The Orbital *X*-Band Real-Aperture Side-Looking Radar of *Cosmos-1500*

A Ukrainian IEEE Milestone candidate

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We revisit the development and operation of the orbital *X*-band real-aperture side-looking radar (RA-SLR) onboard the USSR satellite *Cosmos-1500* in the historical context. This radar was conceived, designed, and tested in the early 1980s and then supervised, in orbit, by a team of Ukrainian scientists and engineers led by Prof. Anatoly I. Kalmykov (1936–1996) at the O. Y. Usikov Institute of Radiophysics and Electronics (IRE) of the National Academy of Sciences of Ukraine (NASU). It had a magnetron source, a 12-m deployable slotted-waveguide antenna, and an onboard signal processing unit. Instead of preplanned meticulous experiments, only five days after placement into the polar Earth orbit in the autumn of 1983, the SLR of *Cosmos-1500* rendered truly outstanding service. It provided a stream of microwave images of the polar sea ice conditions that enabled the rescue of freighters in the Arctic Ocean. Two years later, similar imagery was equally important in the rescue of a motor vessel (MV) in the Antarctic. However, the way to success was far from smooth. Besides the technical problems, Kalmykov had to overcome the jealousy and hostility of his home institute administration, colleagues from Moscow research laboratories, and high-level USSR bureaucracy. Later, Kalmykov's radar was released to the industry and became the main instrument of the USSR and Russian series of remote sensing satellites *Okean* and Ukrainian satellites *Sich-1* and *Sich-1M*. We believe that the RA-SLR of *Cosmos-1500* is a good candidate for the status of an IEEE Milestone in Ukraine.

Digital Object Identifier 10.1109/MGRS.2023.3294708
Date of current version: 25 July 2023

INTRODUCTION

In NASA's Space Science Coordinated Archive, there is a page devoted to the Earth satellite *Cosmos-1500* launched 40 years ago in a country that does not exist anymore, the USSR [1]. It communicates brief information on that mission.

> "The Cosmos 1500 spacecraft was a precursor to the operational Russian Okean series of oceanographic remote sensing missions. The Cosmos 1500 tested new sensors and methods of data collection and processing. Cosmos 1500 had the capability of overlapping and processing images from its sensors. Data from Cosmos 1500 were sent directly to ships or automated data receiving stations and applied in navigation in northern oceans. The instrument complement was highlighted by an all-weather Side-Looking Real Aperture Radar operating at 9.5 GHz. Other instruments included a multispectral scanner, a scanning high-frequency radiometer, and transponders for collecting data from ice and buoy transmitters."

Although the organizations and, in part, the people who conceived, designed, and built the main remote sensing instrument onboard *Cosmos-1500*, an *X*-band RA-SLR, are still alive, the time is merciless, and the memory tends to turn humans' experience into a legend. We would like to introduce the readers to the history of the creation and operation of *Cosmos-1500*. Many interesting details of that story can be found in reviews [2], [3], [4], [5] and a book [6]. However, most of them have never been translated into English and remain unknown to international readers. Besides, the years that have passed since 1983 and the experience of the post-USSR developments enable us to reveal important details that escaped earlier publications, ensure proper positioning of that achievement, and add a "human dimension" to the whole story. This article builds upon the preceding short conference paper [7], which has been considerably extended.

IMAGE LICENSED BY INGRAM PUBLISHING

THE THREE-HEADED DRAGON OF USSR SCIENCE

In the USSR, science was a state-owned dragon of three heads, tightly controlled by the Communist Party (CP), whose goals—technological efficiency and political control—had always contradicted each other [8]. The first head was the research and development (R&D) establishments of the ministries, each ministry being a "state inside the state" in the USSR, where no companies existed. Many of these establishments, in engineering sciences, were called *design bureaus* (DBs) [9]. This head, the richest, was responsible for the applied research and designing and testing of prototypes. To facilitate technology transfer to the industry, every DB was associated with some plant. Of the ministries, the most powerful were those of defense, the nuclear industry, the space industry, the radio industry, communications, the aircraft industry, the shipbuilding industry, the maritime fleet, and some others.

The second head was a network of large laboratories called *R&D institutes* of the Academy of Sciences (AS) of the USSR (in reality, this was the AS of Russia) and similar academies of sciences of the union republics. The AS of the Ukrainian SSR [now NASU)] was the largest of the latter, hosting around 25% of all AS research laboratories and manpower [8]. This head, officially, was responsible for fundamental research using direct state funding; however, it was allowed to compete for the projects funded by the ministries. The third head, the poorest, represented the university science where professors were encouraged to take projects funded again by the ministries. This activity was concentrated exclusively in large cities.

Since Stalin's times, the research patterns of all academies of sciences and universities were heavily biased toward technical and engineering sciences with either military or double-purpose applications in mind. The CP and government priorities were crystal clear: 1) nuclear weapons, 2) missiles to deliver nuclear weapons, and 3) radars to aim and guide nuclear weapons. From the 1950s to the end of the USSR in 1992, military-flavored research projects contributed sizable funds to the budgets of all AS institutes that related to what we can call, for brevity, *the IEEE scope of interests*. Still, there existed an important difference between the AS R&D institutes in Russia and outside of Russia; the latter could not have more than 25% of the total budgets coming from the ministries and industry, while the former were allowed to exceed this limit.

Such a limitation had, obviously, political origins and reflected the distrust of "union republics." It was established by the Science Department of the Central Committee of the Communist Party of the Soviet Union (CC CPSU) as the supreme supervising and controlling body over all ministries, academies, and universities.

Of some 50 R&D institutes of NASU, the second-largest cluster, after Kyiv, was and still is in Kharkiv. In particular, IRE (now IRE NASU) used to be the national research center of physics and technology of microwaves and millimeter waves. The IRE is the focus of our story, together with the Institute of Marine Hydrophysics (IMH NASU) in Sebastopol (currently occupied by Russia). Another R&D establishment that played a crucial role was the DB "Yuznoye" [now DB Pivdenne (DBP)] in Dnepropetrovsk (now Dnipro). This is an engineering laboratory, now independent and then associated with the Yuzhmash (now Pivdenmash) Industry, which was, since the mid-1950s, one of three major rocket, missile, and spacecraft industrial complexes in the USSR [9]. Of course, Pivdenmash belonged to the extremely powerful USSR "Ministry of General Machine Building," an Orwell-style cover for the Ministry of Space Industry. For instance, the famous SS-18 Satan heavy intercontinental ballistic missile (ICBM) and some of the military satellites were developed and manufactured here until 1992.

