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INVESTIGATION OF THE IONOSPHERE AND OF THE INTERPLANETARY GAS WITH THE AID OF ARTIFICIAL SATELLITES AND SPACE ROCKETS

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CONTENTS

I. INTRODUCTION

We shall consider certain possible experiments with the aid of satellites and space rockets, aimed at investigating the ionosphere. We have in mind principally the external heretofore inaccessible part of the ionosphere, extending from a height of 300 or 400 km above the principal maximum up to thousands of kilometers from the earth and going over into the interplanetary gas. We propose here to study the electromagnetic properties of these media (density of charged particles, their elastic collisions with each other or with neutral particles, inhomogeneous electronic or ionic formations, and also plasma waves, electromagnetic radiation from particles, and similar phenomena).

These problems differ physically in many respects from the problems previously solved either by earth-based means or by high-altitude rockets. On the one hand, we are now investigating a medium that represents a rather strongly ionized and highly rarefied plasma. In many respects, processes in such a plasma are much simpler than in the internal ionospheric plasma adjacent to the earth. This facilitates, for example, the extraction of important data by means of relatively simple experiments. On the other hand, since the instruments used in these experiments are carried by bodies whose velocities exceed or are commensurate with the thermal velocity of the particles in the gas medium, it becomes necessary to account for the interaction of the body with the plasma as well as with the radiation field in which the body moves. It is hardly possible to obtain from the measurements without such an account any accurate or reliable data regarding the properties of the medium. This makes the performance and analysis of many measurements highly difficult in principle. Finally, it becomes difficult to obtain data on local properties of the medium, i.e., properties of some finite region surrounding the satellite or the rocket, owing to the masking and perturbing effect of ionospheric regions located between the observer and the satellite.

Owing to our limited knowledge of the properties of the investigated medium, the methods used up to now for satellite investigation of the ionosphere were in the main those customarily employed for experiments under earth-based conditions. It is quite clear, however, that useful results will be gained from experiments in which the procedure is based on various phenomena that take place in the vicinity of the satellite and are caused by the satellite itself in this medium. A few such possibilities will be indicated below (see Sec. 13). But the theory of the physical properties of the plasma and of its behavior under different conditions induced by the moving body has so far been very little investigated. Consequently, perhaps the major task of the experiments with the aid of satellites is to investigate the phenomena that occur in the vicinity of the satellite itself. It is obvious that the measured quantities will not yield immediately direct information on the parameters characterizing the medium itself. Such an approach to the research can, naturally, change the character of the individual experiments. This is made necessary, on the one hand, by the circumstances indicated above; on the other hand, experiments of this kind are in themselves of great interest, being one of the means of experimentally investigating a plasma that cannot be readily studied in the laboratory.

In considering the problem of ionospheric research with the aid of satellites, it is best to discuss first the results of analogous experiments made with the aid of high-altitude rockets. It is sometimes believed that this will uncover quite new properties of the ionosphere. This opinion, however, greatly overestimates the progress attained, although there is no doubt that a direct confirmation of previously expected or known data on the ionosphere is significant, and regular research of this kind is itself of importance. Some of the results of these experiments, related to the problems of interest to us, are given in Sec. 1.

1. Summary of Results of Experiments with the Aid of High-Altitude Rockets

One of the main purposes of the investigation of the ionosphere with the aid of high-altitude rockets is to prove that the electron concentration N increases more or less smoothly with altitude z in the lower part of the ionosphere, in that the E and F layers are characterized by relatively weakly pronounced electron-concentration maxima N_M. A series of N(z) curves obtained in different years at White Sands in the U.S.A. and at Fort Churchill in Canada is shown in Fig. 1. The same figure shows one of the first published N(z) curves.[1,2] This conclusion, based on rocket experiments, was obtained in 1953 – 1954,[1] but it was not new even then and did not contradict the N(z) dependence derived by processing the high-frequency characteristics of the ionosphere (ionograms) obtained by vertical sounding of the ionosphere with the aid of radio waves. Furthermore, a sufficiently consistent mathematical reduction of the ionograms has shown later on, by comparison of the N(z) curves obtained by the two methods, that these curves are fully identical even in many details, as can be seen from Fig. 2.[3] Yet, one must not underestimate the significance of further "direct" measurements of N(z) with the aid of rockets, which permit a detailed investigation of the altitude dependence of the electron concentration.

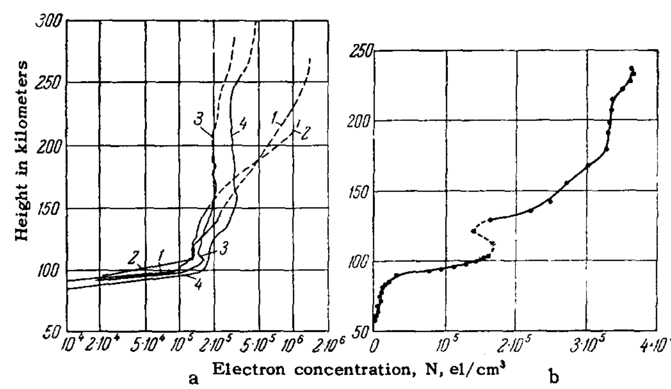


FIG. 1. Dependence of the electron concentration on the altitude, obtained in experiments with the aid of high-altitude rockets. a) White Sands (U.S.A.): 1 – September 29, 1949, 10:00; 2 – October 21, 1950, 18:18, 3 – May 7, 1954, 10:00; 4 – June 29, 1956, 12:09. b) Fort Churchill, Canada, July 4, 1957, 12:16.

