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Surveys of Foreign Scientific and Technical Literature

MODIFICATION OF THE IONOSPHERE

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ATD Work Assignment # 101

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Foreword

This report, *Modification of the Ionosphere*, has been prepared in response to the requirements of ATD Work Assignment No. 101. Based on original Soviet research as well as on Soviet interpretations and analyses of US tests and investigations, the report deals primarily with the effects of nuclear bursts at various altitudes on the physical properties and ionization levels of the upper atmosphere and on radio-wave propagation characteristics. The immediate importance of such research in military strategy and defense planning, particularly of ABM defense systems, is reflected in this report in the statements and observations of responsible Soviet military authorities.

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Introduction

Experiments in ionospheric modification, i.e., the introduction of chemical or radioactive agents into the ionosphere for the purpose of altering electron concentrations and thus ionization levels, have been conducted by the USSR, the US, and Britain in order to develop methods of ensuring communications reliability of friendly forces and disrupting enemy communications in the event of war. Primary attention in this report is focused on Soviet interest in the single most important such experiment, namely, the study of the effects of a nuclear burst at a given height on radar and radio-wave propagation characteristics. Other non-nuclear, but germane, experiments as, for example, investigations of ray paths in artificially created ionized clouds, are also discussed.( ) Although certain ionospheric perturbations (SID, AA, PCA, Es) caused by the x-ray and EUV fluxes emanating from such intense short-lived natural phenomena as solar flares are similar to those resulting from a nuclear burst, they are not discussed in this report for several reasons. First, much is still unknown about the generation mechanism and development of flares, second, flares are uncontrolled phenomena which can occur at any time, and third, their effects are limited to the sunlit hemisphere of the Earth. Nuclear bursts, on the other hand, are scheduled and controlled experiments whose effects may be limited in an area by varying the height and yield of the burst. Similarly, all Soviet papers dealing with the atmospheric effects of the Tunguska meteorite of 1908 have been disregarded as too speculative and insufficiently documented. The communications spectrum, ionospheric regions and layers, and atmospheric nomenclature referred to in the text are given in the appendix.

Since, to a considerable extent, the problem of ionospheric modification involves a combination of military requirements and scientific and technical capabilities, a brief analysis of those aspects of Soviet nuclear warfare doctrine pertinent to the problem precedes the discussion of actual experiments.

Although it is true that some of the Soviet references contained herein (Krasota, Paliy, Shirshev) are, on the authors' admission, based on [unspecified] Western sources, it must be noted that the contents have been published in official Soviet military journals.

USSR Nuclear War Doctrine

Soviet military doctrine is based on the inevitability of nuclear war between the two opposing social systems of capitalism and socialism. This has been stated repeatedly by military leaders like Marshal Sokolovskiy [1] and by political figures. L. P. Prusanov [2], for example, describes the doctrine in these terms:

> The essence of Soviet military doctrine is this: if a future war is unleashed by the imperialists, then it will be the decisive collision between the two opposing social orders, and nuclear rocket weapons will inevitably be used. All this pre-supposes an extremely violent and dynamic character of the conflict, high maneuverability of combat operations, the absence of continuous fronts and well-marked boundaries between front and rear, and the appearance of possibilities for striking sudden blows of great force, both against the troops and the homelands of the warring nations. In connection with this, very great attention is devoted to the initial period of the war.

In fact, not only does Soviet military doctrine hold that nuclear warfare is in accord with the Leninist principle of pursuing political ends by other means, but some Soviet military spokesmen (e. g., Col. A. Ratnikov, Lt. Col. O. Rzheshevskiy [3]) even assert that nuclear war is preferable to conventional war for ideological reasons, since an atomic war would hasten the process of world communization.

It is clear, therefore, that nothing is spared by the Soviet leadership to provide the military-technical superiority in nuclear warfare to ensure victory in such a war. This is clearly defined in the following quote from a Soviet military journal [4]:

> ... Military-technical superiority is such a correlation of quantity of military equipment and weapons, of the degree of troop training in using them and also of the effectiveness of the organizational structure of the army, *that the given side has the advantage before a real or potential enemy and can defeat him...*

While some US military analysts either entirely preclude the idea of a nuclear war between the great powers or else see it fought in a succession of controlled stages, leading European authorities regard it as inevitable and massive. The official French military journal

Revue de Defense Nationale [5] observes that Soviet military doctrine rests exclusively on the concept of a "nuclear blitzkrieg" that begins with a "powerful strike of strategic nuclear weapons." Strikes of massed armored and mechanized forces deep into enemy territory together with the employment of large paratroop forces will follow the first nuclear strike. "The purpose of these actions is to surprise and destroy as quickly as possible whatever potential remains intact after the enemy has been staggered and confused by the nuclear strike. Moreover, the enemy will be denied any possibility of counterattack and his territory will be occupied." The leading Swiss military journal *Allgemeine Schweizerische Militaerzeitschrift* [6] restates this view, noting that it is believed that the Soviet strategy in Europe for the next ten years is to retain the doctrine of the outbreak of war by strategic nuclear strikes accompanied by the simultaneous opening of ground operations supported by tactical nuclear weapons.

Lt. Gen. H. Gaedcke [7], former instructor of tactics at the Berlin War Academy and commander of the II Corps of the West German Bundeswehr, concludes from his analysis of Marshal Sokolovskiy's *Military Strategy* [2nd edition] that the Soviets are convinced the next war will be a nuclear war in which no distinction will be made between front and rear echelons and in which the initial period will be crucial and decisive. The Soviets, Gen. Gaedcke continues, believe all wars automatically escalate into big ones and that big ones become nuclear. Since the Soviets are convinced that the West plans to strike first, they believe that they must therefore take the necessary steps to upset or trump the surprise attack. Gaedcke concludes by admonishing all responsible Western governmental agencies to take all the measures needed to ensure civil defense and national survival.

A British analyst [8] observes that both Soviet and NATO military leaders are planning in terms of ground combat with tactical nuclear weapons following a strategic nuclear exchange between the Soviet Union and the West. After this exchange, the period of "broken-back" war is expected to begin, involving ground forces in Europe, Africa, and the Middle East. The same British source notes that General P. A. Kurochkin, Commandant of the M. V. Frunze Military Academy in Moscow, has justified a preemptive nuclear strike against the US. Soviet strategists, according to this source, realize that the power which makes the first strike will gain a tremendous advantage. He concludes with the observation that the greatest deterrent to a preemptive attack is US nuclear superiority.

It is precisely because of the importance Soviet authorities place on the initial phase and the element of surprise in a nuclear war that the stratagem of ionospheric contamination and disruption of enemy warning systems before the first strike is so vital. As has been observed by the British analyst, the major deterrent to such an attack is US nuclear superiority. Should, however, a state of parity of nuclear strength be approached between the USSR and the US, then tactics and stratagems of which ionospheric modification is one will assume even greater significance. The aphorism "when weapons balance, stratagems must prevail," attributed to Sun Tsu, a military theoretician in the fifth century before Christ, then becomes very appropriate.

The following technical and more specific discussions on military operations involving high-altitude nuclear bursts are therefore in total consonance with Soviet nuclear war policy. An assessment of the potential of the USSR in this regard must commence with a survey of its research capabilities.

History and Present Organization of Ionospheric Research in the USSR

The first operational service providing necessary magnetic field data on which to base operating radio-frequency forecasts was established for the Moscow and Leningrad areas in 1937 by the Slutsk Magnetic Observatory. At about the same time, the Tomsk Ionospheric Station was set up to provide analogous ionospheric data for radio forecasts. During World War II the functions of the Scientific-Research Institute of Earth Magnetism (NIIZM) were transferred to the Vysokaya Dubrava Observatory near Sverdlovsk. Following the war, NIIZM was established in the vicinity of Moscow in Krasnaya Pakhra. In 1956 NIIZM, then known as the Scientific Institute of Earth Magnetism, Ionosphere, and Radio-wave Propagation (NIZMIR) and now known as the Institute of Earth Magnetism, Ionosphere and Radio-wave Propagation AN SSSR (IZMIRAN), was assigned the responsibility of supplying radio-wave propagation and ionospheric data to all interested Soviet governmental offices. Two zonal stations were then established in Irkutsk and Murmansk. In 1957 with the commencement of IGY, NIZMIR had at its constant disposal "urgent" geo- and astrophysical information from worldwide observatories and was designated control center for Eurasia; it began to exchange data with other regional control centers in Washington, Paris, and Tokyo [9].

During the IGY (July 1957—January 1959) ionospheric research activities were broken down into the following seven major projects: 1) the study of the morphology and physics of the quiet ionosphere and ionospheric disturbances, which was conducted by IZMIRAN, the Arctic Scientific Research Institute, Tomsk University, Rostov University, the Crimean Astrophysical Observatory, the Institute of Physics and Geophysics of the Turkmen Academy of Sciences, and field observatories of the USSR Ministry of Communications; 2) the investigation of the heterogeneous structure of the ionosphere and the movements and winds in the ionosphere—IZMIRAN, Moscow State University, Khar'kov Polytechnic Institute, Tomsk University, and the Institute of Physics and Geophysics of the Turkmen Academy of Sciences; 3) the investigation of radio-wave absorption in the ionosphere by means of pulse sounding—Scientific Research Institute of the USSR Ministry of Communications, the Arctic Scientific Research Institute, Tomsk University, Rostov University, Institute of Physics and Geophysics of the Turkmen Academy of Sciences, and stations of the USSR Ministry of Communications; 4) the investigation of atmospheric disturbances and whistlers—IZMIRAN and the USSR Ministry of Communications; 5) the study of tidal movements in the ionosphere and their relation to variations of the geomagnetic and geoelectric fields—IZMIRAN; 6) the study of the relation between the state of the ionosphere and variations in intensity of solar x-ray and UV-radiation (including rocket and satellite data)—IZMIRAN and the Crimean Astrophysical Observatory; and 7) the determination of radio-wave propagation between Moscow and Irkutsk—Irkutsk Branch of the All-Union Scientific Research Institute of Physical Engineering and Radio-Engineering Measurements and Moscow State University [10].

Most of these research projects were continued without interruption through the IGC and into the IQSY, by which time (1964) 22 stations were officially reported [11] to be engaged in vertical soundings of the ionosphere drift measurement, absorption measurement, and other research operations [see Table 1].

The Scientific Research Radiophysics Institute (NIRFI) located in Gor'kiy inauguarated intensive ionospheric investigations in 1957 in connection with the IGY. In 1961 NIRFI introduced systematic studies of the structure of the ionosphere on the basis of the analysis of UHF and HF radio signals from satellites. The Gor'kiy Radiophysics Institute is also active in radioastronomical research and in investigating the effects of solar disturbances on radio-wave propagation [12].

Table 1. Locations of ionospheric stations

No.	Station	Geographic coordinates		Observations		
		Long.	Lat.	V_1	A_1	D
1	Alma-Ata	76 55'E	43 15'N	+	+	
2	Arctic Drifting Stations	176—157	75—99	+		
3	Ashkhabad	58 22'	37 56'	+		+
4	Khabarovsk	135 10	48 31'	+		
5	Dikson Island	80 24	73 30'	+	+	
6	Zuy (Irkutsk)	104 02	52 28	+	+	+
7	Voyeykovo (Leningrad)	30 42	59 57	+		
8	Krasnaya Pakhra (Moscow)	37 19	55 28	+		+
9	Murmansk	33 03	68 57	+	+	+
10	Provideniya Bay	186 36 W	64 23	+		
11	Rostov-on-Don	39 41 E	47 13	+	+	+
12	Salekhard	66 32	66 32	+		
13	Verkhneye Dubrovo (Sverdlovsk)	61 04	56 44	+		
14	Tiksi Bay	128 54	71 36	+		
15	Tomsk	84 56	56 28	+	+	+
16	Yakutsk	129 43	62 01	+		
17	Yuzhno Sakhalinsk	142 43	47 01	+		
18	Kheys Island	58 03	80 37	+		
19	Moscow	37-38	55 44			+
20	Tbilisi	44 48	41 43	+		
21	Mirnyy	93 01	66 33 S	+	+	
22	Vostok	106 52	78 27	+		

Designations: V_1 - Vertical sounding; A_1 - absorption (pulse method); D - drifts

Special responsibility for high-latitude ionospheric studies in the USSR has been assigned to the Polar Geophysical Institute (PGI). This institute, primarily concerned with the investigation of the ionosphere, auroras, geomagnetism, cosmic rays, and crustal movements in the area of the Kola Peninsula, was established under the auspices of the Kola Branch of the USSR Academy of Sciences by a decree of the Presidium of the Academy on 11 October 1960 [13].

The Ionosphere and Radio-wave Laboratory of the PGI, in addition to conducting regular vertical soundings of the ionosphere, measures radio-wave absorption in the zenith by the pulse method, studies drifts, makes riometer observations, and pursues field-intensity studies. This laboratory also investigates the following aspects of the high-latitude ionosphere: the morphology of ionospheric disturbances, the properties and movements of inhomogeneities, the vertical distribution of electron density, and the frequency dependence of radio-wave absorption in the ionosphere from the point of view of the effects of the special characteristics of the polar ionosphere on the stability of radio communications.

With respect to the coordination of ionospheric research data for the purpose of radio-frequency forecasting, all of the above-named research institutes are subordinate to IZMIRAN. Radio forecasts in the USSR are compiled in three major centers: Moscow (Central IZMIRAN), Irkutsk (Siberian Division of the Institute of Terrestrial Magnetism, Ionosphere, and Radio-wave Propagation--SibIZMIR), and Murmansk (PGI). IZMIRAN compiles long-range forecasts for the entire earth's surface as well as short-range forecasts for the USSR and the Arctic; SibIZMIR forecasts radio communications conditions for Siberia and the Far East; and PGI provides information on the state of the ionosphere in the Arctic and compiles radio forecasts for the high-latitude regions [14].