FIGURE 1. Anatoly Kalmykov in his office at IRE NASU around 1990.

PREHISTORY, NAMES, AND DATES

Since 1976, IMH in Sebastopol and DBP in Dnipro were involved in the design of experimental USSR satellites *Cosmos-1076* and *Cosmos-1151*, equipped with low-resolution radar-like sensors called *scatterometers* [1], [2], [3], [6]. Their task was determining the parameters of the sea waves, in line with a secret decree of the CC CPSU on the development of the general-purpose orbital remote sensing system "Resurs." By that time, IMH had already enjoyed collaboration around sea wave research, using coastal and airborne sensors, with the radar group of Kalmykov at IRE NASU in Kharkiv [10], [11], [12], [13], [14], [15] (Figure 1).

However, the "scatterometers" of the late 1970s, which were a sort of radar prototype device, had failed to satisfy the customers, who were from various state services and organizations, including polar navigation, maritime and port services, meteorology, etc. This proved the necessity of more concentrated efforts aimed at the development of active microwave sensors, i.e., radar.

Thanks to the fact that the work on the whole subsystem "Resurs-O" (i.e., oceanic survey satellites) was supervised from DBP (see the "Obstacles to Overcome: Not Only Technical" section), Kalmykov could expect to be in the center of the associated design and testing. However, he lacked both equipment and R&D manpower. Part of the problem was the extreme hostility of the then-IRE administration [6].

According to insiders [16], by the summer of 1979, Kalmykov had given up and decided to move to IMH in Sebastopol. As stated by the same source, it was the IMH director who persuaded the top bosses of the extremely powerful USSR Ministry of Space Industry to intervene and rescue Kalmykov's team at IRE. The then-director of IRE, V. P. Shestopalov, received a phone call from Moscow, suggesting that he urgently organize, at IRE, a research unit dealing with space radio oceanography and sea ice sensing. The ministry also promised to allocate IRE significant funds dedicated to such research. As a result, a 20-strong Department of Earth Remote Sensing Techniques was created at IRE on 1 September 1979, headed by Kalmykov.

Immediately, the department initiated the R&D of a novel all-weather active orbital sensor, specifically designed to study the sea surface and ice covers. This was an *X*-band RASLR. One group was designing a 100-kW pulse power magnetron source, another group designed a slotted-waveguide antenna, and still another group was responsible for the signal processing. A prototype airborne system allowing in-flight testing was also designed, and systematic flights onboard a dedicated MI-8 helicopter were organized. Besides, it was decided to add another passive sensor to the SLR, working in the millimeter-wave range—a Ka-band radiometer, also developed at IRE. Moreover, to produce the images, an onboard electronic data processing block was developed at DBP and IMH and added both to the airborne prototype and to the orbital system.

The very first airborne experiments soon confirmed the high efficiency of the designed instruments for studying the water and ice surfaces [17], [18], [19], [20]. The joint use of microwave images obtained from the *X*-band SLR and Ka-band radiometer offered, in principle, more efficient study of the state of the sea and ice than using the data from each individual sensor. However, initial tests had also shown that obtaining reliable information on the water-surface waving needed a much deeper level of data processing than available at that time. In contrast, quite reliable data were obtained in a simpler way in the helicopter observations of ice. The results of airborne studies convinced Kalmykov of the favorable prospects for radar observations of sea ice from space.

Still, attempts to interpret the ice-sounding data beyond simple discrimination between thin and thick ice did not lead, unfortunately, to the creation of an adequate model. The phenomenon of the scattering from the ice turned out to be much more complicated than the scattering from the water surface. Still, other possible applications emerged, such as wind measurements and oil slicks detection [18], [20].

The *Cosmos-1500* satellite (Figure 2) was launched on 28 September 1983 from Plesetsk by the *Tsyklon-3* rocket vehicle (a derivative of a heavy ICBM SS-18) and placed into low-altitude near-circular polar orbit. It remained operational until 16 July 1986. This was the first ever civil satellite to carry an *X*-band RA-SLR working at the wavelength of 3.16 cm with vertical polarization; the swath width was about 460 km, and the spatial resolution was 2.4–3.2 km in the flight direction and 1.3-0.6 km in the normal direction [4], [22], depending on the incidence angle (see Table 1).

The antenna system was based on the 12-m-long slotted waveguide, which was kept folded at the launch and then automatically unfolded in orbit. This radar was supplemented with a 37-GHz horizontally polarized side-looking passive radiometer, designed at IRE NASU, and a four-channel visible range imaging system from the Institute of Radio-Engineering and Electronics (IRE RAS) in Moscow. The polar orbit was selected to provide data on the ice conditions in the Arctic in the hope to be useful for the navigation of ships in the northern latitudes, which were not visible from geostationary satellites. The chosen RA-SLR parameters were considered as optimal for all-weather studies of the polar sea ice covers and the dynamics of ice formation, migration, and melting.

Besides carefully selected radar parameters, the high efficiency of the SLR *Cosmos-1500* system was expected due to the simultaneous acquisition of overlapping images from two other sensors so that three different wavelength bands were involved. This could enable the improved interpretation of images and the elimination of errors in retrieved parameters. Further, the onboard preliminary processing of the radar data and the transmission of the

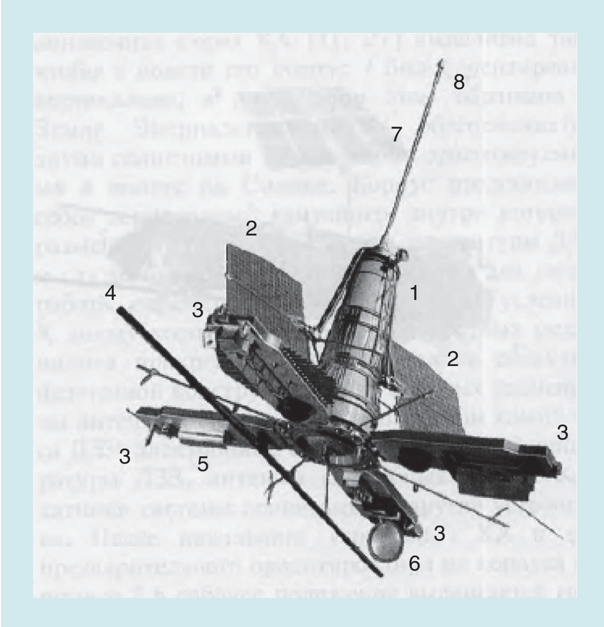


FIGURE 2. *Cosmos-1500* and its microwave remote sensing instruments: (1) bus, (2) solar panels, (3) rotatable instrument panels, (4) SLR antenna, (5) radiometer, (6) optical sensors, (7) telescopic mast, and (8) gravitational stabilizer [3].