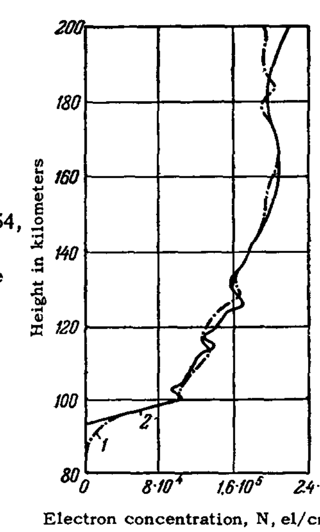


FIG. 2. Dependence of the electron concentration on the altitude, obtained on May 7, 1954, 10:00, at White Sands (U.S.A.) Curve 2 was calculated from the ionogram obtained at the same time.

The curves shown in Figs. 1a and b start with z ~ 80 – 90 km. At the same time, measurements near the base of the ionosphere, at altitudes of 50 or 60 km, are a very important problem. This region has been least investigated and the processes in it are more complicated than in the higher parts of the ionosphere, while rocket measurements encounter here difficulties of various kinds. Many experimental difficulties were recently overcome and, through measurement of the difference in attenuation and refraction of the ordinary and extra-ordinary waves, certain experiments have yielded not only the tails of the N(z) curves at the base of the ionosphere, but also the dependence of the effective number of collisions $\nu(z)$ on the altitude in this region. Such N(z) and $\nu(z)$ curves, obtained at Fort Churchill in Canada during a period of increased radio-wave absorption in the ionosphere, are shown in Figs. 3 and 4. The $\nu(z)$ dependence shown in Fig. 4 is the first experimental curve of this type.[4] No experimental methods of investigating $\nu(z)$ at altitudes greater than those shown in Fig. 4 have been found thus far.

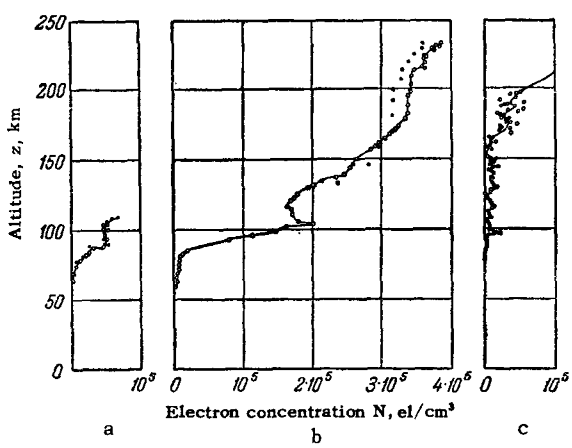


FIG. 3. Dependence of the electron concentration on the altitude, obtained at Fort Churchill (Canada) with the aid of rockets. a) November 15, 1956, 13:32; b) July 4, 1957, 12:16; c) February 4, 1958, 00:17.

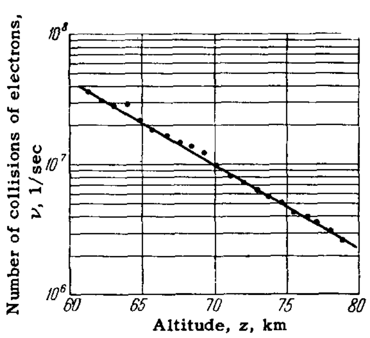


FIG. 4. Dependence of the number of collisions of the electrons on the altitude, obtained with the aid of a rocket on July 4, 1957, 12:16.

Some of the launched high-altitude rockets were used to measure also the dependence N(z) above the principal maximum of electron concentration of the ionosphere, $N_M F2$.[5] The corresponding curve is given later (see Fig. 22), where it is compared with the average course of N(z) in the outer ionosphere, obtained earlier with radio signals from a satellite (see Sec. 9), and demonstrates the sufficiently slow decrease in electron concentration above $N_M F2$.

Over a number of years, many investigations have been devoted to the following question: is the electric force that acts on the electrons in the ionosphere equal to the macroscopic value of the field E? This question arises because the distance between particles in the ionosphere is considerably greater than the dimensions of the particles themselves, and these particles can be considered as point dipoles. It is therefore not clear a priori whether it is legitimate to write the equation of motion of the electron in the form

$$m\ddot{\mathbf{r}} + \frac{e}{c}[\dot{\mathbf{r}} \times \mathbf{H}] + m\nu_{\text{eff}}\dot{\mathbf{r}} = e\mathbf{E}, \qquad (1)$$

or whether E must be replaced in (1) by the effective field

$$\mathbf{E}_{\text{eff}} = \mathbf{E} + 4\pi a \mathbf{P}, \qquad (2)$$

where **P** is the polarization vector and a is a coefficient that depends on the properties of the medium. If the molecules of the medium can be considered to be point dipoles arranged at random or are located in the sites of a cubic lattice, a = 1/3, and the term $4\pi\mathbf{P}/3$ is usually called the Lorentz polarization correction.

This question is also important in quantitative calculations. Thus, for example, when account is taken of the polarization correction, the index of refraction of the ionosphere (disregarding the earth's magnetic field) is

$$n^2 = 1 - \frac{4\pi N e^2}{m\omega^2\left(1 + \frac{4\pi e^2 N}{3m\omega^2}\right)},$$

and not

$$n^2 = 1 - \frac{4\pi N e^2}{m\omega^2}. \qquad (3)$$

Accordingly, the electron concentration at the point where the wave is reflected (n = 0) is determined from the condition $4\pi e^2 N/m\omega^2 = 3/2$, and not from the usually employed $4\pi e N/m\omega^2 = 1$, i.e., N differs in the two cases by a factor 1.5.