Since 1956 there has been regular round-the-clock short-range radio forecasting and since IGY there has been a twice-daily radio broadcasting service of solar and geophysical data. In 1964 it became possible to inaugurate radio forecasting service for the various zones of the USSR rather than the general middle-latitudes forecasts. At present there are monthly, 5-day, and 12-hour forecasting services. Critical frequency forecasts and state-of-the ionosphere reports are made for five regions: the polar cap, the auroral zone, the middle latitudes of the European region, the middle latitudes of the Asian region, and the southern regions, including the Central Asian Republics. Thrice daily, data on chromospheric flares, sudden ionospheric disturbances, etc. are broadcast.

The manner in which the Soviet Armed Forces determine the maximum and minimum operating frequencies for radiocommunications on the basis of the Monthly Forecasts of Radio-wave Propagation issued by IZMIRAN has been described by Cols. Bryushinkin and Shitarev [15]. Radio forecasts are transmitted by radio three times a day in the order indicated in the radiocommunications codes issued to all communications units. Three types of ionospheric reports (IONKaA—ionospheric characteristic, IONDA—ionospheric data, and PROGNOZ—forecast) are used. The main purpose of these procedures, Bryushinkin and Shitarev emphasize, is to ensure uninterrupted and reliable military communications under all conditions.

Because under COMECON arrangements the East European satellite states cannot develop their own rockets or nuclear capability, their role has been limited primarily to contributions in theory and observation. The work, of Professor M. Steenbeck, Director of the Jena Institute for Magnetohydrodynamics, in solar plasma research and in the development of experimental x-ray tubes for use in photographing projectiles in flight, bomb-model detonations, shock-wave propagation, and other high-speed processes must be mentioned as pertinent to the problem of ionospheric modification. Drs. Steenbeck, Radhard, and Kuschel [16] of the GDR are also known to have been conducting joint research with Professor I. Kirko, Director of the Physics Institute of the Latvian Academy of Sciences, in the fields of radiation physics and magnetohydrodynamics, especially the problem of the current of the conducting liquids of a magnetic field in connection with the development of MHD generators. Other East German institutes concerned with the problem of ionospheric modification would be the Kuehlungsborn Observatory for Ionospheric Research and the Heinrich Hertz Institute of the East German Academy of Sciences, whose observations of Operation Starfish are described below.

With regard to other East-bloc ionospheric observational and research facilities, it should be noted that scientific equipment for measuring the differential Doppler effect and the Faraday effect on radio transmissions from artificial earth satellites has been put into operation in the Ionospheric Observatory of the Geophysical Institute of the Czechoslovakian Academy of Sciences in Panska Ves. This installation, the fourth of its kind in Europe, will aid investigators of the Ionosphere Department in their studies of the upper layers of the atmosphere, the ionosphere, and the exosphere [17].

Physical and Dynamic Characteristics of High-Altitude Bursts

The extent of knowledge of the effects of nuclear air bursts on the ionosphere and of their role in the development of an ABM defense capability has, of course, been governed by the history of nuclear bomb testing. The successive periods of testing, moratoriums, and test ban have been determined by military, scientific, and political considerations. Disagreement has arisen among the various authorities as to which consideration should have priority in decision making.

It has been reported [18, 19] that Soviet scientists as early as 1958 discovered an effect in thermonuclear air bursts that could provide the basis of a highly effective ABM defense system, namely, that the x-rays released in thermonuclear bursts above the atmosphere propagate more than several thousand kilometers with little intensity loss, while within the confines of the atmosphere the x-rays soon lose their power and have only limited effectiveness. According to these same sources, the Soviets pursued their studies of the x-ray effect in a series of tests carried out in the Arctic in 1961 and 1962 and found that the radiation which propagates in very rarified space at the speed of light can effectively destroy oncoming missiles at great distances. Essentially this is done through the conversion of the particles into thermal energy as they strike the missile. During these Arctic tests the Soviets are said to have successfully destroyed two oncoming missiles at a height of at least 150 km by this method.

Among the most significant early, primarily theoretical, contributions by Soviet scientists on this problem at that time were those by O. I. Leypunskiy. In 1959 Leypunskiy [20] published a book on the physics of the effect of gamma radiation in atomic explosions based on the theory of multiple scattering of gamma rays developed in collaboration with Ya. B. Zel'dovich. The calculation of the doses, i.e., the absorption of gamma radiation energy, in this work referred to explosions of 20 MT. Pursuing this research, but in direct relation to Argus—type high—altitude detonations, Leypunskiy [21] in 1960 described the magnetic effects of bursts in a space vacuum. The matter composing the bomb will be heated, thus forming a dense plasma moving away from the center of detonation at a velocity of several hundred kilometers per second. As the volume of the plasma will increase, the ion concentration will increase. The movement of plasma transverse to the magnetic field will stop when the kinetic pressure of plasma, which decreases as the plasma volume increases as a result of a decrease in the ion concentration, will become equal to the magnetic pressure.

Since the plasma is diamagnetic, the terrestrial magnetic field in the volume occupied by the plasma will decrease and will be annihilated (neutralized), if the ion concentration is sufficiently high. For numerical calculations, the decrease of neutralization of the magnetic field inside the plasma volume can be represented as being generated by placing an effective magnetic dipole inside the plasma, with the dipole field being oriented in the direction opposite to that of the terrestrial magnetic field. This effective dipole will generate a relatively strong magnetic field even at large distances from the center of detonation, which will be recorded as an appearance of a magnetic disturbance (storm) with a temporal increase in its front corresponding to the dispersion time of plasma. The plasma expansion in the magnetic field may also excite magneto-hydrodynamic oscillations. Magnetic disturbances may also be generated by the subsequent movement of the plasma along the lines of force in the magnetic trap, i.e., in regions distant from the center of the explosion. For the Argus blast (energy = 4.2×10^{19} ergs) Leypunskiy calculated that the amplitude of the magnetic disturbance at the epicenter is $H \approx 100 \times 10^{-5}$ Oe. However, actual measurements reported in American scientific literature show that $H = 10 \times 10^{-5}$ Oe. Thus, the value of H calculated using the magnetostatic model described by the author is an order of magnitude higher than the actual value. Leypunskiy thus concludes that the propagation of the magnetic disturbance may be different. He states that R. L. Al'pert has suggested that the magnetic disturbance is propagated in space between two conducting layers, the ionosphere and the earth, and is therefore only weakly attenuated with distance. The disturbance reaches this spherical layer as a magnetohydrodynamic wave in the ionosphere propagated along the lines of force with little attenuation.

One of the first papers based on actual tests (US Hardtack and Argus) describing the physical phenomena occurring in the upper atmosphere and near space as the result of high-altitude bursts was published by Ya. L. Al'pert [22] in mid-1962, shortly after the appearance on 4 June 1962 of an official Soviet protest against the US tests. Al'pert, using Western sources and experience, presents a general picture of the effects of such a burst.

In 1962 K. G. Ivanov [23] reviewed the results of investigations of the geomagnetic effects caused by the detonation of nuclear devices in the lower atmosphere (below 80 km) published in the period 1959—1961. He assumes in this study that the initial variation of the geomagnetic field caused by the burst near Christmas Island on 28 April 1958 [Operation Yucca of Hardtack Phase I) was induced by the passage of the shock wave through the ionosphere. The shock waves caused by the bursts near Johnston Island on 1 August 1958 [Operation Teak] and 12 August 1958 [Operation Orange], Ivanov notes, enhanced the geomagnetic field when they passed through the F layer of the ionosphere. The time lag of the variations after the burst near Christmas Island was found to be equal to the time it took the shock wave to reach the E layer from the place of detonation ($\sim 10^6$ cm above the surface of the earth). The propagation velocity of the shock wave was assumed to be $\sim 3.3 \times 10^4$ cm/sec. The time it took for the shock wave to travel from the point of detonation near Johnston Island to heights of 200—300 km was estimated by Ivanov by using formulas derived from the theory of a point explosion in a nonhomogeneous atmosphere. The times were found to be 1—2 min for the event of 1 August 1958 and 2—9 min for the event of 12 August 1958. The delays therefore were 2 and 5 min, respectively.

Among the indirect effects of high-altitude bursts on the ionosphere I. Krasyakov [24] referring to the Teak, Orange, and Starfish tests, notes the generation of radio emission in a broad range from 1.5 Mc to 400 Mc. This artificially generated radio emission manifests itself as an increase in atmospheric noise; its level at the lower frequencies exceeds cosmic noise. Krasyakov lists the following characteristics of artificially generated radio emission: a characteristic frequency spectrum with a maximum of about 20—30 Mc (in the higher frequencies the emission strength decrease is inversely proportional to the cube of the frequency), a latitudinal and time dependency, and some polarization. Krasyakov emphasizes the danger caused by high-altitude bursts to efficient satellite communications.

Yu. P. Rayzer [25] obtained a similarity solution for the problem of a plane shock wave propagating through a nonuniform medium of variable density which may be approximated by an exponential function

$$\rho_0 = [\rho]e^{x/\Delta},$$

where Δ = constant. Rayzer assumes that the shock propagates in the direction of density decrease, though the effect of gravity is neglected. The equation of motion of a shock wave reaching the boundary of the atmosphere $x = -\infty$, $\rho_0 = 0$ at time $t = 0$ is derived. A similarity solution is also considered for the motion of a gas expanding into the vacuum at $t > 0$. Numerical calculations are made for the ratio of specific heats $\gamma = 1.2$ and $\gamma = 5/3$. The solutions obtained are used to describe the flow field in the upper region above an explosion in a nonuniform atmosphere. Rayzer points out that in principle the air accelerated upward to a high velocity by the shock wave should escape the earth's gravitational field and "splash" into the vacuum, but that because of strong ionization the upward motion is limited by the retardation effect of the earth's magnetic field.

A. T. Onufriyev [26] has analyzed the motion of the vortex ring of a nuclear or chemical explosion with gravity taken into account, using a series of equations that also takes into account the effects of turbulent mixing and adiabatic expansion. In the same article, Onufriyev also considers cases of vortex motion in which the internal density differs little or not at all from the ambient density. Such studies, he notes, are important in monitoring radioactive fallout distribution following a nuclear burst. The explosion sequence is traced from the initial propagation of the shock wave to the formation and gradual ascent of the fire ball causing the rising air to form the vortex ring, and finally, to the subsequent flattening of the atomic cloud into the characteristic mushroom shape. The cloud development process is initially controlled by a force caused by the difference in density between the cloud and the ambient atmosphere, then by frictional forces causing turbulent mixing and the vortex motion, then, as the ascent velocity increases, the cloud-top flattening is caused by pressure differences, until finally the ascending cloud assumes the form of a torus or anchor ring in which the air rotates around a horizontal ring-axial line and around which a circulatory air current is generated. Owing to the circulation surrounding the vortex ring, a Zhukovskiy force perpendicular to the direction of the ring motion is set up, drawing the ring off to the side and decelerating the ascent. Onufriyev solves the problem of the ascent of the vortex ring on the assumption that: 1) the pressure inside the ring equals that of the ambient atmosphere; 2) density, temperature, velocity, and vorticity inside the ring are similar throughout; 3) turbulent mixing of hot and cold air occurs at the ring surface; 4) the motion of the vortex ring is the same as that of a round cylinder; and 5) the temperature and pressure in the atmosphere agree with the international standard atmosphere.

Effects of High-Altitude Nuclear Bursts on Communications

Highly detailed papers on the effects of nuclear bursts on radio-wave propagation, based on unspecified Western sources dealing with the US tests of 1958 (see Table 2), have appeared with increasing frequency in Soviet military journals. In addition to having access to an abundance of open Western literature on these tests, Soviet Kosmos satellites regularly overfly Johnston and Eniwetok Islands. Kosmos 3 and 5 were specifically involved in monitoring US tests.

Table 2. US nuclear warhead tests of 1958

Code name	Time and date of firing	Geographical coordinates	Strength of bomb	Height of burst
Teak (US)	1050 GMT 1 Aug '58	17 N 169 W (Johnston I.)	4 MT	77 km
Orange (US)	1030 GMT 12 Aug '58	17 N 169 W (Johnston I.)	4 MT	41 km
Argus (US)	0230 UT 27 Aug '58	38 S 12 W	2 KT	480 km
Argus (US)	0320 UT 30 Aug '58	50 S 8 W	2 KT	480 km
Argus (US)	2210 UT 6 Sep '58	50 S 10 W	2 KT	480 km

A paper written in 1966 by Col. Ya. I. Fayenov and Maj. I. S. Krasil'nikov [27] discussed in general terms the effects of the Teak and Orange events during Operation Hardtack (1958) as a function of height and yield of the burst.

From the military point of view the general effects of a nuclear air burst at different altitudes have recently been described by Cols. V. A. Mikhaylov and I. A. Naumenko [28]. Depending upon the mission, Mikhaylov and Naumenko write, nuclear bursts may be set off at various heights. To destroy oncoming aircraft or missile, for example, the burst would occur at great heights, a so-called high-altitude burst. Damage to the aircraft in such a case occurs either through damage to the craft itself or to the crew. The shock wave or optical radiation can destroy the craft, while the penetrating radiation can kill the crew. Because air density in a high-altitude burst is almost zero, the energy of the burst is transmitted only to the substance from which the nuclear charge is composed and to associated devices, i.e., the carrier rocket. All of this matter is heated to extremely high temperatures, evaporates, and is converted into a highly ionized gas or plasma. In the case of a space detonation, unlike other bursts, a significant part of the energy is emitted into surrounding space in the form of light ultraviolet and soft x-radiation. The latter two types of radiation in the case of ground, atmospheric, or even high-altitude bursts are absorbed by the air surrounding the place of the burst.