TABLE 1. PARAMETERS OF THE SLR OF *COSMOS-1500*.

Wavelength	3.1 cm
Polarization	VV
Viewing angle range	20–46°
Antenna pattern width	
In the azimuthal plane	0.2°
In the elevation plane	42°
Spatial resolution	
Along the flight direction	2.4–3.2 km
Transverse to the flight direction	1.3–0.6 km
Average resolution in the swath, provided via APT	
In the UHF band	0.8 × 2.5 km
In the VHF band	2 × 2.5 km
Receiver sensitivity	–140 dB/W
Transmitter power	100 kW
Pulse duration	3 µs
Pulse repetition frequency	100 Hz
Orbit altitude	650 km
Orbital inclination	82.6°
Swath	450 km

Reproduced from [4] after correction of typos and translation mistakes.
VV: vertical transmit-vertical receive.

synthesized images, using the simple 137.4-MHz Automatic Picture Transmission (APT) channel, to hundreds of users, including a central site in Moscow and autonomous points in Kharkiv and Sebastopol, was also a very big step ahead.

Here, Kalmykov had to fight with Moscow colleagues from IRE RAS, who wanted to have a full monopoly on satellite imagery. Many details of the SLR of *Cosmos-1500* design and operation can be found in reviews [2], [3], [4], [5], [6], [21], [22], [23]. Being a general-purpose instrument, it outperformed greatly the preceding USSR military orbital SLR "Chaika" aimed at the search of massive surface targets such as the U.S. Navy air carriers [3] (see the "Other Contemporary Orbital Radar Systems: A Monster in the Shadow" section).

WHEN LENIN WAS HELPLESS: RESCUE MISSIONS OF THE *COSMOS-1500* SIDE-LOOKING RADAR

The work program of the new spacecraft envisaged many weeks of meticulous tests and experiments; however, this had to be greatly revised at the very beginning as the onboard Ka-band radiometer failed to operate. Moreover, only five days after placement into the polar Earth orbit in the autumn of 1983, the SLR of *Cosmos-1500* obtained a new task, which was absolutely unexpected. By the time of the launch of the spacecraft, a true drama had developed on the Northern Maritime Route, which runs all the way from the Atlantic to the Pacific along the Arctic coasts of the Russian Federation. That September, extremely strong northwest winds pushed the heavy multiyear ice to the De Long Strait near Wrangel Island, where a caravan of 22 freighters (perhaps several caravans as sometimes 40 and even 57 ships plus five icebreakers are mentioned) got blocked. The ships were loaded with cargo worth some US$8 billion [23], which was carried as winter supplies to the Arctic regions of the USSR. The MV *Nina Sagaidak* was soon crushed by the ice and sank (Figure 3), and there was a real threat of further losses, especially as the polar night was approaching.

The authorities created ad hoc interservices staff to monitor and guide the caravans. Besides conventional icebreakers, the first USSR nuclear-powered icebreaker *Lenin* was sent to the De Long Strait. However, soon, she got one propeller crushed by the ice and the other damaged. Her brand-new nuclear-powered sister ship *Brezhnev* (named after the recently deceased general secretary of the CC CPSU) had also failed to crush the pack ice. In the polar night season, air surveillance was pointless, and the SLR of *Cosmos-1500* became the only available source of trusted sea-ice information (as already mentioned, the other all-weather instrument, the onboard Ka-band radiometer, failed to work) in and around the De Long Strait.

Already, the first radar images of the disaster area (Figure 4) showed that the situation was not hopeless. Indeed, 100 km north of the caravan, near Wrangel Island, an extensive polynya (a sea area where the ice is either absent or very thin) could be seen, together with a strip of wide cracks and crevasses in heavy multiyear ice along which it was possible to direct the caravan to the polynya. Although the ad hoc staff of the rescue operation was reluctant to trust the microwave imagery, in the total absence of alternatives, it took up the risks and ordered the icebreaker to go north. On reaching the polynya, the icebreaker and the freighters turned southwest and, in a few days, sailed in safe waters.

FIGURE 3. The MV *Nina Sagaidak* sinking in the Arctic Ocean in September 1983.

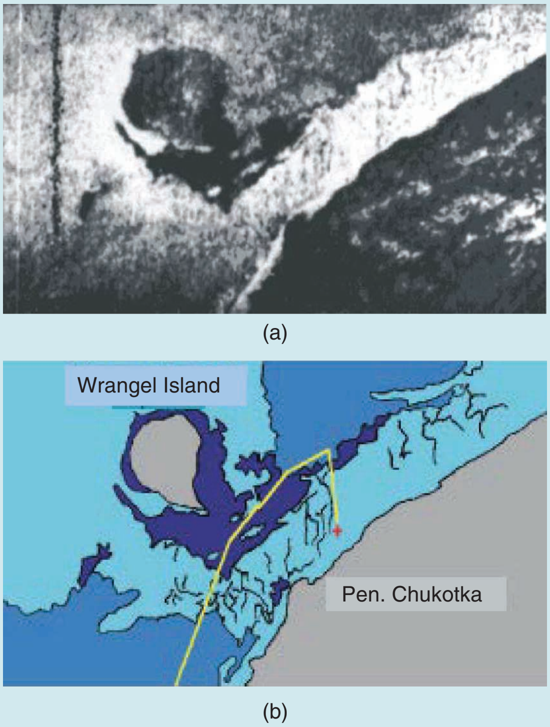


FIGURE 4. The rescue mission of the USSR freighter caravan in the De Long Strait, October 1983. (a) A radar image and (b) a topical map demonstrating the ships location and the route of their escape from the heavy ice area (■ thin young ice, ■ one-year ice, ■ thick perennial ice; rescue route is the yellow line. Pen.: peninsula. (Source: Reproduced from [4].)

Amazingly, within its 33-month lifetime, the SLR of *Cosmos-1500* was destined to fulfill another rescue mission, this time in the Southern Hemisphere [2], [3], [4], [5], [6], [23]. The research MV *Mikhail Somov*, sent in 1985 to the Antarctic to bring a rotation crew to a USSR polar station, was blocked in the 5-m-thick ice. To rescue her, a USSR icebreaker was sent all the way from the Northern Hemisphere; this was the conventional vessel *Vladivostok* as New Zealand, where the final replenishment had to take place, had already prohibited nuclear-powered ships from using its harbors. What is important for our story is that onboard the *Vladivostok*, a satellite information reception point was deployed to ensure the quick reception of microwave radar images from *Cosmos-1500*.