A theoretical solution of this problem entails complicated calculations, which require a detailed account of the interaction between the electrons and the surrounding particles. Attempts at simplifying such calculations lead to results which are in direct contradiction. The opinions regarding the need for the polarization correction were contradictory for a long time; in the latest theoretical papers in this group[6,7] the authors have reached the conclusion that there is no need for the polarization correction. It has been impossible to obtain a sufficiently convincing experimental answer to this question, owing to the difficulty in interpreting the results of the corresponding experiments made on the earth's surface. The problem has been simply and elegantly solved with the aid of rockets, by simultaneous measurement of the indices of refraction of the ordinary and extraordinary waves.[1,2] Figure 5 shows the results of these measurements. The abscissas of Fig. 5 are the values of $4\pi Ne^2/m\omega^2$, determined from the measured values of the index of refraction of the ordinary wave (solid lines) with (Fig. 5b) and without (Fig. 5a) account of the Lorentz polarization correction. The figures show the simultaneously obtained values of the index of refraction of the extraordinary wave (circles) and the calculated theoretical curves (dotted). It is seen from the figure that the circles fall near the theoretical curve for the coefficient of refraction of the extraordinary wave, shown in Fig. 5a for the case when the Lorentz correction is disregarded. Thus, the results of these experiments give an unequivocal answer to the question of the nature of the effective field in the ionosphere, and a single rocket experiment has in fact settled a long-standing discussion and resolved the doubts connected with it.

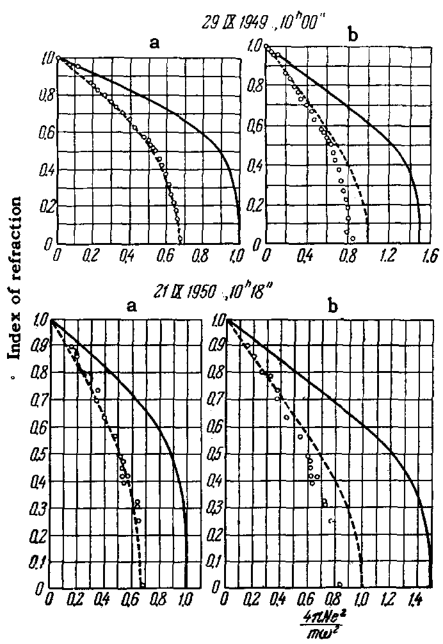


FIG. 5. Comparison of the theoretical and experimental dependences of the coefficients of refraction on $4\pi e^2N/m\omega^2$ with (a) and without (b) allowance for the Lorentz polarization correction. The solid lines establish the connection between the rocket-measured values of the coefficient of refraction of the ordinary wave and the values of $4\pi e^2N/m\omega^2$ calculated from them. The dotted curves are for the extraordinary wave, calculated from the same values of $4\pi e^2N/m\omega^2$. The circles represent the simultaneously measured values of the coefficient of refraction of the extraordinary wave.

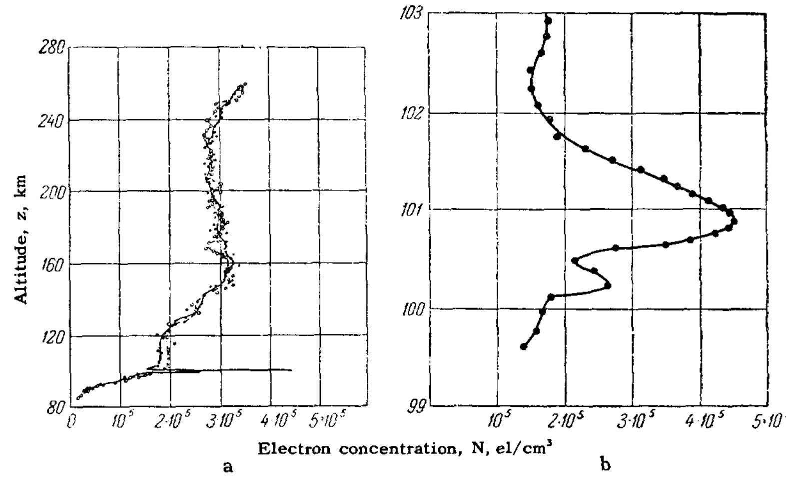
That rocket experiments afford a possibility of investigating higher-order effects can be seen also from the following. It is well known that radio waves are frequently subject to secondary reflections from the E region of the ionosphere. These reflections are associated with the appearance of a semi-transparent or screening layer E_{spor} of increased ionization. The data accumulated to date have implied that E_{spor} is a thin layer of electronic origin. One could not exclude, however, the possibility that the E_{spor} reflections were frequently due to parts of the E region with increased ionization gradients. Until recently there was no direct proof that the appearance of E_{spor} is accompanied by increased ionization. Numerous launchings of rockets have shown that the E_{spor} reflections appearing near the surface of the earth are usually accompanied by large electron-concentration gradients with not more than 10% overall increase in the electron concentration. On June 29, 1956, when a launched rocket landed several tens of kilometers from its launching site, the E_{spor} state noted during the launching was intensified, and a clearly pronounced layer of increased ionization was observed directly.[8] The electron concentration almost doubled within a region 1 or 2 km thick at an altitude of 101 km (see Fig. 6). This experiment thus proved convincingly that very thin regions of intense ionization are produced sporadically in the E region and these are apparently sharply delineated in space and develop quite rapidly in time.

2. Certain Problems in Present Day Research

When setting up experiments on the ionosphere and the interplanetary gas with the aid of satellites and rockets, it is best to agree first on the problems that are of greatest interest.