All of these radiations are absorbed by the object in flight and heat it to high temperatures. Since a space burst occurs where there is no air, Mikhaylov and Naumenko note, there is no shock wave formed. The destructive factor in a nuclear burst in space is the radiation in a wide wavelength range, with greatest intensity at short wavelengths. In the case of a space burst the charged particles move in the terrestrial magnetic field, if the burst occurred at a height not in excess of several earth radii, i. e. , not lower than 150—200 km and not higher than 20, 000—30, 000 km. Each charged particle moves in orbits around the magnetic lines of force. Computations show that at heights not exceeding several thousand km, the size of the orbits described by the particles ejected during a nuclear burst range from several hundred meters to several tens of km. Therefore, the authors conclude, practically all particles of matter ejected from a nuclear burst travel along magnetic lines of force. About half of all particles travel northward, while the other half travel to the Southern Hemisphere of the earth. The particles may be seen as travelling inside magnetic tubes having diameters less than 100 km. Eventually such particle fluxes reach the denser layers of the atmosphere and are absorbed at a height of about 150 km. They produce strong ionization of the atmosphere over an area of several thousand square km and create intensive artificial auroras accompanied by magnetic storms, radio interference, and radar interference. The significance of the heights referred to by Mikhaylov and subsequent investigators is best indicated by Table 2 in the appendix showing an internationally accepted profile of the ionosphere.

V. A. Baranul'ko [29] in an even earlier work also noted the strategically important fact that artificial auroras generated by a nuclear burst also occur in the magnetically conjugate point. A nuclear burst in the Southern Hemisphere, therefore, could almost as effectively create intense radio-wave absorption at the conjugate points in the Northern Hemisphere, resulting in shortwave communications disruptions. In planning an air defense in the Northern Hemisphere, it therefore becomes vital to secure the regions at the magnetically conjugate points of the Southern Hemisphere. In the case of the USSR, this would mean primarily the South Indian Ocean area.

In a very recent paper A. I. Paliy [30], author of *Radio Warfare* [Radiovoyna, *Voyenizdat*, 1963] an important work on the techniques of radio intelligence and counterintelligence translated into most of the satellite languages, reviews the effects of high-altitude bursts on the ionosphere and draws similar conclusions. Paliy writes: Knowing the structure of the terrestrial magnetic field, it is possible to direct the electrons along force lines to the conjugate point in one hemisphere and disrupt radioelectronic communications there. To accomplish this, one can select the corresponding conjugate point of the nuclear burst in the other hemisphere.
Paliy concludes by observing that

> ... if a nuclear detonation is set off before a missile launching, then the charged particle streams could prevent the radar stations in the ABM system from detecting them. Experiments have shown that reflections from the ionized regions create the most intense interference to radar stations in those cases where the radar beam is perpendicular to the force lines of the terrestrial magnetic field. If the beam is inclined at an angle exceeding 20°, the intensity of radiointerference is substantially reduced.

The Soviet Union has been most active in pursuing geophysical research at magnetically conjugate points, both independently and in conjunction with France. Thus, for example, V. M. Driatskiy [31] of the USSR Arctic and Antarctic Scientific Research Institute has described the results of exclusively Soviet research of auroral absorption at the conjugate points of Mirnyy Station, Antarctica, and Kheys (Heis) Island in the Arctic. Radiometers operating at 3. 8 and 32 Hz were used to record the cosmic radio-noise level. During 1964 alone, Mirnyy Station recorded 137 cases of cosmic-noise absorption of intensity $>$ 0. 3 db, while Kheys Island recorded 416. Similar, and, in some respects, even more sophisticated studies are being conducted by France and the USSR at the magentically conjugate points of the Kerguelen Islands in the Indian Ocean, and Sogra (Arkhangel'sk). A mobile station on a barge in the Dvina River was also used. Recently, a direct teletype communication link was established between the two points, permitting the immediate exchange of information on auroras, radio-wave propagation, ionospheric disturbances, etc. Such studies need not, of course, be expressly undertaken for military strategic purposes to be so used.

A. I. Leonov [32], Marshal of the USSR Signal Troops and member of the USSR Ministry of Defense, has described the effects of a nuclear burst on communications in greater detail. Radar station operations, Leonov observes, can be interferred with by high-altitude nuclear bursts in various ways. The nuclear burst is accompanied by two different electromagnetic effects. One consists in the emission of short-duration electromagnetic pulses as the result of the asymmetry in the distribution of the electric charge in the region surrounding the explosion, and, owing to the rapid expansion of a conducting plasma, formed in the burst in the terrestrial magnetic field. The second effect is connected with the significant disturbances of the electromagnetic waves used in radiocommunications and in radar which arise from the influence of the ionizing radiation of the nuclear burst or from fission products or water vapor introduced into the atmosphere as the result of the burst.

Ionization, Leonov continues, is the main reason for disruption of radar station operation in a wide frequency range. Ionization can occur directly or indirectly under the influence of gamma rays and neutrons of primary nuclear radiation, beta particles and gamma rays of residual nuclear radiation, and under the effects of x-rays and even ultraviolet rays present in the primary thermal radiation. Consequently, after a nuclear burst the electron density in the atmosphere in the burst area increases sharply, affecting radar signals in at least two ways. First, under certain conditions it can cause a decrease in the wave energy and thus attenuate the signal and second, the wave front propagating from one region to another with a different electron density will follow a curved path, i. e., refraction will occur. Clearly, Leonov notes, the ionized regions produced in the atmosphere from a high-altitude nuclear burst will affect the behavior of all radar signals whose propagation paths pass through these regions.

The effect of the atmospheric ionization on the radar station depends on the height of detonation and yield of the burst as well as on the type and operating frequency of the station. Bursts at heights lower than 16 km do not cause significant nor prolonged ionization and thus do not have a serious effect on radar operation. In the case of bursts at heights above 16 km and especially those above 70 km, where air density is low, considerable ionization occurs, having a substantial effect on the operation of these stations.

High-altitude nuclear bursts, according to Marshal Leonov, have a considerable effect on the operation of long-range radar detection stations which must detect targets at great distances, i. e., when the signal reflected from the target is only slightly greater than background noise, because even slight signal losses can decrease the effective range of target detection.

Tracking or guidance radar stations serve to intercept an already detected target at a distance considerably shorter than the maximal distance of detection. Consequently, the signal can be attenuated to a greater degree without disrupting normal station operation.

Radar station signal attenuation is directly proportional to electron density and inversely proportional to the square of the signal frequency, i. e., a considerably greater signal attenuation will be observed in the case of stations operating in the meter wavelength range and less noticeable signal attenuation will be observed for stations operating in the centimeter range.

In many cases radar refraction caused by electron density changes resulting from a nuclear burst can be just as important as attenuation. The degree of ray deviation in this case is directly proportional to electron density change and inversely proportional to the square of the signal frequency. Leonov concludes that signal reflection will occur when the angle of ray incidence is great; the radar signal will be returned without passing through the attenuating layer.

On the basis of an analysis of unspecified Western sources, Cols. P. Krasota and L. Katrechko [33] have written what is perhaps the most detailed account of the effects of a nuclear burst on radio communications. An abbreviated translation follows:

> At least two different mechanisms exist for the formation of an electromagnetic pulse during a nuclear burst. The first is associated with the appearance of some irregularity in the distribution of the electrical charge in the burst zone (surface or at low altitudes); the second is the result of the interaction of the plasma formed during the burst with the earth's magnetic field and is characteristic of bursts in the ionosphere.
>
> Gamma-rays, formed at the time of burst, collide with molecules and atoms and ionize them, forming electrons and positive ions. The electrons begin to move rapidly in radial directions from the center of the burst. If the burst occurs on the surface

or at a low altitude, the earth hinders the spread of fission products and they are ejected upward. When the burst takes place close to the upper boundary of the atmosphere, the gamma-rays, moving upward, rarely encounter the atoms and molecules of the rarefied air. The rays which are directed downward ionize the air at much shorter distances from the center of the burst.

In both cases, the electrical charge is distributed unevenly in a vertical direction, leading to the formation of a current pulse and the emission of electromagnetic energy. The cause of the electromagnetic pulse may also be the time-varying radial electric field in the region of the burst.

The electrons and positive ions which are formed as a result of ionization propagate from the center of the burst at various velocities: the heavy ions lag behind the lighter electrons moving at a faster rate. This relative displacement of positive and negative charges also generates a varying electric field which produces an additional radio-signal.

In addition, in passing through the air, each electron, especially at the end of its path, generates a large number of "electron-ion" pairs. Subsequently, a large number of electrons, under the influence of the radial electric field, are forced back toward the center of the burst. This also causes the appearance of a current pulse and, consequently, the emission of electromagnetic energy at frequencies up to 100 Mc. A large portion of this emission energy is distributed at the mean frequency of 10—15 kc.

The formation of an electromagnetic pulse due to the interaction of the plasma of the nuclear burst with the terrestrial magnetic field is also characteristic of a high-altitude burst.

The only object affected by a nuclear burst in the ionosphere is the terrestrial magnetic field. Immediately after the burst, a rapidly expanding plasma is formed which strives to displace the magnetic field from the portion of space which it occupies. This leads to a distortion of the terrestral magnetic field. The interaction between the geomagnetic field and the charged particles of the expanding plasma causes a disturbance which affects the necessary propagation of radio waves.

As a result of ionization, the electron density in the burst area increases. Fig. 1 shows the electron density in the daytime in various layers of a normal ionosphere. The increase in the electron density depends on the altitude of the nuclear bursts.

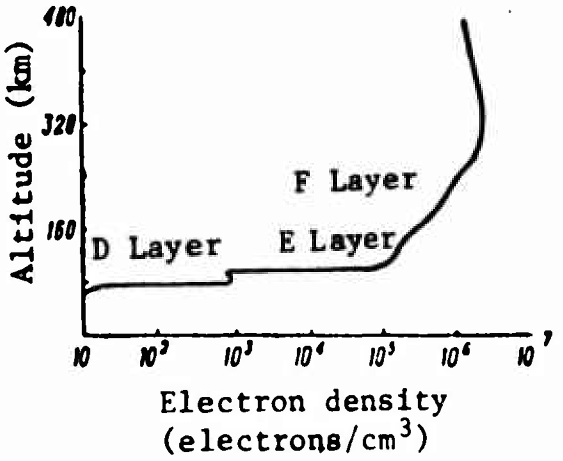
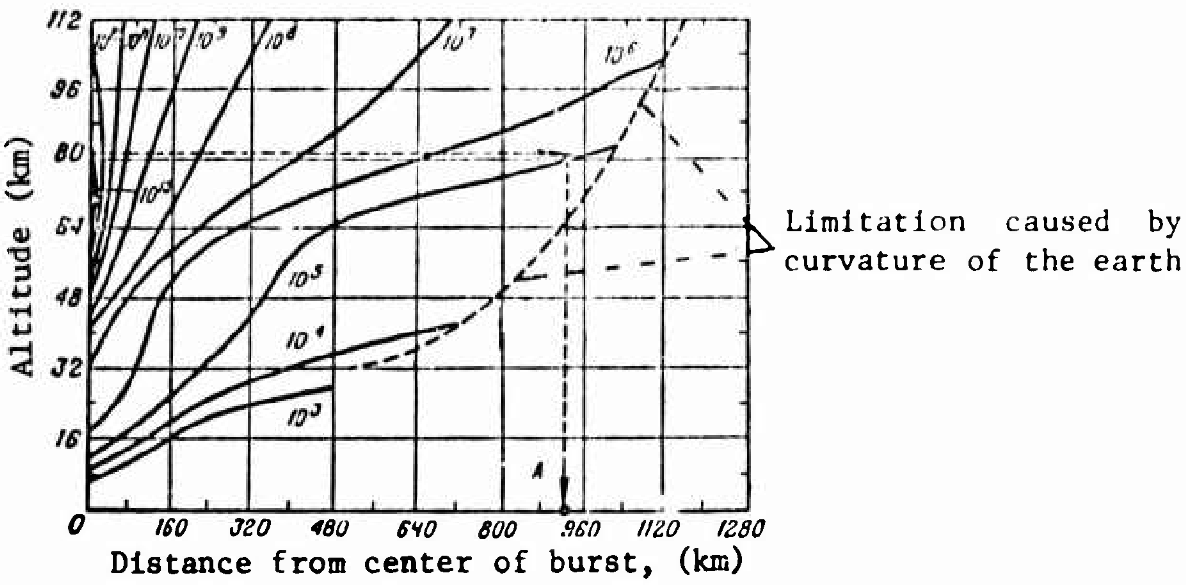


Fig. 1.

For bursts at altitudes less than 16 km, ionization of the surrounding atmosphere will be observed at a distance not exceeding several hundred meters from the fireball. The free electrons almost instantaneously recombine with the neutral particles of the atmosphere and, therefore, their lifetimes will be very short. However, with bursts of megaton yield the radioactive cloud may rise to an altitude from which a considerable portion of the gamma-rays will reach the D layer of the ionosphere; the free electrons which are formed in this region may exist for several minutes. But since the gamma-radiation of the fission products, which have risen to a great altitude, will continue for a prolonged time, a large-yield burst, even at a low altitude, may cause high electron densities in the D layer for several hours.