The high polar orbit of *Cosmos-1500* was well suited for such a mission. Its images (see Figure 5) enabled daily corrections of the icebreaker route in the ice fields both on the way to the blocked ship and back to the clean waters.

At the crucial phase of the operation, radar images revealed a wide polynya in heavy ice, stretching toward the drifting ship. Thanks to this, instead of using a helicopter to evacuate the crew of the drifting ship, which would have had to be abandoned, the icebreaker rushed toward *Mikhail Somov*, freed her from the trap, and led her out of the ice [23].

When preparing this publication, we discovered that in today's Russia, the role of *Cosmos-1500* and its RA-SLR in the maritime rescue missions of 1983 and 1985 is subject to total oblivion. In several "documentary" films made in the 2010s, and even in the Russian-language Wikipedia, the existence of *Cosmos-1500* is not mentioned at all, and instead, it is the "intuition" of icebreaker captains that is highly credited. Okay, intuition can be a powerful thing, especially when it is supported by microwave radar images received twice a day. A comprehensive 675-page Russian monograph [24], published in 2010 by the leading staff of the USSR space synthetic aperture radar (SAR) works at the Vega State Co., mentions *Cosmos-1500* and its SLR. However, it does not mention its polar seas missions; instead of IRE NASU, the development of this radar is linked to the Kharkiv Institute of Radio Electronics, which was a technical university.

It should also be noted that within the 19-month period between two polar rescue missions and after the second of them, the RA-SLR of *Cosmos-1500* was engaged in its main operational tasks: research into the remote sensing of the mesoscale phenomena caused by the interaction between the ocean and the atmosphere. This related, first of all, to the detection and tracing of cyclones, typhoons, and hurricanes; however, less powerful formations, such as quasi-regular convective cell structures, cloud fronts, and vortices were also studied [2], [6], [23]. Figure 6 shows optical [Figure 6(a)] and microwave [Figure 6(b) and (c)] images of the tropical cyclone Diana dated 11–12 September 1984. The images of Figure 6(a) and (b) were obtained at the same time, and that of Figure 6(c) was obtained 14 h later. These images allowed the correct estimation of the velocity of the cyclone translocation, around 7 km/h, and its total power, about 1.2×10^8 MW.

OBSTACLES TO OVERCOME: NOT ONLY TECHNICAL

When creating the RA-SLR of *Cosmos-1500*, Kalmykov had to solve many problems of organizational, technical, and human nature. Until 1972, Kalmykov closely collaborated with IRE's theoreticians and enjoyed support and encouragement from the first IRE director, O. Y. Usikov. All that changed when the latter was replaced by V. P. Shestopalov by the decision of the CPSU Committee of the Kharkiv Region. The new director was a relative newcomer in the R&D institute as, until the end of the 1960s, he was just an associate professor in physics at second-level universities in Kharkiv. His career sky-rocketed when a cousin of his wife became a secretary of the CPSU Committee of the Kharkiv Region. It is no surprise that (as explained in [3], [6]) he was looking at space radar research, which promised both heavy responsibility and tight control from Moscow, as a high-risk activity that should be avoided. As mentioned, by 1979, Kalmykov had gotten so desperate that he decided on moving to IMH. In Sebastopol, his friend (and the head of

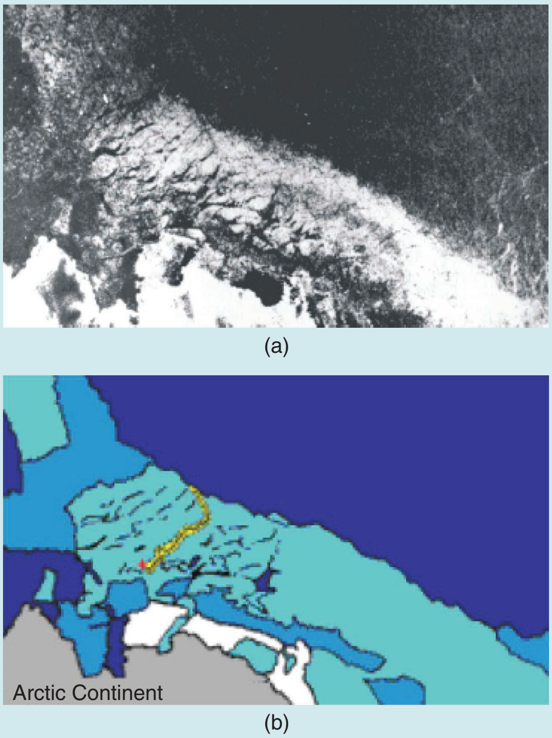


FIGURE 5. The rescue mission of the USSR MV *Mikhail Somov* in the Antarctic, July 1985. (a) A radar image and (b) a topical map demonstrating the ship location and the escape route of the icebreaker *Vladivostok*. (Reproduced from [4]; the color legends are the same as in Figure 4. Note a misprint: the continent edge is Antarctica.)

the collaborating group) was V.V. Pustovoytenko, who had his own troubles with his administration but was supported both by Moscow and Dnipro.

As admitted in [3], [6], the resistance of V. P. Shestopalov was partially overcome only due to the extraordinary personal efforts of S. N. Konyukhov, the head of the rocket division of DBP in Dnipro, who was made responsible for the whole remote sensing payload for the "Resurs-O" program. Here, it should be explained that, in the USSR, R&D centers located not in Russia but in other republics seldom coordinated the state programs. Usually, this was entrusted either to the industry bosses, the military, or the R&D centers in Moscow and Leningrad. Konyukhov was a rare exception. Perhaps this was because of the success of ICBM SS-18 development at DBP. Besides, it was his predecessor at DBP, V. M. Kovtunenko, who initiated, in 1974, the development of equipment for the study of oceans from orbit [3], [5], leading to the previously mentioned secret decree of the CC CPSU and the government (1977) about the creation of the system "Resurs." Still, it was the success of SAR work onboard the *U.S. Seasat* in 1978 and its huge effect on the USSR political and military leaders that caused a decision to speed up the work.