There is no doubt that one of the basic problems facing us in the nearest future is the measurement of the charge density as a function of the distance from the earth up to the top of the atmosphere, i.e., up to altitudes of several thousand kilometers and farther beyond in interplanetary gas. Since we speak here of research with the aid of satellites and space rockets, the measurements proposed begin essentially with altitudes of 300 or 400 km, where the principal maximum of the ionosphere is usually located. An important factor in these investigations is the location of the top of the atmosphere, i.e., the region where the traces of the main components of the atmosphere, oxygen and nitrogen, become negligible and hydrogen predominates. Of greatest interest in the interplanetary regions are, firstly, measurements of the charge concentration and, secondly, experiments that determine simultaneously the density and composition of the neutral particles and the flux of ultraviolet and x rays from the sun. The order-of-magnitude values of these parameters are by now fairly well known up to altitudes of 800 or 1,000 km. It is very important therefore to measure these quantities in each experiment with sufficient accuracy, so that an attempt can be made to determine the ionization balance at different altitudes and to ascertain the variation of the temperature with altitude, so as to obtain data on the character of the interaction of the radiation flux with the atmosphere and on the inelastic collisions between particles, and proceed to solve the basic problem of the composition of the ionosphere and in general of the plasma around the earth. Naturally, prolonged measurements will be necessary

FIG. 6. Dependence of the electron concentration on the altitude, obtained at White Sands (U.S.A.) on June 26, 1956, 12:09. The scale in Fig. (b) is much smaller than in Fig. (a).



to obtain the longitude, latitude, and time dependences of these quantities. The expected degree of ionization of the atmosphere at altitudes of 1,000 km and somewhat above is on the order of unity, i.e., the concentration of neutral particles n is approximately equal to the concentrations of the electrons (N) and of the positive ions (N_+). Above this region, where the number of neutral particles becomes considerably less than the number of charges, the measurement of the variation of N with altitude is in itself of great interest. In particular, such a measurement will provide an idea of the variation of n and of the temperature T. Of basic significance, naturally, is the determination of the character of variation of the charge concentration in the transition to the interplanetary gas, with simultaneous measurement of the composition of the gas particles. The measurement accuracy required here is also quite high. It is desirable to determine the concentration accurate to a factor on the order of two or three. It follows from various measurements and estimates that the expected interplanetary-gas concentration ranges within several times ten or several times one hundred particles per cubic centimeter. Information on the temperature T is even more speculative; it is assumed that T is several thousands or hundreds of thousands and more degrees! However, it is necessary to know accurately the variation of these quantities in the outer ionosphere at the transition to the interplanetary gas. In general, the nature of the interplanetary gas is itself subject to question; does it exist independently of the particle streams from the sun which perturb it, or is the interplanetary gas itself made up of these particle streams? Suitable experiments will apparently permit a direct measurement of the speed of the incoming particle fluxes and determine their density. In the interplanetary gas region closest to the earth the particle streams may already be transported in the form of plasma clusters with frozen-in magnetic field. These will manifest themselves in a specific manner in the measurement of various physical quantities. The character of the expected effects will differ, if for no other reason, because the particle-stream velocity amounts to tens and hundreds of kilometers per second, and the cosmic rocket or satellite can be considered as a stationary body within this stream. It is possible that these experiments will also disclose the intrinsic radiation of these streams at gyrofrequencies.

Along with the indicated problems, it is important to search for methods of determining the altitude variation of the number of collisions $\nu(z)$, i.e., to investigate elastic processes in this medium. These processes depend directly on the concentration of the heavy particles (neutral atoms or molecules, ions) and the temperature of the medium. It is precisely by investigating these quantities that it may become possible to study the behavior of $\nu(z)$, since so far no other sufficiently simple and lucid methods of measuring ν have been found for the regions through which pass the orbits of satellites and space rockets.

Such experiments, in view of the long lifetime of the satellites circling the earth, will naturally permit accumulation of data on the spatial inhomogeneity of the ionosphere — both in its large-scale aspects (sporadic layers, latitude and longitude effect) and the small-scale aspects (cloud formation).

Satellites and space rockets can apparently serve also as means of investigating nonstationary phenomena in a highly$^{1-1}$ rarefied plasma, i.e., processes that lead to excitation of waves in a plasma, to its intrinsic radiation at plasma and gyrofrequencies, to nonequilibrium temperature variations, and to similar phenomena. The plasma region in the vicinity of a moving body is the laboratory in which these effects are created; an investigation of these phenomena, both by setting up suitable measurements on the bodies themselves and by means of different kinds of observations of the flying body from the earth's surface, is of great interest. It must be borne in mind here that the plasma through which a satellite or rocket travels varies over a very wide range. Thus, in the vicinity closest to the earth ($z \sim 200$ to 1,000 km) the degree of ionization of the plasma (i.e., the ratio of the concentration of the neutral particles to the electrons, $p = n/N$), ranges from $p \sim 10^5$ to $p \sim 1$; next, we apparently have $p \sim 10^{-3}$ at $z \sim 3{,}000$ km followed by a further decrease. In this region the Debye radius $D = \sqrt{\frac{kT}{4\pi e^2 N}}$ changes from fractions of a centimeter to several centimeters, and then reaches 100 or 200 cm in the interplanetary gas, i.e., D is at first much smaller than the linear dimensions of the body and gradually becomes commensurate with it. At the same time, the velocity of the body V is at first almost one order of magnitude greater than the thermal velocity of the heavy particles v_i, and then, at a distance on the order of several earth's radii from the earth, it decreases to $V \sim v_i$, while in interplanetary gas, to the contrary, the velocity of the body is much less than the thermal velocity of the heavy particles, and the body can be assumed to be at rest in these plasma regions. In accord with the changes in the actual conditions, the character of the expected phenomena that takes place in the plasma near the satellite or rocket should change substantially along the orbits of these bodies as they pass through different parts of the earth's atmosphere.

We see thus that the problems involved are greatly varied in their physical nature. It is obvious that only by using different experimental methods to solve adequately the various problems can considerable progress be expected in this field.

As already noted, great difficulties which are frequently of principal character make the measurement methods used at the present time far from satisfactory. Some of these methods are reviewed in the following sections. Let us consider first, however, the distinguishing features of the various types of measurements.