When the burst occurs at an altitude of 16—64 km, where the density of the air is comparatively low, a portion of the primary gamma-rays, neutrons, and, to an insignificant degree, thermal x-rays will reach the D layer and ionize it. Maximum densities of free electrons occur in a layer with a thickness of about 16 km, at an altitude up to 72 km. The horizontal distances at which ionization occurs may be considerable (see Fig. 2). Thus, in case of a 1MT burst at an altitude of 48 km, the electron density at a distance of 64 km and an altitude of 72 km is 10^7 electrons per cm^3; at a distance of 128 km from the center of the burst it is 10^6 electrons per cm^3. This exceeds the natural density in the D layer by approximately a factor of 1000 and 10,000.



Limitation caused by curvature of the earth

Fig. 2. Calculated values of the electron density at an altitude of 72 km for a 1 MT burst (at various altitudes) as a function of distance

The basic ionizing agent driving bursts at altitudes from 64 to 112 km is the thermal x-rays, although here, too, ionization caused by gamma- and beta-radiation and neutrons remains important. Thus, all ionizing agents at the indicated altitudes may increase the free electron density in the D layer by a factor of several million. Moreover, conjugate zones will be formed in each of the earth's hemispheres.

If the burst occurs at altitudes from 112 to several hundred kilometers, various types of radiation which are propagated upward almost leave the atmosphere. At the same time, the radiation directed downward will ionize the D layer. The radial propagation of plasma will be retarded primarily by the terrestrial magnetic field. At the same time, some products of detonation, having retained their charge for a prolonged time, may form regions consisting of high-energy beta-radiation electrons which will remain in place for several days. A study of the nature of the indicated factors made it possible to draw a number of conclusions concerning the nature of their effect on radio signals of various frequencies.

At frequencies of 3—30 kc the signals are propagated in a waveguide formed by the surfaces of the earth and the ionosphere. Since these waves hardly penetrate the ionosphere, the additional ionization generated by the nuclear burst will not lead to a noticeable attenuation of these signals. However, the distance over which the signals are transmitted between the transmitter and receiver depends on the reflection height.

If the density of the electrons in the lower portion of the ionosphere increases, reflection occurs at a lower altitude and the wave is propagated through a shorter distance. Therefore, the most noticeable effect of the nuclear burst on systems which operate in the extremely long wavelength band will appear as a sudden phase shift of the signal at the time of disturbance. As the ionosphere returns to a normal state, the phase shift also disappears. Such changes in conditions for propagation may appear over very great distances—up to several thousand kilometers from the burst.

The systems operating in the 0.03—0.3 Mc and the 0.3—3 Mc frequency bands are characterized by propagation of signals along the earth's surface. Therefore, additional ionization of the ionosphere does not interfere with communications in these bands.

The short waves (3—30 Mc) are used for communications over distances of 8,000—10,000 km. They are propagated by being successively reflected from the ionosphere and the earth. Each reflection is accompanied by a loss of energy; therefore, satisfactory communication may be achieved during no more than three or four reflections. The increase in electron density in comparison with the normal density, for example by $5 \cdot 10^3$ electrons per cm^3, will lead to the disruption of communications in the lower portion of the band (at about 5 Mc). If the density is increased to 10^5 electrons/cm^3, communications are disrupted in the upper portion of the band (20 Mc). Using these parameters, Table 1, and the graphs presented in Figs. 2, 3, and 4*, an approximate evaluation of the time and space deviation within the limits of which communications will be disrupted by a high-altitude nuclear burst with a yield of 1 MT is made.

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*Fig. 2 and Table 1 are used to estimate the effect of ionization due to the primary nuclear radiation and a part of thermal x-rays; Figs. 3 and 4 — to estimate the ionization caused by residual beta- and gamma-radiation burst products.

From Fig. 2, it can be seen that a 1 MT burst at an altitude lower than 16 km can produce excessive electron densities (10^4—10^5 electrons/cm^3), sufficient to disrupt shortwave communications over a small area. The lifetime of the electron densities is measured in seconds. Consequently, low-altitude bursts will have no significant effect on communications in the shortwave band if, of course, the apparatus is not rendered inoperative by the electromagnetic pulse and the line of communication does not pass directly through the region of the burst or its cloud.

Also using Fig. 2, it can be seen that a 1 MT burst at an altitude of 80 km during the day will affect shortwave traverses whose paths pass at a distance of up to 900 km from the center of the burst (point A). From Table 1, it can also be concluded that to reduce electron density from 10^5 to 10^4 electrons/cm^3, i.e., to restore normal communications conditions in the upper portion of the band, approximately 1000 seconds (17 minutes) are required, and in the lower portion of the band — not more than 3 hours. However,

Table 1

Electron density electrons/cm^3	Time required to reduce the electron density by a factor of 10 (in sec)	
	Day	Night
10^8	Less than 1	Less than 1
10^7	" 10	" 10
10^6	" 100	" 15
10^5	" 1000	" 15
10^4	" 10000	" 15

the fission products must be taken into account. This can be done by making use of graphs similar to those presented in Figs. 3 and 4. For example, from Fig. 3 it can be seen that 3 hours after a megaton burst at altitudes of 64—112 km, the fission products extend over a radius of about 2400 km (point B) and

the excess density of electrons at this distance will reach 1. $5 \cdot 10^3$ electrons/ cm^3 (point C) at night and $5 \cdot 10^4$ electrons/ cm^3 (point D) during the day. In other words, by this time conditions for restoring communications in the lower portion of the shortwave band in the indicated zone are still not restored. They will return to normal after more than 10 hours of day time.

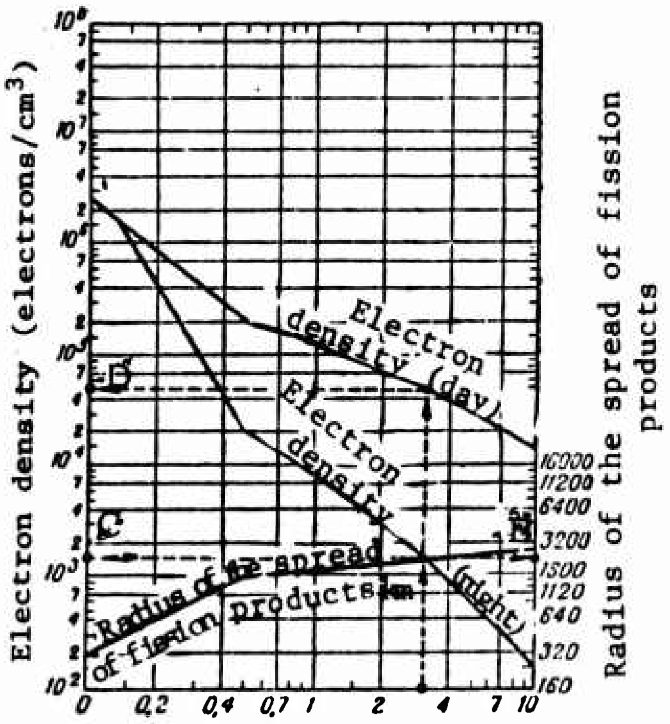


Fig. 3. Variation of the radius of the spread of the burst products and the corresponding electron density in the D layer with time after 1 MT nuclear burst at altitudes of 64—112 km

Similarly, from the graphs on Fig. 4 it can be established that a signal which is propagating 800 km (point E) from the center of the burst of a megaton charge detonated at an altitude of 16—64 km will begin to experience the effect of radiation from the radioactive cloud after 5 hours (point F). The excess electron density at the indicated point will reach $6 \cdot 10^3$ electrons/cm^3 (point G) at night and 10^5 electrons/cm^3 (point H) during the day. This will cause a disruption of communications in the entire shortwave band during the day and in its lower portion at night. Normal conditions for communication are restored at night 9—10 hours after the burst; during the day they are restored much later.

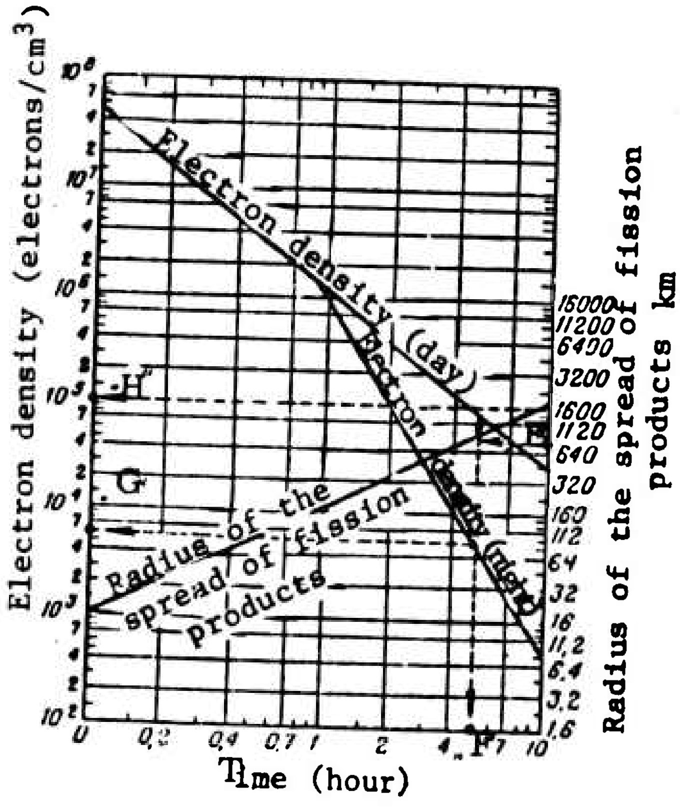


Fig. 4. Dependence of the size of the radius of the spread of burst products and the corresponding electron density in the D layer on time after a nuclear burst at altitudes of 16—64 km

Meter (30—300 Mc), decimeter (300—3000 Mc), and centimeter (3000— 30000 Mc) radio waves are used for communication within limits of direct visibility, and due to the scattered reflection in the ionosphere and troposphere, for communciation over long distances.

The increased ionization caused by the nuclear bursts has no significant effect on radio communications within limits of direct visibility. However, if the burst occurs on a line between two stations, an interruption of communications for several seconds is possible. With respect to systems which use ionospheric scattering, an insignificant increase in the electron density in the ionosphere will lead only to an improvement in the conditions for propagation and to an increase in signal level at the point of reception. For a significant disruption of the operation of such communication lines, it is necessary to conduct a high-altitude nuclear explosion with a yield of more than 100 MT. Radio communications systems which operate on the principle of tropospheric scattering in essence are not subjected to the influence of nuclear bursts.

Table 2 presents generalized data which show the duration of the disruption of the operation of the basic types of radio communication under the influence of nuclear bursts. As can be seen from the table, ultrashortwave, radio relay, and tropospheric lines of communication are the least prone to interference generated by nuclear bursts.

Usually, frequencies in the meter band and higher are used in radar. From an

Table 2

Distance	Types of communication	Duration of communication disruption
Less than 100 km	Radio relay (30—3000 Mc)	Very small
	Ultrashortwave (30—300 Mc)	Very small
	Shortwave (3—30 Mc)	Small
100—1000 km	Radio communication (0.3—3Mc)	Small
	Radio relay (30—300 Mc)	Very small
	Tropospheric	Very small
	Meteoric	Several days
	Shortwave (3—30 Mc)	From several hours to several days
1000—3000 km	Radio communication (0.3—3 Mc)	Several hours
	Radio relay (30-3000 Mc)	Very small
	Tropospheric	Very small
	Meteoric	Several hours
	Ionospheric	Several hours
	Shortwave (3—30 Mc)	From several hours to several days
More than 5000 km	Radio communication (0.3—3Mc)	Several hours
	Radio relay (30—3000 Mc)	Very small
	Tropospheric	Very small
	Ionospheric	Several days
	Shortwave (3—30 Mc)	From several hours to several days

analysis of the effect of nuclear bursts on radio communication, it follows that their effect on signals in this frequency band are insignificant if the radar and the target are located below the ionosphere. Exceptions are bursts in the immediate proximity of the radar in the region between the radar and the target. However, if the signal is to pass through the ionospheric layer, the effect of the burst may be significant: such signals will be attenuated.

As was noted, the maximum attenuation of a radio signal passing through the ionosphere is observed within a 16-km-thick layer at an altitude of about 72 km. In this region the density of electrons up to 1 electron/cm^3 will cause attenuation of a 1 Mc signal by approximately $2.5 \cdot 10^{-5}$ db/km. The attenuation is directly proportional to the electron density and inversely proportional to the square of the signal frequency. At frequencies below 10 Mc, the frequency characteristic becomes complex. The attenuating effect of the nuclear burst on 10 Mc or higher frequency radar signals may be calculated using the graphs in Figs. 2, 3, and 4. As an example, let us calculate the attenuation of a 100 Mc signal from a tracking radar. Let us assume that the target, 1.5 hours after the burst of a 1 MT nuclear charge which took place during the day at an altitude of 16— 64 km, is above the D layer. From the graph in Fig. 4 it can be determined that at this time, the density of the electrons within a radius of 240 km in the D layer reaches $5 \cdot 10^5$ electrons/cm^3. The radial signal, passing through this layer, will be attenuated. In the case of a 10 Mc signal and a density of 1 electron/cm^3 the attenuation is $2 \cdot 5 \cdot 10^{-5}$ db/km. For a signal 10 times greater and a 32-km-thick layer (the signal passes through a layer with a thickness of 16 km and back) the attenuation is 4 db ($2.5 \cdot 10^{-5} \times 5 \cdot 10^5 \times 32 \cdot 10^{-2}$).