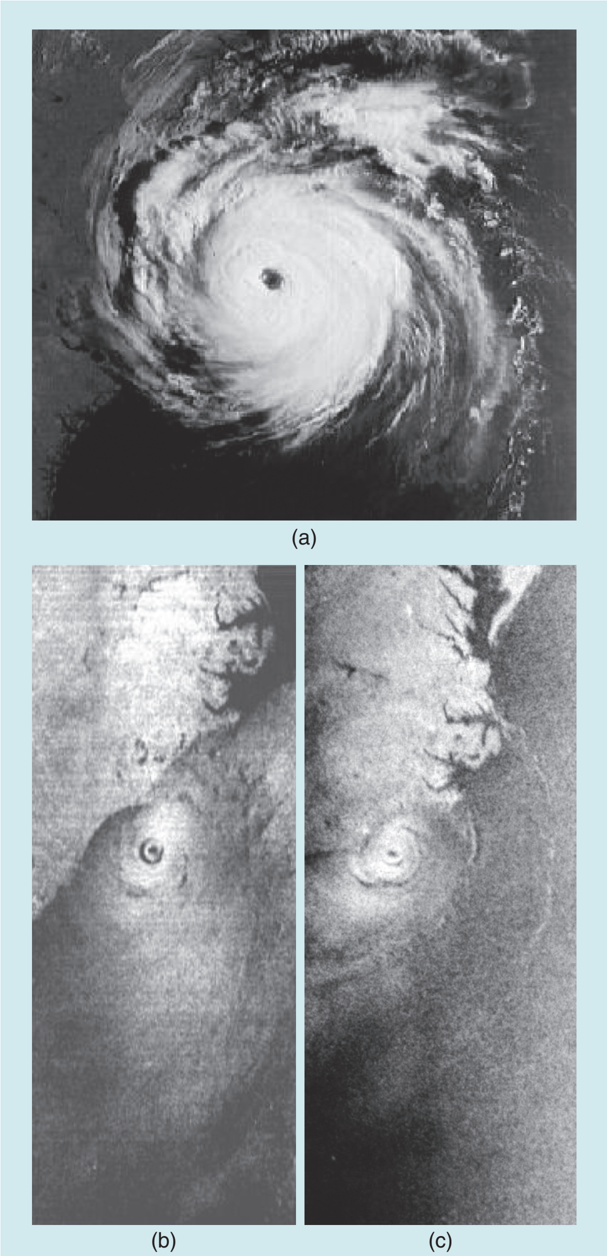


FIGURE 6. Tropical cyclone Diana in the Atlantic Ocean, 11 September 1984. (a) An optical image and (b) and (c) microwave images obtained at 6:30 p.m. (b) and at 8:30 a.m. the next day (c).

Such was the background for the phone call to IRE's director from the USSR Ministry of Space Industry about establishing a space radar R&D unit headed by Kalmykov. However, even after obtaining his own department at IRE, with rich funding from the ministry, Kalmykov's working conditions remained far from perfect.

Thus, Konyukhov coordinated the work of all three Ukrainian R&D centers, one ministerial (DBP) and two academic (IRE and IMH). Still, he was supervised by his ministry in Moscow, where the other powerful organizations, such as IRE RAS and the almighty ministerial Central R&D Institute of Device Building, were developing the optical sensors and, in part, the information storage, processing, and transmission to customers' equipment for *Cosmos-1500*.

As recalled in [3], a mutually beneficial collaboration between the Ukrainian teams was established quickly; however, a similar level of synergy was never reached with the central organizations. In 1983, the conflict culminated in a series of heated discussions where the directors and leading experts of several powerful Moscow R&D centers attacked Kalmykov, Pustovoytenko, and B. Y. Khmyrov (Konyukhov's successor at DBP). They demanded abandoning SLR in favor of SAR and, therefore, transferring the radar development to their laboratories. To rationalize their demands, which were fed by professional jealousy, they referred to the success of the *U.S. Seasat* and used a vague accusation of the allegedly insufficient "information potential" of Kalmykov's SLR data. Still, Moscow SAR designs existed only in drawings and needed at least one more year of intensive development and testing (in reality, the first successful USSR SAR was placed into orbit only in 1991), while Kalmykov had an unbeatable argument—the successful operation of the airborne analog of his SLR. Thanks to this circumstance, Khmyrov expressed full support to Kalmykov, the attacks of the Moscow colleagues were rebuked, the IRE team released the radar, and *Cosmos-1500* was assembled at DBP and launched according to the schedule.

When Kalmykov's SLR got successfully into its orbit, the feud between the developers faded off, at least for a while. However, suddenly, new powerful opponents emerged. As mentioned, already before the placement of the SLR into orbit, a caravan of USSR freighters got blocked by heavy ice in the Eastern Arctic. The situation was made public by the authorities, although with a delay, as usual for the USSR media. When Kalmykov learned about it, he tried to approach the ad hoc committee put in charge of the rescue mission to propose his aid. This happened to be nearly impossible. A legend tells that Kalmykov wrestled his way to the committee meeting room, showing the satellite imagery printouts to the KGB guards; however, more probably, he had found someone who played the role of mediator. Still, this was not the end. Unexpectedly, the top administration of the USSR Chief Directorate of the Northern Maritime Route, the dominant service in the rescue committee, displayed a huge distrust of the satellite data, which suggested a nontrivial escape route—to the north of the disaster site. At the crucial moment, Kalmykov had to voice a threat to file a complaint to the superpowerful authority: the CC CPSU. This worked out, and a nuclear-powered icebreaker was ordered to move north.

OTHER CONTEMPORARY ORBITAL RADAR SYSTEMS: A MONSTER IN THE SHADOW

The first space-based microwave Earth imaging experiment using the L-band SAR of the *U.S. Seasat-A* satellite was conducted in 1978. That radar worked for three months at the wavelength of 23 cm with a swath of 100 km and provided a spatial resolution of 25 m [25], [26]. The results of this experiment exceeded all expectations and showed the high capabilities of orbital systems. However, the radar images were synthesized not onboard but on the ground, with great delay, which prevented their use in time-sensitive applications. Essentially the same test SARs operated onboard the *Space Shuttle Columbia* in 1981 (five days) and 1984 (seven days) [25], [26], [27].