3. Features of Various Types of Experiments with the Aid of Satellites and Rockets

The main experiments used to solve the problems listed above can be grouped in three types.

One group consists of investigations of the unknown properties of the medium through analysis of the properties of radio waves transmitted from the satellite and received at different points on earth. These experiments are of indirect character. The medium is investigated in these experiments through its integral influence on the propagation of the radio waves between the source and observer. Even when the results of the measurements make it possible to determine the parameters of the medium locally, i.e., from point to point along the orbit, the "point" must be taken to mean a certain extended region; this region is frequently commensurate with the "Fresnel zone," Measurements of this type are not sensitive to effects occurring in the vicinity of the body and due to its interaction with the medium. This is a distinguishing feature and great advantage of these experiments. However, an important role is played in these experiments by the masking action of different effects that occur along the path of wave propagation, particularly changes in the state of the medium. This is a serious difficulty in precision measurements of the differential type. We note also that in many cases an analysis of the corresponding data is made very difficult by tumbling of the satellite and its antennas, and this introduces an additional complication in the state of the field of the received radio waves. Some of the obtained data, however, show that in spite of all these difficulties we can investigate with the aid of radio waves not only the integral quantities that characterize the medium, which are of interest in themselves, but also local properties of the medium, particularly in a statistical analysis of a sufficiently large volume of experimental data. Once oriented satellites are developed, the effectiveness of such experiments will greatly increase.

Experiments of the second type are based on methods which make it possible to investigate directly the medium along the orbit of the body. In experiments of this kind it is proposed to use instruments, so to speak "probes," placed on the satellite or on the rocket, and to transmit the measured quantities to the earth with the aid of telemetering devices. Such probes, for example are Langmuir probes, called also ion traps, which determine the density of the positive ions;[9,10] instruments which measure the natural frequency of a plasma, and consequently its electron concentration; manometers, which determine the density of the medium,[43] etc. In experiments of this kind, however, the investigations are made not on the parameters or properties of the medium directly, but only on the region adjacent to the body, a region perturbed by various effects which are due to the motion of the body. Thus, for example, if the velocity of the body is greater than the thermal velocity of the particles, then the density of both neutral and charged particles increases in front of the body, and its value on the body surface is increased by a factor two or three. On the other hand, rarefaction is produced on the rear of the body and at a distance of one or two body radii the concentration of the particles amounts to 1/10 to 1/20 of normal (see Sec. 10). In addition, a complicated redistribution of the electric potential, which exceeds kT/e by several times, takes place in the vicinity of the body, (T is the temperature of the unperturbed medium). Nor can one exclude the possibility of excitation of plasma waves, particularly by the additional charge flux that results from photoemission from the surface of the body, due to the flux of incident radiation from the sun. The linear dimensions of the region perturbed by these phenomena can apparently equal the mean free path of the particle behind the body, i.e., it may be considerably greater than the dimensions of the body itself. Certain phenomena of this kind are described in greater detail later on. They have been little investigated at the present time, however.

It is just as clear that when the properties of an unperturbed medium are measured with the aid of probes it is necessary to take into account the state of the medium in the vicinity of the body, something that necessitates not only a theoretical but also an experimental investigation of the interaction between the body and the plasma. Inasmuch as these processes have been little investigated, the difficulties arising in the analysis and interpretation of different kinds of results of measurements made with the aid of probes are principal in character.

Thus, apparently, in most "direct" experiments, the sought data on the properties of the medium can likewise be obtained only by indirect means, by suitable reduction of the measurement data with allowance for the phenomena that occur in the vicinity of the instrument. Such features are also symptomatic of the third group of experiments, in which the procedure is based on the analysis of the interaction between the body and the medium. Such is, for example, the method of determining the density and temperature of the atmosphere from the change, due to air drag, in the orbit of the body and its velocity.[11,12] Simultaneous measurements with the aid of several Langmuir probes (traps) at different distances from the surface of the satellite, along its axis, apparently make it possible (see Sec. 13) to determine the temperature and the true unperturbed ion density. Along with this, sufficiently accurate measurements of the effective cross section for the scattering of radio waves of different frequencies from an inhomogeneity surrounding the satellite rocket, made from the earth's surface, can also yield information on the properties of the plasma. At the present time it is difficult to predict all the potentialities of experiments of this kind. It seems to us that the development of experimental research on the ionosphere and the interplanetary gas with the aid of satellites and rockets will follow precisely this path, since it aims most closely at the heart of the problem.

II. DOPPLER EFFECT AT RADIO FREQUENCIES

Observations of the Doppler frequency shift of radio waves transmitted from a satellite or a rocket can be used to obtain data on the properties of the ionosphere and the interplanetary gas. For this purpose it is necessary to measure with sufficient accuracy the frequency (or the phase difference) of the oscillations received at the point of observation. This is due to the fact that the dispersion of the intervening medium usually affects the Doppler frequency shift much less than the change in the frequency due to the Doppler effect proper, observed in vacuum, where the velocity of propagation of the electromagnetic waves is constant and equal to the velocity of light c.

Let a source moving with velocity V radiate sinusoidal oscillations $\sin \omega t$. Then the oscillations received at the point of observation are proportional to

$$\sin [\omega t - \Phi(t)] = \sin \psi (t),$$

and $\Phi(t)$ is the retardation of the phase or the optical path of the wave. In an inhomogeneous medium, in the approximations of geometric optics,

$$\Phi(t) = \frac{\omega}{c} \int_{R_0}^{R_c} n\, ds = \frac{\omega}{c} \int_{R_0}^{R_c} \frac{n}{\cos\varphi} dR, \quad (4)$$

where $n = n(R)$ is the coefficient of refraction and ds is the element of the wave trajectory; all the other symbols are explained in Fig. 7. The instantaneous value of the frequency of the received oscillations, which are made non-sinusoidal by the phase modulation, is

$$\frac{d\Psi}{dt} = \omega - \frac{d\Phi}{dt}, \quad (5)$$

with

$$\dot{\Phi} = \frac{d\Phi}{dt} = \frac{\omega}{c} \frac{d}{dt} \left\{ \int_{R_0}^{R_c(t)} \frac{n}{\cos\varphi} dR \right\}. \quad (6)$$

Thus, Eq. (6) determines the frequency shift $\Delta f = \dot{\Phi}/2\pi$ of the radiated oscillations, due to the Doppler effect in an inhomogeneous medium.[13,14] It is, however, more logical and simpler methodologically to derive a final formula for $\dot{\Phi}$ not from the integral (6), but by direct determination of the Doppler frequency shift.