If the direction of the signal is at an angle θ to the vertical, attenuation of the vertical signal is multiplied by sec θ. Thus, if the radar beam forms an angle of 80° with the vertical, the correction factor is approximately equal to 6. Consequently, under the conditions of our example, the attenuation equals 24 db (4 x 6). For radar systems, a reduction in signal power of 12 db will lead to the reduction of effective range by a factor of two.

Non-uniformity of ionization is the cause of interference in the propagation of a radar beam; it causes phenomena similar to the twinkling of stars, random reflection from local objects, or a false echo from ionized sectors.

Clouds which are formed as the result of surface, underground, or underwater nuclear bursts may also reflect electromagnetic waves. A cloud particle is an effective reflector if its dimensions are close to that of the wavelength. Most particles in a nuclear burst cloud are very small (do not exceed 1 mm in diameter), while the shortest radar waves are 1—6 cm. However, during the first stages of development of the burst, there is a sufficient quantity of particles of corresponding dimensions which reflect radar signals from radars which operate in the centimeter waveband. Depending

> on the yield of the burst, the character of the earth's surface, and the scattering rate of the cloud, such conditions may prevail during a period from several minutes to several hours.

The findings and conclusions of Cols. Krasota and Katrechko emphasize the extreme vulnerability of LF, MF, and HF transmissions, the lesser vulnerability of VLF transmissions, and the relative invulnerability of VHF (tropospheric scatter) and UHF (ionospheric scatter) to air bursts. Satellite communications systems, as Krasyakov observed, are also very vulnerable to nuclear burst effects. However, it must be noted that these findings are based on nuclear tests of devices not exceeding 4 MT. It is very possible that a device of even greater power, perhaps deliberately salted to increase residual radioactivity, could render even ionoscatter communications inoperative, causing a total communications blackout. Indeed, Cols. Krasota and Katrechko state that this might be accomplished with a yield figure of more than 100 MT. The Soviet Union has already tested the effects of detonations well over the 4 MT device used as the reference base in the above estimates, including one burst of about 56 MT. Furthermore, the Soviet Government has announced the possession of and plans to test nuclear bombs ranging up to 100 MT [34]. While it is possible for the US and other Western nations to estimate to some extent the effects of such bombs through the use of scaling laws, there is no guarantee that at a certain point a qualitative change does not occur following a succession of quantitative changes. Certainly unique acoustic, electromagnetic, and shock effects might reasonably be expected from the high-altitude detonation of nuclear devices exceeding 40—50 MT. Whether a series of moderate-yield high-altitude bursts could induce the same effects in the ionosphere as a single large-yield device is problematical.

Of course, additional information on the effects of such bursts could be obtained through the remote monitoring of the Soviet tests. But such information is spotty at best and can neither be a substitute for direct experience nor an acceptable basis for national defense planning.

Effects of High-Altitude Nuclear Bursts on Electronic Equipment

The practical effects of the radiation in a nuclear burst zone on the operation of either ground or airborne electronic equipment— scientific instrumentation or military devices—are of prime concern. Again, however, when discussing the problem in direct military context, Soviet writers—in this case L. Shirshev—use the device of basing their discussion on unspecified Western sources. By way of background to the problem the following translation of a brief paper by Shirshev [35], published in a recent issue of a Soviet military journal, is given:

> In the case of surface or high-altitude nuclear bursts, the primary damage factor affecting radio equipment is the shock wave; the overpressure in the shock-front determines its destructive power, the pressure being dependent on the explosive force and atmospheric pressure. At altitudes of hundreds of km, atmospheric pressure is 10^{-6}—10^{-9} mm Hg or less, and the shock wave is practically absent.
>
> Non-protected radio equipment in the shock wave fails to operate properly at overpressures of 0.15 kg/cm^2 or more. As a rule, the lower limit applies to antenna devices. The 0.35 kg/cm^2 overpressure is assumed to be dangerous to non-protected radio equipment.

Light radiation interacting with the material of which the equipment's parts are made can substantially change the physical properties of the material. Thus, plexiglass, polyetheylene, Teflon, cellulose, bakelite, insulating material of cables and conductors, plastic casings and panels of the equipment's units, etc. , would melt and darken when exposed to a 30—70 cal/cm^2 light flux. Under intense light radiation fluxes, some organic materials ignite. As a rule, most of the materials and component parts are protected by various shieldings (housing units, by the body of the rocket or satellite), and are therefore not affected by light radiation. It is believed that exposure to 100 cal/cm^2 light pulse may render the radio-equipment inoperative due to failures in exposed radio parts. Such pulses, generated by powerful nuclear bursts, occur at distances of several km.

The ionizing radiation from a nuclear explosion is a flux of gamma-rays, neutrons, and beta and alpha particles. Gamma and neutron radiations, the so-called penetrating radiation, is most dangerous to radio-equipment.

Gamma rays and neutrons are absorbed and scattered by air atoms; therefore, basically, the penetrating-radiation fluxes are not dangerous at distances where non-protected radio-equipment is put out of order by the shock wave. When the detonation height is increased, the penetrating radiation becomes most dangerous to the equipment.

Gamma radiation travels with the speed of light while the speed of neutrons, which are emitted simultaneously with gamma rays, is directly proportional to the square root of their kinetic energy, and is considerably less than the speed of the gamma rays. Therefore, the gamma rays arrive first at a given point in space, followed by the neutrons. The neutrons, having the greatest energy, cover a given distance more rapidly; those with lesser energy are slower. Fig. 1 shows how the densities of neutron and gamma rays change at a definite point in space.

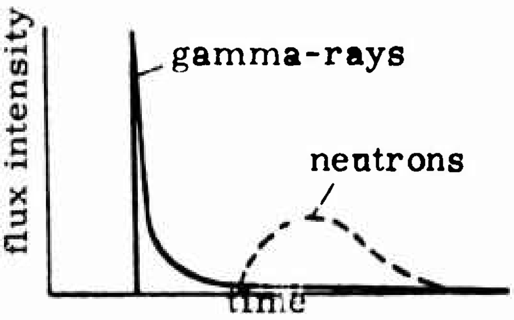


Fig. 1. Variation of neutron and gamma ray densities (or of gamma-radiation dose rate) at a given distance from the nuclear-burst center

As the penetrating radiation propagates through space, the gamma and neutron radiations become separated in time. Thus, the effect of gamma and neutron pulses on the quipment must be considered separately.

The damage occurring in the materials, parts, and electric circuits of radio-equipment exposed to penetrating radiation leads to reversible (temporary) and irreversible (residual) changes in their electrical parameters (Fig. 2).

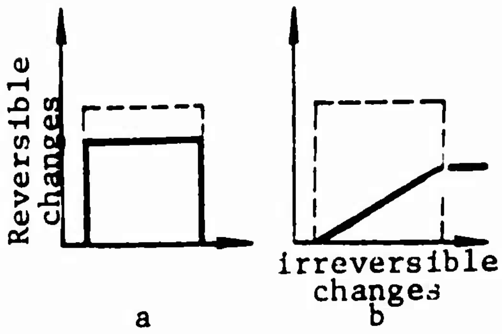


Fig. 2. Changes in the electrical parameters of the materials, parts, and electronic circuits under penetrating-radiation pulses (pulse configuration and the nature of parameter change are shown by broken and solid lines, respectively)

As a result of the effect of powerful gamma-ray flux, reversible changes take place in the electric parameters of the component parts of the radio-equipment (Fig. 2 a). Fundamentally, the changes are caused by the additional charge carriers appearing in the component parts, and by the increased conductivity of the materials. In insulating, semiconducting, and conducting materials, as well as in gas gaps, current heat loss is increased and resistance is lowered. The ignition voltage in the gas-discharge devices is diminished, anodic current in electric vacuum devices is increased, the resistance of resistors is diminished and reverse current in semiconductor devices is increased. The equipment as a whole at the time of exposure to gamma radiation can be considered as some kind of an ionization chamber.

Under the effect of reversible changes in the electrical parameters, the equipment temporarily fails to operate and in a number of cases it breaks down (due to short-circuiting or breakdown).

Under the effect of neutron radiation, irreversible changes take place in the component parts of the equipment Fig.2 b). The nature of the changes depends on the structure of the materials, the total neutron flux, and the absorbed energy (absorbed gamma-radiation dose). As a result, various component parts occasionally break down partially or entirely. For example, certain changes in the electrical parameters of radio parts and transistor electronic devices under the effect of pulse radiation are given in Tables 1 (gamma-neutron radiation) and 2 (neutron radiation per 1 millisec).

Table 1

Parts	Substantial irreversible changes in parameters (parts still remain operative) under the following conditions		Onset of reversible changes under the following gamma-radiation dose rates (R/sec)
	Neutron flux (n/m^2)	Gamma-ray dose (R)	
Transistors	10^{15}—10^{17}	-	10^5
Diodes (Semi-conductors)	10^{16}—10^{19}	-	10^5
Resistors	10^{17}—10^{21}	10^6	10^6
Capacitors	10^{18}	10^7—10^9	10^5
Photocells	-	10^6	10^3
Radio tubes	$3 \cdot 10^{19}$	-	10^7

Radio equipment could break down at fluxes under 10^{17} neutron/m^2 (10^{13} neutron/m^2), at exposure dose rates under 10^7 r/sec and at an exposure dose of 10^6 r/sec. Fig. 3 shows the radii from the center of explosion which would be exposed

Table 2

Type of circuit	Relative value of output voltage, in percentages for the following n/m^2 neutron fluxes			
	10^{14}	10^{15}	10^{16}	10^{17}
Sinusoidal-oscillation generator	100	100	100	100
Amplifier	100	100	80—90	50—60
High-frequency rectifier	100	85—95	30	15—20
Triggers			—	—

to gamma-radiation having a 10^7 r/sec dose rate, 0.35 kg/cm^2 overpressure at the shock-wave front, and 100 cal/cm^2 light radiation flux in the atmosphere and space, plotted against a TNT equivalent.

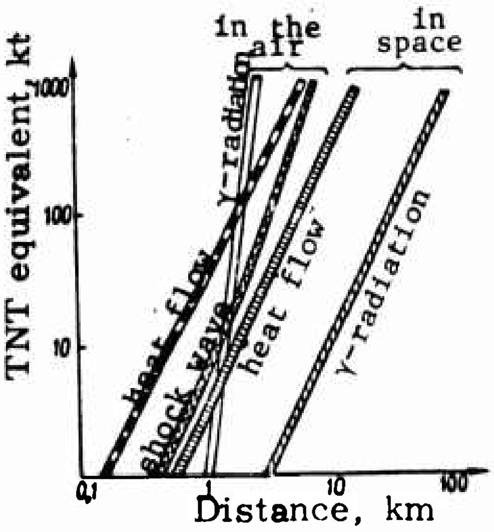


Fig. 3. Radii of damage zones of radio equipment, as a function of burst yield

Radio equipment should remain in operating condition under the effect of penetrating-radiation pulses having a $10^2 - 10^{13}$ r/sec gamma-radiation exposure-dose rate and a flux of $10^{15} - 10^{20}$ neutron/m^2. In cases where an increase of the radiation-resisting capability of the apparatus or the weakening of the effect of penetrating radiation is needed, more radiation-proof radio components, materials and protective shields are used, as well as circuits resistant to the penetrating radiation.

Most semiconductor devices are subjected to the effect of penetrating radiation. Radio parts (resistors and capacitors) have a high resistance. Radio tubes can stand 100-times greater neutron-flux radiation pulses than can resistant transistors (see Table 1).

The resistance of specific types of identical components may differ sharply. For instance, among the semiconductor devices, irreversible parameter changes occur in low-frequency high-power transistors when fluxes are of the order of 10^{15} neutron/m^2, while in tunnel-type semiconducting devices of a similar type the changes occur when the flux is $10^{18} - 10^{19}$ neutron/m^2. Among resistors, the composite-type carbon varistors and wire-wound resistors are the least and the most resistant ones, respectively.

It is believed that it is possible to increase the radiation resistance of radio-equipment by correctly selecting or devising new types of parts.

However, in every case, it is very important to take into account the advisability of replacing one kind of a component with another.

The reliability of radio equipment exposed to penetrating radiation may be increased by improving the circuits. Circuits which have a low critical point to changes in the electrical parameters of components have been produced. It is well-known that the voltage generated after a certain number of charges (due to irradiation) have passed through an electric circuit is proportional to the impedance of that circuit. It follows that the radiation effect can be reduced by the use of low-impedance circuits.

Under gamma radiation, leakage currents are generated in insulating materials. Therefore, by developing circuits resistant to insulation leakages, equipment can be developed which operates without failure when exposed to gamma-pulses.

Under the effects of penetrating radiation, additional current and voltage sources can appear in the various circuits. Therefore, it is also possible to increase the radiation resistance of the equipment by using circuits which block up the excess currents and voltages.

Methods intended to shut off various radio circuits during exposure to penetrating radiation pulses are also important.

It is possible to increase the radiation resistance of circuits by providing considerable clearances between component parts, by reducing the operating voltage in the component parts, by adjusting thermal and electric loads to which the component parts are subjected, and by other similar methods.

Protection (shielding) of the equipment against penetrating radiation from nuclear explosions can be an effective measure, provided the weight and overall dimensions of the equipment are not restricted. If high-density materials (lead, steel, etc.) must be used as protection against gamma radiation, then low atomic-weight materials and substances (materials containing hydrogen and boron, cadmium materials, and special plastics) can be used as protection against neutron fluxes. For instance, to reduce the penetrating-radiation flux by a factor of two, the following are needed: 1. 5—2-cm-thick lead, 2—3-cm-thick iron, or 15—20-cm-thick plastic layers for gamma-rays; and 2. 5—5-cm-thick plastic or 10—12-cm-thick lead layers for neutron fluxes.