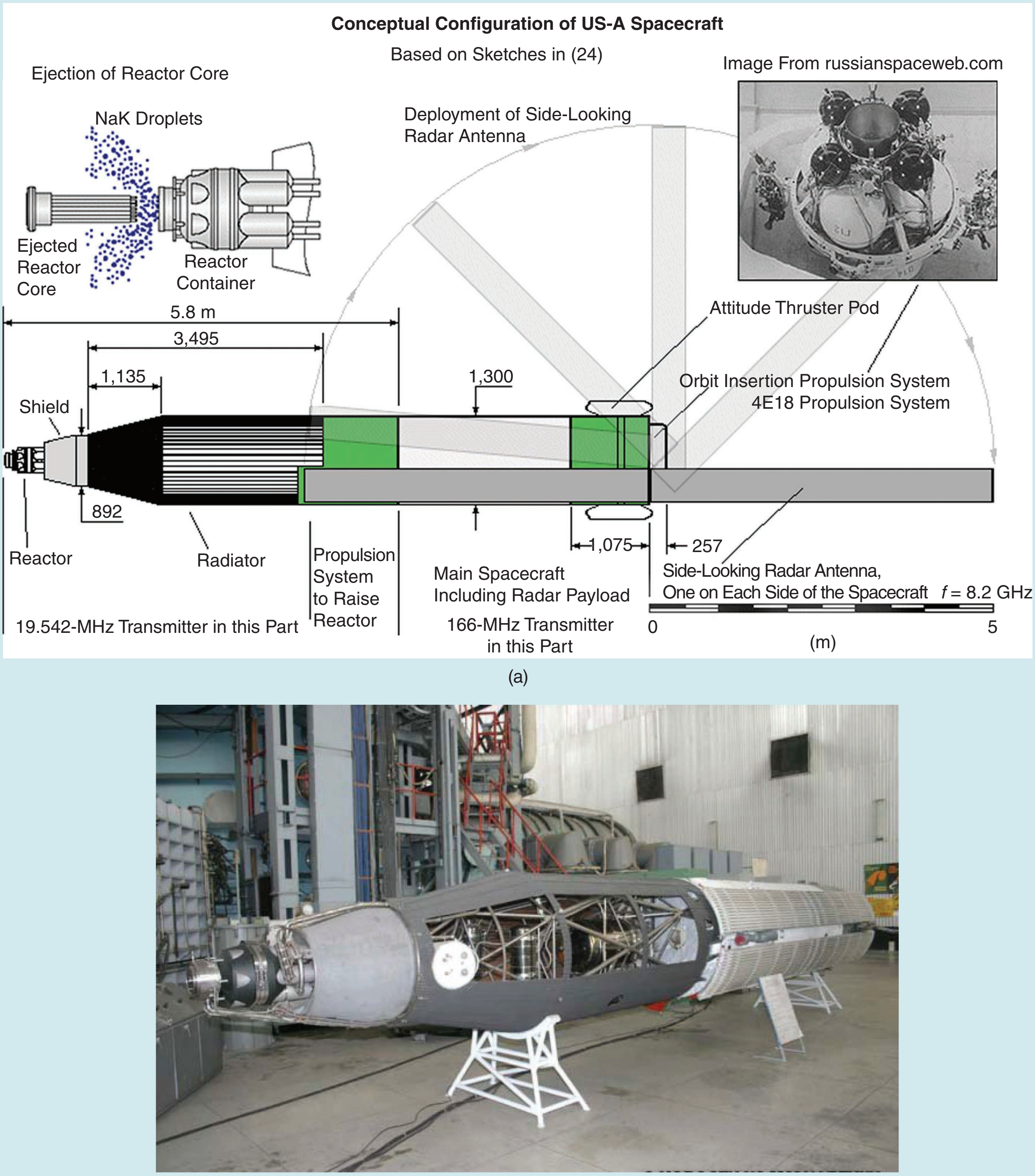
It should be noted that, in parallel to Kalmykov's SLR, the USSR SAR systems were also developed: in Moscow. Test SAR "Travers" was installed onboard the spacecraft *Resurs-O-1* launched as *Cosmos-1689* in 1985 [2], [3] and, later, on the Priroda module of the orbital station (OS) *Mir*. The other SAR required full OS power; it was launched in 1987 onboard *Cosmos-1870* and in 1991 on *OS Almaz-1* [6], [24].

Despite an order of magnitude lower resolution than SAR, SLR was attractive due to higher radiometric accuracy and an order wider swath. It could use an available simple magnetron source, which had less stable characteristics than needed for SAR; additionally, onboard image processing, lower cost, and much quicker delivery were also very important. The orbital system of *Cosmos-1500* had no contemporary analogs in the day-to-day practical monitoring of the ocean and ice. It was true that the *Seasat* and shuttle SAR experiments (and later *ERS-1*, *RADARSAT*, and other SAR systems) were primarily designed to serve oceanography and generally met and even exceeded expectations. However, they turned out to be even more useful for land applications, where a several-day delay in signal processing was not as critical as in maritime navigation. As a result, the practical components of their space radar programs were focused mainly on monitoring land parameters [25], [26], [27].

Still, in deep secrecy, there existed another USSR orbital RA-SLR system for oceanic observations, perhaps a hundred times more expensive than *Cosmos-1500* and all its derivatives. It was initiated as early as 1960, first placed into low-Earth orbit in 1975, and finally, closed in 1988 after at least 39 launches. This radar was called *Chaika*, and it and the spacecraft equipped with it were part of the top-secret naval reconnaissance and targeting system "Legenda" [24]. In the West, they were known as *Radar Ocean Reconnaissance Satellites* (*RORSATs*) [28], [29], [30]. Each RORSAT had two magnetrons (principal and backup); one, or after 1985, two RA-SLRs working at the frequency of 8.2 GHz; and one or two 10-m-long slotted-waveguide antennas to provide left-side and right-side swaths, each 450 km wide (Figure 7). These satellites were designed to find and track U.S. Navy air carriers, first of all, in the North Atlantic and North Pacific, and release the targeting data to the USSR assault triad: Navy bombers of the Tu-22M3 type, superheavy cruise missile submarines of the Oskar-I and Oskar-II (*Kursk*) types, and heavy guided missile cruisers of the *Pyotr Velikiy* and *Moskva* types.

Each component of the triad had to launch many dozens of cruise missiles with conventional and nuclear warheads. For instance, according to a comprehensive description of a retired USSR Navy officer [31], to attack one U.S. air carrier from the air, as many as three full regiments of Tu-22M3 medium-range strategic bombers (i.e., 100 aircraft) were assigned. Some of the bombers and all dedicated submarines and cruisers were equipped with receivers of the "Legenda" system (Figure 8). Through the network of communication satellites known as *Parus*, RORSAT data information was passed on to these assets and a dedicated USSR Navy control center in Noginsk near Moscow [24]. The task of the system was not just to locate and identify naval ships but to provide the targeting data that could, allegedly, be fed directly into antiship missiles, such as the 6-ton X-22 liquid-propellant ones carried by the Tu-22M3.