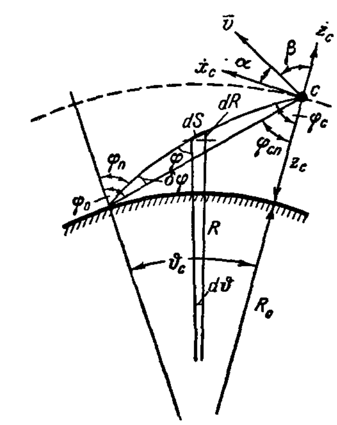


FIG. 7. Illustrating the derivation of the Doppler frequency shift in a spherically-stratified medium.

By definition, when the velocity of the source is much less than the velocity of light

$$\Delta f = \frac{\dot{\Phi}}{2\pi} = V_r : \frac{c}{n_c}, \quad (7)$$

where V_r is the component of the source velocity along the line of sight, and c/n_c is the phase velocity of the wave at the corresponding point ("c" on Fig. 7). In a homogeneous medium, the line of sight, or, in other words, the trajectory s of wave propagation, is a straight line. In our case, however, when we consider a spherically inhomogeneous medium, s is determined from the law of refraction

$$n(R) \cdot R \cdot \sin \varphi (R) = R_0 \sin \varphi_n, \quad (8)$$

where R_0 is the earth's radius, and φ_n is the angle that the incoming wave makes at the point of observation. Therefore, assuming that the motion takes place in the plane of the figure, we have

$$\dot{\Phi} = \frac{\omega}{c} V \left[\frac{R}{R_c} \cos\alpha \sin\varphi_n - \cos\beta \sqrt{n_c^2 - \left(\frac{R_0}{R_c}\right)^2 \sin^2\varphi_n} \right], \quad (9)$$

if we use the relations that follow from (8) for the angle of emergence of the ray from the source

$$\sin\varphi_c = \frac{R_0}{R_c} \frac{\sin\varphi_n}{n_c}. \quad (10)$$

It is seen directly from (9) that the properties of the medium influence the Doppler effect in two ways. In the integral form, the medium causes $\dot{\Phi}$ to depend on the angle of arrival of the wave φ_n, which differs from φ_0 near the earth in the case of a straight-line trajectory by an amount $\delta\varphi$, which depends on the refraction of the wave in the inhomogeneous medium. We note that in a homogeneous medium, other than vacuum, when the coefficient of refraction is everywhere constant, the trajectory of the wave is, naturally, also a straight line; independently of the value of n, we have here

$$\varphi_n = \varphi_0, \quad \varphi_c = \varphi_{cn},$$

and there is no integral effect of the medium on the Doppler effect.

The local effect of the medium is connected with the fact that $\dot{\Phi}$ depends directly on the value of n_c near the source. If the orbit is nearly spherical, when the horizontal velocity of the source is $R_c\dot{\vartheta}_c = V\cos\alpha \simeq V$, and the vertical velocity is $\dot{R}_c = V\cos\beta \ll V$, the Doppler frequency shift

$$\dot{\Phi} \simeq \omega \frac{V}{c} \frac{R}{R_c} \sin\varphi_n \quad (11)$$

depends only on the integral influence of the medium, and $\dot{\Phi}$ determines the refraction of the wave in the ionosphere (see below). In the opposite case, when $\beta = \pi/2$, $\alpha = 0$, and $\varphi_n = \varphi_0 = 0$, i.e., when the source moves strictly upward (rocket experiment), we have

$$\dot{\Phi} = -\omega \frac{V}{c} n_c \quad (12)$$

and thus the Doppler frequency determines directly the value of the coefficient of refraction in the vicinity of the radiator.

Let us calculate now the angle of refraction of the wave $\delta\varphi$ in a spherically inhomogeneous medium; this will enable us to examine more closely the connection between the Doppler frequency shift and the parameters of the medium. We shall start with the usually-realized case, when the frequency of the wave is $\omega^2 \gg \omega_H^2$ (ω_H — gyrofrequency), and $\omega^2 \gg \nu^2$ (ν — collison frequency). In this case we neglect in first approximation the effect of the earth's magnetic field, and we can assume everywhere for the ionosphere

$$n^2 = 1 - \frac{4\pi Ne^2}{m\omega^2}, \quad (13)$$

with $4\pi Ne^2/m\omega^2 \ll 1$. Using the relation

$$R \cdot d\vartheta = \tan\varphi \cdot dR, \quad (14)$$

along the wave trajectory (see Fig. 7) and Eq. (8), we readily find that the central angle is

$$\vartheta_c = \sin\varphi_n \int_{R_0}^{R_c} \frac{dR}{R\sqrt{n^2R^2 - R_0^2\sin^2\varphi_n}}. \quad (15)$$

From purely geometrical considerations

$$\vartheta_c = \sin\varphi_0 \int_{R_0}^{R_c} \frac{dR}{R\sqrt{R^2 - R_0^2\sin^2\varphi_0}}. \quad (16)$$

Equating (15) and (16), we obtain an equation

$$\sin\varphi_n \int_{R_0}^{R_c} \frac{dR}{R\sqrt{n^2R^2 - R_0^2\sin^2\varphi_n}} = \sin\varphi_0 \int_{R_0}^{R_c} \frac{dR}{R\sqrt{R^2 - R_0^2\sin^2\varphi_0}}, \quad (17)$$

which relates the unknown angle φ_n with the angle φ_0 and with the quantity $n(R)$ or $n(R) = N(z)$ — the dependence of the electron concentration on the altitude.