Consequently, the existing shields (casings, covers, and fillings) used for radio-equipment are practically transparent to neutron and gamma-radiations.

It should also be remembered that when neutrons are absorbed by the protecting material, a secondary radiation in the form of gamma rays is generated. The damaging effect of the secondary radiation can exceed that of the primary gamma radiation from a nuclear explosion.

Usually, in order to absorb the secondary radiation in the shields, a protective layer of heavy materials is placed over the internal surface (immediately at the casing of the equipment).

Thus, in order to reduce the penetrating-radiation flux by a factor of from tens to hundreds, a very bulky, heavy, combination-type protection must be provided. An example of a typical shield for protecting radio-equipment against penetrating radiation is shown in Fig. 4. It is assumed that this kind

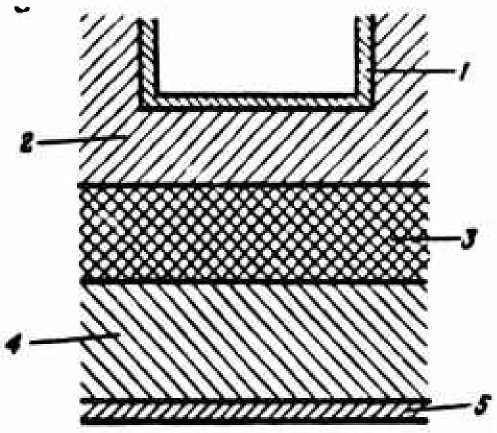


Fig. 4. Shield for protecting radio-equipment against penetrating radiation.

1 - Housing of radio-equipment; 2 - gamma shield (lead and polyethylene); 3 - low-velocity neutron absorber (boron oxides and poly ethylene); 4 - fast-neutron shield (graphite and polyethylene); 5 - shield framework

of protection is most preferable for radio equipment in aircraft and in space vehicles.

Although a great deal of research is being conducted in the Soviet Union on radiation damage in semiconductors, dielectrics, crystals, and other materials, no papers have been published on the effect of radiation from nuclear bursts on materials or electronic components, and on the transient effects at high fluxes. Only a dozen or so articles have been published on radiation defects in simple electronic components, such as diodes and photocells exposed to either artificially produced radiation or natural radiation from Van Allen belts. As an example of Soviet research on radiation effects in electronic components, two of the most recent papers on this subject are abstracted below.

The effect of 1 Mev neutrons on silicon mesa diodes was investigated in [36]. Mesa diodes were fabricated from boron doped, p-type silicon with resistivity of 5 ohm x cm. Each silicon plate with dimensions of 1 x 1 x 0.2 mm had six diodes. Two of the diodes were scaled in a glass ampoule at a pressure of 10^{-4} mm Hg: the rest were maintained at atmospheric pressure. The diodes were irradiated at a temperature of 28° C with an integrated flux of 8.5 x 10^{14} neutrons/cm^2. It was established that bombardment of mesa diodes with fast neutrons results in a decrease of direct current proportionally to the neutron flux. This was attributed to an increase in resistivity of the semiconductor material. The change in direct current is stable, i.e., only 1% of the direct current was restored after the diodes were annealed for 5 days at a temperature of 25° C. The reverse current increased during irradiation. At integrated fluxes of 8 x 10^{14} neutrons/cm^2 the increase in the reverse current did not exceed 50% of its initial value. It is concluded that p-type mesa diodes with resistivity of 5 ohm x cm will remain operational at neutron fluxes not exceeding 1—2 x 10^{14} neutrons/cm^2.

The effect of cyclotron-accelerated 2.3 Mev protons on silicon semiconductor detectors was investigated in [37]. The possibilities of using semiconductor detectors as spectrometric instruments under conditions of prolonged exposure to intensive low-energy proton bombardment have been examined. The capacitance, reverse current energy resolution, and pulse amplitude from the α-particles of 10 detectors (7 lithium diffusion drift and 3 surface barrier) were measured as functions of bias voltage. Irradiation was in stages with integrated flux varying from 10^{10} to 10^{13}—10^{14} proton/cm^2. The detector characteristics were measured before irradiation and after each irradiation stage. The capacitance showed the greatest sensitivity to the irradiation: substantial changes began after exposure to a flux of 10^{11} proton/cm^2. At pronounced decrease in spectrometric properties was observed at integrated fluxes of the order of magnitude of 10^{12} proton/cm^2 (energy resolution was halted; pulse amplitude decreased 10%). However, the surface barrier detectors irradiated with a flux of up to 10^{12} proton/cm^2 regained their initial properties after annealing at room temperature for several days. At fluxes of the order of 10^{13} proton/cm and greater, irreversible processes occurred—the detectors lost their spectrometric properties.

Radio-wave Propagation in Artificially Generated Ionized Clouds

Somewhat less directly concerned with the ionospheric effects of nuclear bursts, but, nonetheless, an integral part of ionospheric modification studies is the problem of radio-wave propagation in disturbed plasmas. In this regard considerable attention has been paid by Soviet investigators to the problem of radio-wave propagation in artificially generated ionized clouds such as those created by the passage of a rocket or missile through the atmosphere. The basis of such work excluding Western studies, seems to have been laid by Ya. L. Al'pert, who is associated with IZMIRAN (Institute of Terrestrial Magnetism, Ionosphere, and Radio-wave Propagation). In early 1965 Al'pert [38] published a major review article with both theoretical and experimental data based on the literature available since the beginning of large-scale experimentation with satellites and space probes. In this article, Al'pert describes in detail the effects arising in the neighborhood of a satellite, spaceship, or probe in the ionosphere or interplanetary space and the nature of their changes with increasing distance from the earth. Part 1 deals with the characteristics of the various media and Part 2, with the properties of bodies. Part 3 consists of a discussion of the perturbation of the concentration of particles, including such sections as the case of a rapidly moving body in near and distant zones, scattering on the track of a body, and the motion of a quasi-stationary body and finite and infinite particles. Part 4 describes the flux of particles in the neighborhood of the body; Part 5—the potential of a body in plasma; Part 6—excitation of longitudinal plasma waves; and Part 7—evaporation (erosion) from the surface of an artificial earth satellite in plasma. A number of electromagnetic effects are mentioned which, unfortunately, are not discussed in detail due to lack of space (such as the effect of a high-frequency field on plasma).

A. N. Kazantsev and colleagues [39] have proposed a geometrical optics method based on the solution of ordinary differential equations to describe ray paths in a three-dimensional inhomogeneous magneto-active ionosphere. This theory may be used not only to investigate radio-wave propagation in an inhomogeneous magneto-active ionosphere, but also to calculate the field intensity of radio waves emitted by satellites and the trajectories and delay time of whistlers, as well as to study the refraction and Doppler frequency shift in the ionosphere. Kazantsev et al. [40] subsequently applied this method to describe the dynamics of a radio beam in a horizontally inhomogeneous troposphere and ionosphere. The numerical solution of the problem was obtained by the Runge-Knutta method of utilizing a "Strela" computer.

Also relying on the principles of geometrical optics, N. P. Mar'in [41] investigated the propagation conditions for electromagnetic beams in cone-shaped ionized trails in the atmosphere formed by a point ionization source. The accuracy limits of geometrical optics are accepted by Mar'in inasmuch as he assumes that the electromagnetic wave-beam propagation can be represented by a series of orthogonal equiphasal planes. Mar'in's mathematical analysis is based on these assumptions in order to obtain a system of equations for a series of beams. He shows that the constants of these equations can be selected so as to determine two arbitrary points intersected by a given beam or the direction of a beam at a given point inside the trail.

In the second part of his analysis, Mar'in is concerned with determining the density of the energy flux associated with the beam during its passage through the ionized trail, with the conditions simplified in that energy losses inside the trail are disregarded. He attempts to establish a valid formula for determining the density of the energy flux through any elementary area located on a sphere the center of which coincides with the origin of the coordinates associated with the trail as described above. A direct relationship is established for a given observation point with known coordinates for the dependence of the density of the energy flux upon the angle of incidence of the illuminating beam and the geometry of the trail. Mar'in illustrates his results by an analytical determination of the diagram of a plane wave reradiated by the trail as applied to the radar signal illumination.

In another paper Mar'in [42] investigated radio-wave propagation in an artificially created ionized toroid caused by the ascent of an ionized cloud into the free atmopshere. To determine path trajectory in a toroid, he solves the eikonal equation in a toroidal coordinate system by differentiation, after making certain assumptions for the purpose of simplification relative to the selection of the distribution function of free electrons in a roroid. A system of equations is obtained that determines the path trajectory in a toroid and a formula is derived for the effective reflecting surface of the toroid for observation points separated by a distance considerably greater than the diameter of the toroid. An example of computing the trajectory of a beam propagating in a plane passing through the rotation axis of the toroid at different angles to the axis is given. Mar'in presents conclusions on the conditions necessary for radar detection of the toroid.

Using principles of geometrical optics, Mar'in [43] then determined ray paths in ionized clouds formed at great heights in the heterogeneous atmosphere of the earth as the result of the diffusion of particles capable of ionizing the air. An instantaneous point source in the atmopshere, the density of which varies exponentially, produces an ionized cloud having a maximum electron concentration at point $r = r_m$, $\theta = 0$ located below the source. At this point the refraction coefficient can be less than 1 and can even have negative values. As $(r - r_m)$ and θ increase, the refraction coefficient tends to unity. To determine the ray paths Mar'in uses a bispherical coordinate system. He derives an equation for the boundary of the region t opaque to radio waves.

Still another aspect and application of artificial luminescent cloud research has been investigated by N. N. Tantsova [44] of the USSR Institute of Applied Geophysics. Known amounts of nitrogen monoxide were released from rockets in the upper atmosphere for the purpose of measuring the concentrations of oxygen and nitrogen atoms. By observing the diffusion of the spherical gas cloud produced in the reactions and by knowing the original NO concentrations and the rates of reaction, Tantsova was able to compute the concentration of nitrogen and oxygen atoms and develop equations relating radiation intensity, cloud size, reaction rate, oxygen concentration, and nitrogen monoxide concentration.

Soviet Monitoring of Project Argus

Public announcement by the US Government of Project Argus, the detonation of three atomic devices launched from the Norton Sound in August—September 1958 in the South Atlantic to heights in excess of 300 km, was delayed until late March 1959, after Soviet publications began to allude to the tests. On 8 March 1958 an article in *Izvestiya* by Professors I. S. Shklovskiy and V. I. Krasovskiy [45] reported the detection of very highly energetic particles of probable artificial origin in the lower radiation belt. The Soviet scientists wrote:

> As it appears to us, it is not to be excluded that this zone has, if we may say so, an artificial origin. . . . Calculations

> performed by us show that several
> such [referring to US Nevada tests]
> high-altitude explosions would be fully
> sufficient for the formation of the lower
> zone of fast charged particles.

It would appear much more likely from subsequent Soviet articles, however, that not only the USSR, but other countries, had foreknowledge of the tests and were monitoring them. In any event, arrangements made by the international scientific community for worldwide cooperative geophysical monitoring programs during the International Geophysical Year would make it extremely difficult to conduct such tests secretly.

According to V. A. Troitskaya [46], the US Argus tests conducted in August—September 1958 were recorded as short-period oscillations at Soviet telluric current stations by means of special earth-current recorders designed by A. G. Ivanov in 1950. The Argus tests, according to Soviet data, occurred as follows:

	Argus I	Argus II	Argus III
yield in kt	1—2	1—2	1—2
date and time	0230 GMT;27/8/58	0320 GMT;30/8/58	2210 GMT;6/9/58
coordinates	lat. 38 S; long. 12 W	lat. 50 S; long. 08W	lat. 50 S; long. 10 W

The tests, according to Troitskaya, were successfully monitored not only by the US, but by France and the USSR as well. Comparison with the telluric records of the Johnston Island tests shows that there is a substantial difference between the type of short-period oscillation caused by a burst below the ionosphere (Johnston) and one above (Argus). If the nuclear burst occurs above the ionosphere, regular oscillations of 1—2 seconds occur and last for a few minutes; if they are of 2—4 seconds frequency, they last for 30—40 seconds and are less regular. Nuclear blasts occurring below the ionosphere set off a sudden impulse with a telluric current amplitude of 0.5—1 mV/km in the USSR, according to Troitskaya.

In a later paper Troitskaya [47] finds the onset time of oscillation for the Argus III experiment to be within 1 second at all telluric stations (Table 3) regardless of longtiude or latitude. Moreover, the commencement times could be determined much more accurately for these artificially excited pulsations than for SSC, owing to the sharp front of the first movement.

Table 3. Commencement time of pulsations excited by the explosion of Argus III on 6 September 1958

Station	Commencement time	
Mirny	No records	
Borok	22h12m36.7s	±0.5s
Sinatsk	22 12 36	±0.5
Alushta	22 12 36.7	±0.5
Alma-Ata	22 12 36.7	±0.5
Lovozero	22 12 36.8	±0.5
Pyramida	22 12 37	±0.5
Cape Chelyuskin	22 12 38	(uncertain)
Heis	22 12 37.5	(uncertain)
South Sakhalin	22 12 38	(uncertain)

It is interesting to note that the effects of Project Argus were recorded on the French Kerguelen Islands in 1958 and that Troitskaya now heads the Soviet investigators taking part in the current Franco-Soviet space investigations at the magnetically conjugate points of Kerguelen and Sogra. Her French counterparts today are J. Vigeneron and G. Laurent.