The reason for such a tremendous concern was that in the 1970s and early 1980s, the USSR submarine-launched ballistic missiles (SLBMs) had limited range and accuracy, so to fire them, the submarines had to come nearer to the U.S. East and West Coasts. Therefore, the U.S. Navy air carriers were viewed as an extremely dangerous force, able to block or destroy the USSR submarine fleet in their home bases at the Cola and Kamchatka Peninsulas. Still, traditionally, according to the USSR and Russian military doctrine and ethos, all bombers, submarines, and cruisers taking part in a raid on a U.S. air carrier were viewed as expendables. As for the bombers, probable losses were estimated at 50%; "Legenda" was not trusted by the pilots and the air staff, and a suicide raid of two dedicated Tu-16 reconnaissance aircraft was always envisaged to make visual contact with air carriers [31]. Similarly, the Navy staff always sent a destroyer or even a trawler to follow every U.S. air carrier task force. Both submarines and cruisers shared the same nickname of “single-shot assets” as the reloading of their missiles was not available. According to [31], they expected no more than 30 min of life after firing their first and the last salvos of 24 or 20 (or 16) “Granit” cruise missiles, respectively. Moreover, the submarine reflector antenna of the “Legenda” receiver was a huge retractable structure christened *Punch Bowl* by the North Atlantic Treaty Organization (NATO) fleets (Figure 9). To use it, the submarines had to stay at periscope depth for long hours preceding their attack, which should have added to the kamikaze spirit of their crews.



(a)

(b)

FIGURE 7. (a) RORSAT concept and configuration. (Source: [28].) (b) A demonstration copy at the DB “Arsenal” in St. Petersburg showing the nuclear reactor at the forward end and two unfolded SLR antennas in the rear. (Source: [24].)

(a) (b)

FIGURE 8. (a) "Legenda" satellite receiver antennas on the *Pyotr Velikiy* nuclear-powered USSR cruiser (a)—white radome on a vertical structure at the side of the tower—and (b) on the sunken *Moskva* cruiser (b)—similar light-grey radome just above the rear launch tube. To eliminate the shadowing of antennas, the same equipment was placed at the portside.

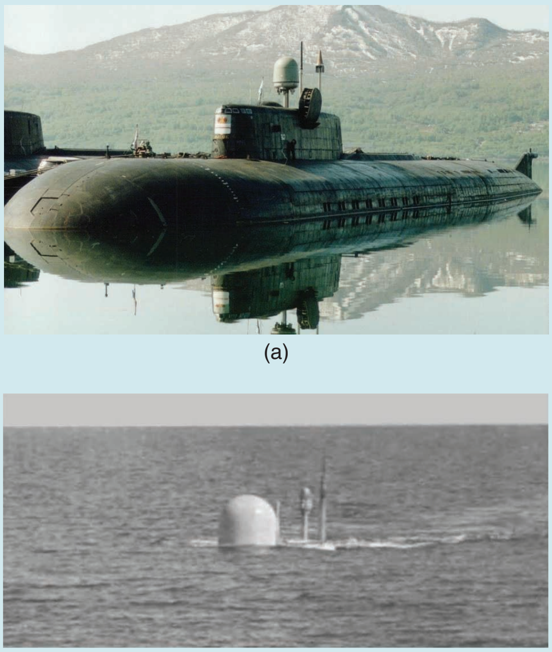
The whole USSR orbital naval reconnaissance and targeting system "Legenda" carried the same stigma of hopeless gigantomania and kamikaze spirit. The USSR electronics of that time were quite backward and unreliable; additionally, the signals backscattered from ships are accompanied by intensive clutter due to the sea waving and precipitation effects. To compensate for insufficient sensitivity and poor signal processing, USSR developers used an extremely monstrous approach. First, the RORSATs used small fast neutron nuclear reactors ("Buk") to provide the 3-kW power needed to feed the radar; second, they always flew at low orbits of 250–270 km with a 65° inclination that made their lifetimes short, less than two months on average. Even more—to enable determining the direction and speed of the sea target with such an incoherent sensor as SLR—a primitive but efficient solution was found—nuclear RORSATs were launched in pairs and placed into identical orbits with a half-hour separation [28].

The combination of a low orbit and a nuclear power source introduced a serious risk of accident or uncontrolled reentry [29].

> "To counter the problem, each RORSAT consisted of three major components: the payload and propulsion section, the reactor, and a disposal stage used to lift the reactor into a higher orbit, with an altitude of 900 km, at the end of the mission."

Each of at least 33 reactors launched in 1975–1988 contained more than 30 kg of weapon-grade (enriched to 90%) uranium-235, besides the sodium-potassium coolant. This means that presently about 940 kg of highly enriched uranium and a further 15 tons, mostly shaped as tens of thousands of radioactive coolant droplets, 0.6–2 cm in diameter, orbit Earth [29].

There were several accidents of the malfunctioning of RORSATs that triggered public attention to the danger they presented. On 24 January 1978, five years before Kalmykov's success, *Cosmos-954* failed to throw its nuclear reactor into a high "graveyard" orbit and instead crashed over Canada's Great Slave Lake, contaminating a wide area. The debris was examined by U.S. Lawrence Livermore National Laboratory scientists, which enabled them to get a better understanding of the design and mission of RORSATs. This catastrophe led to a two-year break in RORSAT launches, used for improvements in their design. Still, another similar accident happened at the beginning of 1983 with *Cosmos-1402* when separate parts of the reactor fell into the Indian and Atlantic Oceans.



(a)

(b)

FIGURE 9. (a) and (b) "Legenda" receiver antenna in a radome on the top of the coning tower of the USSR Oskar type submarines (one of them was the ill-fated *Kursk*, which exploded in 2000) (a) in the harbor and (b) at sea. (Sources: [32], [33].)

According to the U.S. Central Intelligence Agency assessment, RORSATs were able to track U.S. air carriers in good sea and weather conditions; however, they became useless otherwise. These spacecraft were so tremendously expensive and slow in production that their launches were usually tied to the massive naval drills of the U.S. and NATO fleets, thus leaving lengthy gaps in air carrier tracking. By the end of the 1980s, the USSR SLBMs had improved their range and accuracy to the extent that the submarines could stay on patrol just in the Sea of Okhotsk, which obtained the name of "a submarine aquarium." Therefore, the RORSAT program was terminated in 1988, although the other part of the "Legenda" system, higher-orbit electronic intelligence satellites (EORSATs), survived, and their derivatives are still in operational use by the Russian Navy [9].