If we assume now that the wave arrives in a direction which is far from tangential, so that the condition

$$\frac{4\pi e^2 N}{m\omega^2} \ll \cos^2\varphi_n \quad (18)$$

is satisfied, we obtain from (17)

$$\sin\varphi_0 = \sin\varphi_n \frac{\int_{R_0}^{R_c} \frac{dR}{R\sqrt{R^2 - R_0^2\sin^2\varphi_n}} + \frac{2\pi e^2}{m\omega^2} \int_{R_0}^{R_c} \frac{NR\,dR}{\sqrt{(R^2 - R_0^2\sin^2\varphi_n)^3}}}{\int_{R_0}^{R_c} \frac{dR}{R\sqrt{R^2 - R_0^2\sin^2\varphi_0}}}. \quad (19)$$

It is clear from (19) that when $4\pi e^2N/m\omega^2 \ll 1$ we have

$$\delta\varphi = \varphi_0 - \varphi_n \ll 1 \text{ and } \sin\varphi_n \approx \sin\varphi_0 - \delta\varphi\cos\varphi_0. \quad (20)$$

Therefore, expanding (19) in powers of $\delta\varphi$, we have ultimately

$$\sin\varphi_n \simeq \sin\varphi_0 \left\{ 1 - \frac{2\pi e^2}{m\omega^2} \frac{\int_{R_0}^{R_c} \frac{NR\,dR}{\sqrt{(R^2 - R_0^2\sin^2\varphi_0)^3}}}{\int_{R_0}^{R_c} \frac{R\,dR}{\sqrt{(R^2 - R_0^2\sin^2\varphi_0)^3}}} \right\}, \quad (21)$$

and the angle of refraction is

$$\delta\varphi \simeq \tan\varphi_0 \frac{2\pi e^2}{m\omega^2} \frac{\int_{R_0}^{R_c} \frac{NR\,dR}{\sqrt{(R^2 - R_0^2\sin^2\varphi_0)^3}}}{\int_{R_0}^{R_c} \frac{R\,dR}{\sqrt{(R^2 - R_0^2\sin^2\varphi_0)^3}}} = \tan\varphi_0 \frac{2\pi e^2}{m\omega^2} \overline{(N_R)}, \quad (22)$$

where the ratio of the integrals in (22) is denoted by $\overline{(N_R)}$.

Substituting (20) in (9) and recognizing that $\delta\varphi$ and $4\pi e^2N/m\omega^2$ are small compared with $\cos^2\varphi_0$, and consequently also with $\{1 - (R_0/R_c)^2\sin^2\varphi_0\}$, we obtain a final relation between the Doppler frequency shift and the unknown value of the angle of refraction and the electron concentration N_c, as functions of the horizontal and radial velocities of the source; namely, we have

$$\dot{\Phi}=\frac{\omega}{c}\left\{R_0\sin\varphi_0\dot{\vartheta}_c-\dot{R}_c\sqrt{1-\left(\frac{R_0}{R_c}\right)^2\sin^2\varphi_0}\right\}$$
$$-\frac{\omega}{c}\left\{R_0\cos\varphi_0\dot{\vartheta}_c\delta\varphi+\frac{R_0^2}{R_c^2}\frac{\sin\varphi_0\cos\varphi_0}{\sqrt{1-\left(\frac{R_0}{R_c}\right)^2\sin^2\varphi_0}}\dot{R}_c\delta\varphi\right.$$
$$\left.-\frac{2\pi e^2}{m\omega^2}\frac{\dot{R}_c}{\sqrt{1-\left(\frac{R_0}{R_c}\right)^2\sin^2\varphi_0}}N_c\right\}. \qquad (23)$$

In different cases $\delta\varphi$ can be expressed directly in terms of the integral electron concentration

$$N_n=\int_{R_0}^{R_c}N\,dR=\int_0^{z_c}N\,dz, \qquad (24)$$

so that the quantity N_n is introduced in (23) in lieu of $\delta\varphi$. Thus, for example, on parts of the orbit where the sphericity of the earth and of the ionosphere can be neglected, i.e., where z_c/R_0 is so small that the medium can be considered plane-stratified, it follows from (22) that

$$\delta\varphi\simeq\tan\varphi_0\frac{2\pi e^2}{m\omega^2}\frac{\int_0^{z_c}\left\{1+\frac{z}{R_0}\left(1-\frac{3}{\cos^2\varphi_0}\right)\right\}N\,dz}{z_c\left[1+\frac{z_c}{R_0}\left(1-\frac{3}{\cos^2\varphi_0}\right)\right]}\simeq\tan\varphi_0\frac{2\pi e^2}{m\omega^2}\frac{N_n}{z_c} \qquad (25)$$

and we obtain in lieu of (23)

$$\dot{\Phi}=\frac{\omega}{c}\{\dot{x}_c\sin\varphi_0-\dot{z}_c\cos\varphi_0\}$$
$$-\frac{\omega}{c}\sin\varphi_0\frac{2\pi e^2}{m\omega^2}\left(\frac{\dot{x}_cN_n}{z_c}+\tan\varphi_0\frac{\dot{z}_cN_n}{z_c}-\frac{\dot{z}_cN_c}{\cos\varphi_0\sin\varphi_0}\right) \qquad (26)$$

or

$$\dot{\Phi}=\frac{\omega}{c}\dot{r}_c-\frac{\omega}{c}\frac{2\pi e^2}{m\omega^2}\left(\frac{\dot{r}_cN_n}{z_c}+\frac{\dot{z}_cN_n}{z_c\cos\varphi_0}-\frac{\dot{z}_cN_c}{\cos\varphi_0}\right)$$

where $\dot{x}_c$, $\dot{z}_c$ and $\dot{r}_c$ are respectively the horizontal, vertical, and radial velocities of the source (relative to a straight line of sight).