L. Sajti [48] an Hungarian investigator, has reported that pulsations following the Johnston Island nuclear blast were registered at several stations. They were observed at the time by the Hungarian station at Tihany (ϕ = 46° 54'N; λ = 17° 53. 6'E). The following data were recorded at Tihany: sudden onset of pulsation, $09^h00^m15^s$ (GMT) and amplitude of 1.7 gamma for about 30—40 seconds, followed by irregular pulsations for 60—80 seconds. The magnetic disturbance lasted for 7 minutes and reached its maximum during the first and third minutes. Maximum amplitude of the telluric currents was 12. 6 mV/km (N-S); magnetic register, 5. 2 gamma. The station's graph bears a close resemblance to the records from La Habra, California, and to those registered at Christ Church in that the maximum also occurred during the first and third minutes.

A comparison of the data registered in California after the 1962 blast with data registered after the blasts of 1—12 August 1959 [Argus experiment] led Sajti to conclude that the higher the nuclear blast occurs, the larger is the area in which it is felt and the shorter are the pulsations.

Soviet Monitoring of Operation Starfish

Soviet monitoring of the 9 July 1962 US high-altitude nuclear detonation by means of Kosmos-3, -5, and -17 provides an indication of their technical ability in this regard (see Table 4). As is well known, Soviet satellites systematically overfly both Johnston and Kwajalein Islands, where the US has been reported to be testing ABM systems. Starfish—a device of about 2 MT yield—was successfully detonated at a height of about 200 miles above Johnston Island on the fringes of outer space, causing auroras to appear in Honolulu, Samoa, and New Zealand, as well as disruptions in long-range communications to Japan, Australia, and elsewhere. Operation Starfish was, however, but one success in a series of high-altitude tests marked by failures, attributed to the Thor rocket, on 5 June, 21 June, 27 July, and 17 October. The tests were ended and declared a success on 5 November.

Table 4. Soviet satellites monitoring US tests

Name	Launch	Period	Perigee	Apogee	Inclination	Decayed
Kosmos-3	24 April 62	93.8	229	720	49.0	17 Oct 62
Kosmos-5	28 May 62	102.8	203	1600	49.1	2 May 63
Kosmos-17	22 May 63	94.8	260	788	49.0	2 June 65
Elektron-1	30 Jan 64	169	406	7100	61	in orbit
Elektron-2	30 Jan 64	1360	460	68000	61	in orbit

In 1964 Yu. I. Gal'perin and A. D. Bolyunova [49] published a paper describing the effects of Operation Starfish monitored by Kosmos-5. They reported that at the time of the detonation, a hard radiation burst was detected far beyond the limits of the satellite[s direct visibility. This burst was attributed to gamma rays generated by the explosion and was referred to as the "gamma aurora." In the first minutes following the burst, positively charged particles (protons), alpha particles, and fission fragments (positrons) drifting westward were detected by the approaching Kosmos-5. Ten minutes later electrons with an energy of several Mev began to predominate. In the magnetic conjugate point of Johnston Island at altitudes of about 500 km, and in the vicinity of the Brazilian magnetic anomaly at altitudes of 200—300 km, relatively soft electrons were detected whose absorption in the atmosphere were, according to Gal'perin and Bolyunova, evidently the cause of an auroral display above the Pacific. The maximum intensity registered above the South Atlantic one hour after the explosion was on the order of $2 \cdot 10^9$ electron/cm^2/sec. The maximum intensity of the radiation belt formed after the detonation occurred above the magnetic equator at an altitude of about 1350 km above Johnston Island; intensity varied with longitude. Data from

Kosmos-5 indicate that during the first few days a rapid drop in intensity was noted which gradually tapered off so that after the first four months the intensity at the center of the belt had declined by approximately an order of magnitude. An increase in the background radiation was detected at a height considerably below that of the permanent radiation belts. The decay rate of this surplus over the background caused by cosmic rays approximates the rate of intensity decrease at the maximum of the artificial belts, Gal'perin and Bolyunova conclude.

Bolyunova [50] in another paper described the measurements of this burst as recorded by Geiger counters onboard Kosmos-3 in the area between 30—49 north latitude and 20—150 east longitude at heights between 220—540 km. Kosmos-3 corraborated the findings of Kosmos-5 with regard to the increased counter rates over the cosmic-ray background. The excess intensity was found to be almost independent of the coordinates of the satellite; intensity fell off with time.

In early 1965 Gal'perin [51] attempted to construct a physical picture of the development of the artificial radiation belt produced by the high-altitude nuclear burst of 9 July 1962 on the basis of measurements of the intensity of relativistic electrons in the belt and in the γ-radiation flare. Direct observations of auroras accompanying the nuclear burst showed that the final radius of the plasma did not exceed 600 km, which is less than the radius of plasma cloud expansion in vacuum and even less than the radius of the spherical plasma cloud (this radius was estimated by taking into account the height of the screening layer for γ-radiation). Thus, Gal'perin concludes the cloud was located beneath the horizon of Kosmos-5. However, according to data from Kosmos-5 and Ariel, fission fragments penetrated into the higher altitudes. Gal'perin estimates that in about an hour after the burst there were $\sim 1.5 \cdot 10^{25}$ electrons having an energy > 20 Kev in the artificial belt. Direct measurements indicated tha the γ-radiation flare and the radiation belt were both caused by the entry into the geomagnetic field beyond the limits of the burst cloud of some radioactive fission products. In conclusion, Gal'perin proposes three possible mechanisms of particle ejection beyond the cloud limits.

Gal'perin [52] was able somewhat later on the basis of analysis of the results of measurements on Kosmos-5 during the early stages of the existence of the artificial radiation belt (obtained mainly on 9—10 July) and the later measurements of the intensity and decay rate (obtained chiefly by Kosmos-5 in the summer and fall of 1962 and by Elektron-1 and Elektron-2 in 1964) to refine his reconstruction of the intensity distribution of the hard electrons injected into the magnetosphere by the burst up to L$\sim$ 2. 3. Integration of this distribution over volume showed that the total number of injected electrons captured in the belt during the first hour after the burst, having the invariant coordinate $h_{min} \geqslant 300$ km, was about $1.5 \cdot 10^{25}$; the number of electrons with the energy $E \geqslant 1.5$ Mev was $4 \cdot 10^{24}$. Given an average capture effectiveness in the case of isotropic injection of $\sim$ 0. 5, the products of about 10^{25} fissions would, according to Gal'pern, have had to rise to great heights to form the belt in order to inject this amount of hard electrons by β-disintegration. Computation of the intensity and time-dependence of the γ-radiation of these fission products at a high altitude shows that they correspond to the intensity and time-dependence of the γ-flare phenomenon recorded by Kosmos-5 during the burst. This indicates that not later than 3 seconds after the burst the products of about 10^{25} fissions appeared above the horizon of Kosmos-5, i. e., at heights $\geqslant$1200 km, and that their γ- and β-radiation caused the γ-flare and artificial hard electron belt, respectively. The upper limit of total fissions ω in the Starfish explosion, based on Geiger counter measurements on Kosmos-5 at its closest distance to Johnston Island 20 minutes after the burst, was found to be $\omega \leqslant 2 \cdot 10^{26}$.

During this research, Gal'perin was associated with the Department of Physics of the Upper Atmosphere of the USSR Academy of Sciences under the direction of V. I. Krasovskiy.

Referring to data obtained by Gal'perin and Bolyunova, Yu. V. Kukushkin and A. S. Strelkovo [53] in 1966 continued the examination of the physical development of the cloud from Operation Starfish and the movement of contaminating γ- and β-active fission products entrained in the geomagnetic field. During this explosion, these investigators note, a plasma cloud with a radius of about 1000 km was formed, containing γ-active ions. Radiation from some of these ions, above the horizon, was recorded by Kosmos-5. After the ions were entrapped in the geomagnetic field, they began to move toward the conjugate points, and, as a result, as they rose in the equatorial region, they were able to cause the radiation later observed on Ariel. The spectrum of long-lived electrons (in the geomagnetic field) should, according to Kukushkin and Strelkov, correspond (rather than to the spectrum of fissions electrons) to the spectrum measured several seconds after fission products have been in the cloud of diamagnetic plasma and the short-lived β-active isotopes have decayed as they moved to great heights. They suggest that " γ-glow" observed on Kosmos-5 after the Johnston Island explosion may be explained by the γ-radiation of fission products rising above the horizon and conclude by pointing out that the effect cannot be caused by radiation from nuclear explosions if the source is below the horizon.

In 1967 on the basis of open-source Western literature S. I. Kozlov [54] examined the ability of the riometric stations in Western Samoa (Apia) and the inability of the riometric stations in Alaska to record the "gamma aurora" effect resulting from the high-altitude thermonuclear burst of a 9 July 1962 over Johnston Island. At the precise time of the burst, Kozlov writes, Kosmos-5 was in orbit some 7500 km away from the burst at a height of 1442 km. The satellite succeeded in recording the flash of hard (gamma) radiation during a two-minute period. The regions of maximum radio-wave absorption for the stations in Alaska and Apia at the time of the burst were outside the zone of direct visibility from the point of detonation. Kozlov shows that the riometric stations in Alaska were unable to record the "gamma aurora" effect, since the gamma radiation of the fission fragments ejected during a short time into the zone of direct visibility only slightly ionized the atmosphere above the Alaskan stations. Kozlov determines atmospheric ionization by integrating the kinetic equations containing the function of the rate of electron production by the gamma ray fragments for specified initial conditions. The absorption that was observed in Alaska during the burst was caused by another ionizing agent, he concludes. It was possible to record the "gamma aurora" effect in Apia, however, even though not all of the absorption observed could be attributed to the ionizing effect of the gamma radiation of the fragments.

Somewhat later Kozlov [55] analyzed the experimental data obtained on Wake Island during the 9 July 1962 high-altitude thermonuclear absorption over Johnston Island. The purpose of the analysis in this case was to explain the sudden 2db increase in 20—50 Mc radio-wave absorption, three seconds after the explosion. The ionizing effect of 2 Mev and 14 Mev neutrons on the atmosphere up to 100 km was analyzed first. Kozlov rejects this ionization mechanism however, and instead, shows that 0. 413 Kev x-rays and fission product gamma rays generate enough electrons to cause a 2-db absorption at 30 Mc frequency. Electron densities are obtained as a function of altitude for various time intervals, x-ray energies, and gamma ray fluxes. Kozlov concludes the analysis to be approximate because of lack of reliable information on ion recombination and dissociative electron recombination coefficients.

Kozlov and Yu. P. Rayzer [56] have examined the problem of the coefficient of dissociative recombination in the lower ionosphere up to ∿100 km. Using Western riometer data at 30Mc obtained at Midway Island, Kozlov calculated the coefficient of dissociative recombination at the time of Operation Starfish. The calculations differ from those of

R. E. Le Levier [*Journal of Geophysical Research, v. 69, no. 3, 1964, p. 481*] and those of I. S. Albus and I. D. Kraus (*A note on some signal characteristics of Sputnik I. Proc. I. E. E., 1958, no. 3, 610-611).*

Of the East European satellite states German and Czech investigators have reported on the Starfish and other high-altitude bursts. P. Nitzsche [57] of the GDR Heinrich Hertz Institute, for example, analyzed the absorption effect of Operation Starfish on HF lines, in this case the 2614 MHz Norddeich-Neustrelitz line. In his analysis Nitzsche considers such aspects of the problem as VLF phase disturbances, the role of x-ray and gamma radiation as a cause of ionization, the eastwared drift rate of trapped beta particles, SEA and SID effects, and decibel attenuation data. Nitzsche attempts a physical interpretation of the data base obtained with the movement of the HF particles in the geomagnetic dipole field considered in the first approximation.

In a broader but related study K. G. Ivanov [58] investigated the geomagnetic effects of Operation Starfish on the basis of data obtained from 72 geomagnetic stations. The distribution of the horizontal vectors of the geomagnetic changes along the earth's surface are presented and the results are computed graphically. Ivanov establishes that the geomagnetic field changes can be represented by four current loops in the ionosphere situated symmetrically to the equator and the meridian passing through the epicenter of the explosion. He maintains that his distribution pattern is more precise than similar work done by Japanese scientists.

L. Krivsky [59], a Czech scientist, reported that his investigation of atmospherics at 27 kc showed that Operation Starfish had caused an increased atmospherics level analogous to that in a period of anomalous x-ray emission during medium-importance solar flares. This disturbance, Krivsky states, indicates that such effects occur at the antipodal point of explosion.

J. Smilauer [60], of the Pruhonice Observatory, later presented information on the method of calculating ionospheric H(h) profiles from vertical sounding data used at the Geophysics Institute of the Czechoslovak Academy of Sciences in processing data taken at the Pruhnoice Observatory. An example cited as a use of the sounding technique is given by article reviewer E. Chvoykova who writes:

> An example of the use the sounding technique is the verification of the influence of a high nuclear explosion, carried out on 22 October

> 1962 around 03·40 UT above Central Siberia, on the upper ionosphere. Its influence on the lower ionosphere was apparent in attenuation measurement carried out at the ionospheric observatory of the Geophysical Institute in Panska Ves. At first no pronounced effect was seen on the ionograms since at the time of the explosion there was a low electron concentration with a decreasing tendency. A decrease in the total electron content and an increase in attenuation were recorded, as well as a lowering of the critical frequency.

