place.

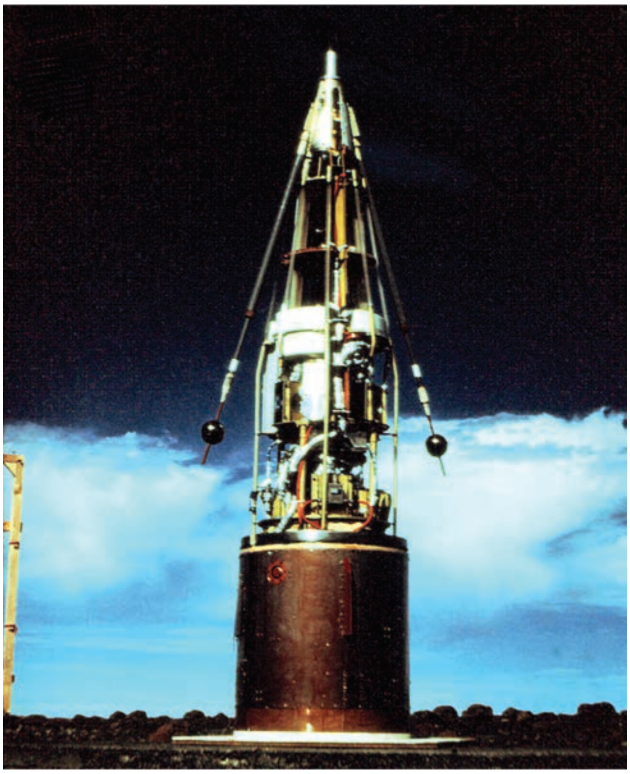
The responsibility for synchronizing all hardware components of the experiment, both onboard and ground-based, which were located in different hemispheres of our planet, as well as issuing the rocket launch command, was entrusted to Yu.M. Lankin. The rocket traveled north along the magnetic meridian in a ballistic trajectory, reaching an altitude of approximately 200 km. The electron beam gun injected a time-modulated by a complex program current (0.5 A) of high energy (15 and 27 kV) into the magnetosphere at various angles relative to the rocket's axis (–70°, 0°, +70°). The nose cone separated at a significant distance (~10 km) ahead of the rocket. It was equipped with radio receivers and frequency switches ranging from 0 to 5 MHz to study emissions resulting from the interaction of the electron beam with the ionosphere. Optical and radar observations of the electron beam were conducted at the magnetically conjugate point in the Arkhangelsk region.

The second launch took place on February 15, 1975. Unlike the first, this launch was conducted eastward, with the electron beam deflected at angles of –30°, 0°, and +70° relative to the rocket axis.

The electron injector functioned according to the full program and, as the primary scientific instrument on board, was largely responsible for the overall success of the experiment. The electron beam, injected from Kerguelen Island, traveled over 10000 km and induced an artificial aurora in the magnetically conjugate point in the Arkhangelsk region, which was recorded by radar. Microwave radio emissions were detected as a result of the interaction of the electron beam with the ionospheric plasma. Additionally, the beam was intercepted after being magnetically reflected from the conjugate point, as well as from the atmosphere when injected downward toward Earth.

The analysis of telemetry data confirmed that both launches of the "Eridan" rocket were successful. All Soviet and most French instruments operated normally and fulfilled their planned objectives.

The ARAKS project made an outstanding contribution to plasma physics (the emergence of plasma instability in an unbounded space induced by an electron beam) as well as to geophysics (geomagnetic field topography, etc.). Valuable scientific information was obtained regarding the injection processes, the interaction of the injected beam with the environment, and the behavior of a cesium plasma jet, which was intended to compensate for the positive charge of the



rocket body arising from the deflection of high-energy electrons from the accelerator.

Moreover, new effects were discovered that had not been previously anticipated. In particular, intriguing data were obtained on the occurrence and development of plasma instabilities — processes of fundamental interest for the study of controlled thermonuclear reactions.

From a practical standpoint, understanding the physics of wave-particle interactions may soon lead to highly significant, albeit somewhat unconventional, applications, such as earthquake prediction and the restoration of radiation belts for biosphere protection.

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