For our story, it is interesting to admit that the frequency of operation, the type of microwave source and antenna, and the swath width of Kalmykov's RA-SLR and the "Chaika" SLR were rather similar to each other. Kalmykov had security clearance and should have known about the existence of naval RORSATs designed by the rocket and missile DB "Prikladnaya Mekhanika" (Applied Mechanics) in Moscow (now Khrunichev State Co.). He could even know about their design principles because EORSAT satellites were designed at DBP and produced serially at the Yuzhmash Industry in Dnipro. Moreover, he should know from his IMH colleagues that the development of the signal processing for SLR "Chaika" was facilitated by the Black Sea experiments with its airborne analog on a dedicated turboprop aircraft [24].

However, given the USSR spy mania and intensive and even brutal rivalry between the rocket DBs, Kalmykov could not know anything except general terms. Note the difference in the satellite composition: vertical for *Cosmos-1500* versus longitudinal for RORSATs (see Figures 2 and 7). This was apparently connected to the flight altitude; low-orbit RORSATs had to have a more "aerodynamic" shape to reduce the effect of the atmosphere, while *Cosmos-1500* could instead neglect it. It is also important that his SLR was developed 10 years later than "Chaika" and integrated Kalmykov's multiyear collaboration with IRE's theoreticians around the sea and ice backscattering research. In terms of onboard signal processing, *Cosmos-1500* implemented two relatively new, at least for the USSR space programs, operations: incoherent integration of eight successive images along the swath and compression of the image intensity dynamic range across the swath using the automatic gain control. Additionally, telemetric data on the current parameters of the SLR units were also transmitted to the ground stations. Therefore, the SLR of *Cosmos-1500* can be safely considered as an original instrument.

FIGURE 10. The spacecraft *Cosmos-1500* with microwave equipment for remote sensing of Earth at the permanent USSR Exhibition of Achievements of National Economy in 1985. (Source: [4].)

POST-HISTORY: FROM USSR AWARDS TO A POSSIBLE IEEE MILESTONE

Two polar sea rescue missions of *Cosmos-1500* gave a rare chance to the USSR authorities to present the USSR space program as a peaceful, truly useful, and efficient activity, while in reality, it was heavily biased to military use, poorly balanced, and plagued by the fierce rivalries of different players, and it suffered from numerous accidents and catastrophes [9]. These missions were broadly highlighted in the USSR newspapers and on TV. Already in 1985, a full-size copy of *Cosmos-1500* was displayed in Moscow at a permanent exhibition (Figure 10).

This publicity and attention helped obtain fair recognition at the national level. In 1987, Kalmykov and his nine colleagues were awarded the National Prize of Ukraine in Science and Technology with the citation, "For the development and implementation of radar methods of Earth remote sensing from aerospace platforms." The recognition at the USSR level was restricted to several state orders, the highest of which, Lenin's Order, was given to the same IRE director who nearly pushed Kalmykov out in 1979. For comparison, the developers of the secret naval SLR "Chaika" and the whole system "Legenda" were awarded, despite its low efficiency and RORSAT disasters, a secret Lenin's Prize of the USSR.

As mentioned previously, the design and development of the *X*-band orbital RA-SLR of *Cosmos-1500* led to the successful overcoming of a wide range of scientific and technical problems. This enabled the technology transfer to the

R&D Institute of Radio Measurements in Kharkiv (now the RADMIR Institute), which had a small-series production line. In all, essentially the same SLR was exploited on six remote sensing satellites of the USSR/Russia Space Operative System Okean in 1986–2004 and two Ukrainian satellites named *Sich* in 1997 and 2004. It was successfully used to detect and monitor many critical situations and natural phenomena on a global scale [2], [3], [4], [5], [6], [19], [20], [21], [22], [23].

When Ukraine got its independence in 1992, its space industry, centered around DBP and Pivdenmash, hoped to keep working, although Ukraine had no launch sites and only a few tracking and control facilities. Indeed, Russia was dependent on DBP for the maintenance of its major nuclear ICBM force of several hundred silo-based SS-18 and for the supply of Tsiklon boosters and EORSAT satellites. As a part of the bargain, two Ukrainian radar remote sensing satellites named *Sich* were launched from the Russian launch sites. The first, *Sich-1*, was fully operational for three years: from 1997 to 2000. However, the second of them, *Sich-1M*, was placed into the wrong orbit and failed to deliver the expected data. Given that Russia's president in 2004 was the same as today and in view of the Russian invasion of Ukraine, one can guess that the "wrong orbit" of *Sich-1M* was one more secret-service operation, aimed at denying Ukraine sensitive information and spoiling its reputation as a reliable spacecraft developer.

After 1992, Kalmykov had to restrict his work to the airborne analog of his SLR. Such a system, called *MARS*, was developed and used by various Ukrainian ministries and services [34], [35], [36], [37], [38], [39]. However, the unexpected death of Kalmykov in 1996 from kidney trouble left a void that was hard to fill.

Broadly speaking, the development and operation of the RA-SLR of *Cosmos-1500* initiated, 40 years ago, a new research area and discipline in the Ukrainian microwave community—remote sensing of Earth from aerospace platforms. Therefore, at the national level, its impact is truly huge. In the context of the USSR science and technology, it played the role of a prototype for the family of sea ice-monitoring satellites that provided safe navigation in the Arctic from 1986 to 2004. Besides, it was used by Russian researchers to study the formation and dynamics of the ice covers of the Sea of Okhotsk [40] (it is quite possible that this research was initiated by the USSR military as that distant sea, bounded by the scarcely inhabited Russian Far East territories and Kuril Islands, became a sanctuary for the USSR fleet of nuclear-powered Typhoon-type SLBM submarines in the late 1980s). At the global level, it was one of the cornerstones of what was christened *oceanography from space* [25] and had initiated the systematic use of radar images for safe polar navigation.

As we believe, all of the previously presented information suggests that the SLR of *Cosmos-1500* satisfies the requirements of the IEEE History Committee to be nominated as an IEEE Milestone in Ukraine.

ACKNOWLEDGMENT

We thank the Physics Benevolent Fund of the Institute of Physics, U.K., for one-off emergency support in the context of solidarity with Ukraine. Alexander I. Nosich acknowledges the support of the European Federation of Academies of Sciences and Humanities via a research grant from the European Fund for Displaced Scientists and the hospitality of the Institute of Electronics and Numerical Technologies of the University of Rennes, France.

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