P. V. Vakulov [61] has described the use of Kosmos-17, equipped with 2 scintillation counters and 1 gas-discharge counters, to investigate the Van Allen belts and primary cosmic radiation to heights of 800 km. During measurements in the inner radiation belt, large electron fluxes resulting from Operation Starfish were recorded. The mean lifetimes of these electrons were determined for different magnetic envelopes. Values of absolute fluxes of the electrons were obtained as well as the energy spectrum of protons and proton fluxes entrapped in the inner belt. The regions in which the satellite recorded the entrapped radiation were delineated and it was found that they corresponded well with those that had been theoretically expected from analysis of L, B charts. A more detailed description of the instrumentation on this satellite has been provided by S. N. Vernov et al. [62]. The apparatus carried by Kosmos-3 and Kosmos-5 have been described in even greater detail by Yu. I. Gal'perin and V. I. Krasovskiy [63].

Conclusions

As early as 1964 Marshal Leonov [64], Commander of the USSR Communications Troops, stated:

> The Soviet Armed Forces have a first rate communications technology, incorporating the latest advances of science and engineering. Our communications troops have at their disposal modern radio and radio-relay facilities that

> ensure reliable high-fidelity communications over practically all distances. Tropospheric communications facilities are widely used for control; ionospheric communications are being introduced. Problems dealing with the improvement of reliability and protection of communications during operations under conditions following high-altitude nuclear bursts or radio interference are being successfully solved. Special equipment is being used on communications lines to increase transmission reliability necessary to ensure the normal operation of electronic computers and other means of automatic control of troops. Work on the development of an automatic channel switching capability and automation of other communications processes is yielding positive results. Equipment to ensure rapid secret transmission of commands and signals has found wide application on long-range communications lines.

It is clear from the preceding discussion and from Marshal Leonov's statement that all possible precautions are being taken in the Soviet Union to ensure communications reliability in the event high-altitude nuclear bursts are set off in a future conflict in order to disrupt communications. It also appears that the Soviets have at their disposal not only the experience gathered from US atmospheric tests of bombs up to about 4 MT, but also a considerable amount of information, unshared by the US, derived from the detonation of bombs having a yield in excess of 40—50 MT—a yield which, in the opinion of some, could introduce qualitative changes in the ionosphere not predicted by scaling laws. Owing to the vulnerability of LF, MF, and HF transmissions, the USSR, as Leonov notes, is further developing the efficiency of radio-relay, troposcatter, and ionoscatter links.

Soviet-bloc technical communications literature substantiates Marshal Leonov's claim to the further development of communications systems (line-of-sight, radio-relay) relatively immune to the effects of high-altitude bursts. In 1966 it was reported [65] that a tropospheric radio-relay system was being introduced in geographically inaccessible areas of the Soviet Union. Television transmissions over 300—400 km without intermediate stations were the goal. In 1968 the Leningrad

Institute of Electrical Engineering [66] announced the establishment of an experimental direct television transmission link between Leningrad and Petrozavodsk, based on the utilization of the peculiar property of the tropospheric topside (height, ~12 km) to reflect ultra-short waves. Because of temperature differences the tropospheric topside reflects UHF transmissions, providing the waves are incident at a specific angle. Tests showed that direct transmissions over distances in excess of 400 km were possible.

An even more impressive government sponsored program to establish a large-scale radio-relay system capable of bridging distances of 12,000 km by means of an extensive station network with each station having a maximum range-of-sight of 50 km is now being set up in the vicinity of Moscow. Upon completion, this experimental directional radio-relay system, called the Druzhba network, will be able to transmit various kinds of communications simultaneously, including long-distance telephone conversations, telegrams, radio photos, computer center data, TV programs, and even newspaper matrices [67].

Theoretical studies are being made [68] of the effect of terrestrial sphericity on the propagation of VLF radio waves in the "earth-lower ionosphere" waveguide. VLF transmissions, though not as invulnerable to high-altitude nuclear bursts as VHF and UHF transmissions, are nonetheless more reliable than LF, MF, and HF transmissions.

The Soviet ABM system, the Tallin System, as described by H. Baldwin [69], extends from the GDR-Polish boundary on the Baltic Sea north through Tallin and Arkhangel'sk, to the Arctic Circle east of the Urals. The Tallin defense system is believed to consist of weapons systems capable of producing x-ray effects against incoming missiles. The USSR is reported to have an operational booster rocket capable of putting an 80 MT warhead above the atmosphere. As noted above, an 80 MT yield would probably be capable of disrupting even ionoscatter links. This "exospheric rocket," or defense missile, is designed to intercept the incoming missiles above the atmosphere. Since both orbital and global rockets may be used for the purpose of ionospheric contamination as well as direct ground-to-air bombardment, it is useful to examine the relative advantages and disadvantages of these space weapons systems as described by an East-bloc source. H. Endert [70], an East German writer of missile and nuclear strategy, has provided a useful analysis of the known Soviet space weapons systems, referred to by NATO as SCRAG.

Endert notes that global rockets, intended to strike targets 20,000—30,000 km away, follow Keplerian elliptical orbits with the earth as one of the foci. The cutoff velocity of such rockets is 7910 m/sec. Though the flight time to target is long owing to the eccentric orbit (apex can be 10,000 km above earth's surface), the global rocket has the advantage of being able to approach its target from any direction, thus making defense difficult. According to Endert, orbital rockets have the shortest flight time to target as they are located in circumterrestrial orbit only 200 km above the earth. While an ICBM would require 32 minutes flight time to strike a target 10,000 km away, an orbital rocket can cover the distance in 23 minutes. An orbital rocket would require 68 minutes to strike a target around the earth, i.e., 30—40 minutes less time than would be required by a global rocket. The trajectory of an orbital rocket is not easily reconstructed by enemy defense as it does not follow a ballistic orbit like an ICBM and may in addition change its orbital parameters. Finally, Endert concludes, the nuclear warheads of an orbital rocket can be fired from any point along its orbit. Fig. 1 compares the trajectories of global and orbital rockets.

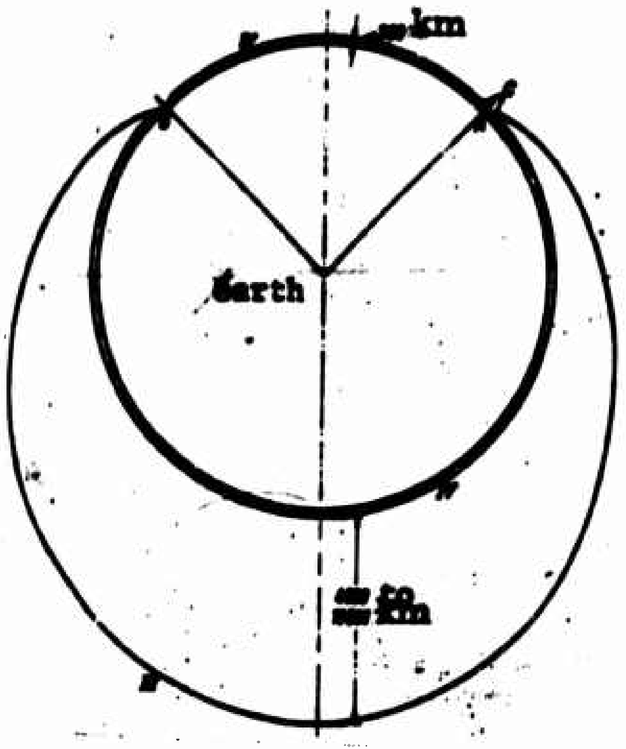


Fig. 1. Global and orbital rocket trajectories

III - Global rocket trajectory; IV - orbital rocket; A - launching site; B - target; C - cutoff point at 200 km.

In a recent analysis of Soviet launch facilities and satellites Kenneth W. Gatland [71] identifies Plesetsk as a likely part of the Soviet ICBM complex. Gatland observes that Plesetsk has maintained a steady launch rate since the first Kosmos was sent aloft from there on 17 March 1966. In 1967, 26 Kosmos satellites were launched from Plesetsk compared with 28 from the older site at Tyuratam. In addition, Plesetsk launchings continue without a seasonal break despite the severe winters in that area. With regard to satellite types, it is significant in discussing the possible use of satellites in ionospheric modification missions that the Meteor-class weather satellites characterized by a near circular orbit at ∿600 km are launched from Plesetsk into near polar orbits. Another important series of Kosmos satellites (139, 160, 169, 170, 171, 178, 179, 183, 187, 218) launched not from Plesetsk but from Tyuratam into extremely low orbit (∿145 km) and having a very short lifetime (∿ 1.5 hr) are believed to be test vehicles for the FOBS.

It may also be noted that both Plesetsk, the launch site, and Sogra, the conjugate point research center, are both on the Tallin line.

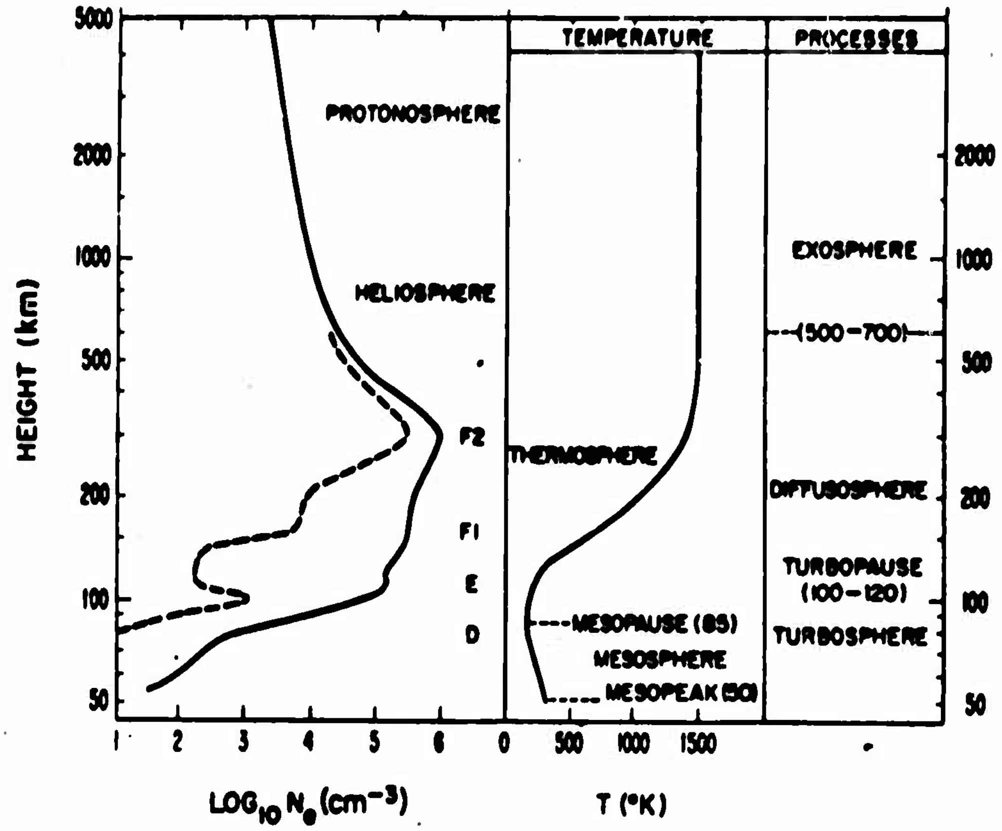
On the basis of 1) the general Soviet nuclear war doctrine with its emphasis on the importance of the first strike, 2) Soviet possession of nuclear devices with yields in excess of 50 MT capable of causing almost total radio disruption, 3) Soviet development of orbital weapons systems which may be used for ionospheric modification purposes as well as ground bombardment, 4) numerous Soviet studies on the effects of nuclear bursts on radio propagation, and 5) explicit statements of Marshal Leonov and other Soviet authorities, it must be concluded that the USSR already has a nuclear-missile-satellite weapons system capable of causing almost complete radio communications blackouts over large segments of the earth's surface for varying lengths of time. This capability may be used either to disrupt enemy defense communications networks should the USSR attack or to block incoming missiles should the USSR be attacked.

Appendix

Table 1. Ionospheric regions and layers

Height range (km)	Region	Layers
50–90	*D*	*D*
90–(120–140)	*E*	E_1, E_2, E_s
Above (120–140)	*F*	F_1, $F_{1\frac{1}{2}}$, F_2

Fig. 1. Atmospheric nomenclature



[Source: Davies [72]].

Table 2. Ionospheric densities, pressures, and temperature

Schicht	h'(km)	n (cm^{-3})	n (cm^{-3})	p (Torr)	T (K)
E	120	up to $2 \cdot 10^5$	$6 \cdot 10^{12}$	$2{,}5 \cdot 10^{-4}$	500
F_1	220	up to $2 \cdot 10^5$	$1 \cdot 10^{11}$	$1 \cdot 10^{-5}$	1000
F_2	300	up to $2{,}5 \cdot 10^5$	$2 \cdot 10^{10}$	$3 \cdot 10^{-6}$	2000

h' is the apparent height of the center of the layer; n (col.2) is the electron density; n (col.3) is the density of the neutral gas particles; p is the gas pressure; T is the gas temperature.
[Source: Rotsch [73]].

Table 3. Communications spectrum

Name of range	Frequency range*	Wavelength range
Very-low-frequency (VLF)	3—30 kc	10^7—10^6 cm.
Low-frequency (LF)	30—300 kc	10^6—10^5 cm.
Medium-frequency (MF)	300 kc-3 Mc	10^5—10^4 cm.
High-frequency (HF)	3—30 Mc	10^4—10^3 cm.
Very-high-frequency (VHF)	30—300 Mc	10^3—10^2 cm.
Ultra-high-frequency (UHF)	300 Mc-3 k Mc	10^2—10 cm.

*The abbreviations kc, Mc, and kMc refer to kilocycles (10^3 cycles/sec), megacycles (10^6 cycles/sec), and kilomegacycles (10^9 cycles/sec), respectively.

[Source: Glasstone [74]].

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