It is seen from (22), (23), (26), and (27) that a relation exists between the Doppler frequency shift, measured at the point of observation, and the electron concentration of the medium in which the source moves. The corresponding methods of measuring $\dot{\Phi}$ and a suitable technique for reducing the experimental data (a technique which is not always simple) make it possible to determine independently from these formulas the values of N_n and N_c along the orbit of the source. In this case, however, one must bear in mind an important consequence of these formulas. The quantity $\dot{\Phi}$ consists of two components. The first, in the first set of curly brackets of (23) and (26), determines the Doppler frequency shift in vacuum, where n = 1 and the wave velocity is c. This can be called the "optical" component of the Doppler effect. The second term in these formulas depends on the electron concentration and vanishes when N = 0. It is easy to show that this term is considerably smaller than the optical component, in the same degree as $2\pi e^2N_c/m\omega^2$ or $2\pi e^2N_n/m\omega^2z_c$ is less than unity. Thus, for example, in the ionosphere at 40 Mc/sec, the optical component of the Doppler effect is 10 to 200 times greater than the N-dependent component of $\dot{\Phi}$, and is a thousand times and more greater in interplanetary gas. Since the "optical" Doppler frequency shift at 40 Mc/sec is at most of the order of 1,000 cycles, it follows that the unknown effect due to the influence of the medium is at the most a few cycles and is in many cases only a fraction of a cycle. It is therefore difficult to obtain any data on the medium by measuring the overall Doppler effect, and such measurements call for a practically unattainable accuracy in the measurement of the variation of the frequency of the received oscillations. At the same time, it is possible to exclude the optical component and to determine the Doppler frequency shift due to the effect of the medium alone.

4. Elimination of the "Optical" Component of the Doppler Frequency Shift

Measurements of the phase difference (or of the frequency difference) of two synchronized oscillations, which start out in phase from a moving source, yield directly the Doppler-frequency component due to the influence of the medium.[13,16]

Actually, the reduced phase difference or, what is the same, the difference between the instantaneous values of the frequency of two synchronized oscillations

$$\sin[\omega_1t-\Phi_1(t)]\text{ and }\sin[\omega_2t-\Phi_2(t)]$$

is

$$\delta\Phi=\Phi_1-\frac{\omega_1}{\omega_2}\Phi_2\quad\text{or}\quad\delta\dot{\Phi}=\dot{\Phi}_1-\frac{\omega_1}{\omega_2}\dot{\Phi}_2. \qquad (27)$$

Therefore, when measuring the corresponding quantity at the output of the receiver, one registers instead of $\dot{\Phi}$ the frequency difference $\delta\dot{\Phi}$, which equals in our case, with allowance for sphericity,

$$\delta\dot{\Phi}=\frac{\omega_1}{c}\sin\varphi_0\frac{2\pi e^2}{m}\left(\frac{\omega_1^2-\omega_2^2}{\omega_1^2\omega_2^2}\right)$$
$$\times\left\{R_0\dot{\vartheta}_c(\overline{N_R})+\left(\frac{R_0}{R_c}\right)^2\frac{\sin\varphi_0}{\sqrt{1-\left(\frac{R_0}{R_c}\right)^2\sin^2\varphi_0}}\right.$$
$$\left.\times\dot{R}_c(\overline{N_R})-\frac{\dot{R}_cN_c}{\sin\varphi_0\sqrt{1-\left(\frac{R_0}{R_c}\right)^2\sin^2\varphi_0}}\right\}, \qquad (28)$$

and in the plane case

$$\delta\dot{\Phi}=\frac{\omega_1}{c}\sin\varphi_0\frac{2\pi e^2}{m}\left(\frac{\omega_1^2-\omega_2^2}{\omega_1^2\omega_2^2}\right)$$
$$\times\left(\frac{\dot{x}_cN_n}{z_c}+\tan\varphi_0\frac{\dot{z}_cN_n}{z_c}-\frac{\dot{z}_cN_c}{\cos\varphi_0\sin\varphi_0}\right). \qquad (29)$$

In (28) and (29) $\delta\dot{\Phi}$ is proportional to N_n and N_c, and the optical component of the Doppler effect is completely eliminated. Therefore, a measurement of the difference in frequency or in phase, which can be performed accurate to a small fraction of a cycle, yields the value of $\delta\dot{\Phi}$ and the required data on the electron concentration of the ionosphere and allows us to investigate small variations of this concentration. Since the measured quantity $\delta\dot{\Phi}$ depends in general on two unknowns N_n and N_c, or $\delta\varphi$ and N_c, it is necessary, naturally, either to perform two independent sets of measurements or to obtain from the experiments linearly-independent equations for these quantities. Different experimental techniques can be used to solve this problem. We shall merely note here that in accurate measurements of $\delta\dot{\Phi}$, under conditions when the ionosphere is sufficiently quiet, it is apparently possible to obtain data on the variation of the electron concentration $N(R_c) = N(Z_c)$ along the orbit even from measurements of $\delta\varphi$. For this purpose it is necessary to calculate numerically, within finite intervals, the quantities

$$\frac{\Delta(\overline{N_R})}{\Delta R_c} = \frac{N_c R_c}{\sqrt{(R_c^2 - R_0^2 \sin^2\varphi_0)^3}} \tag{30}$$

or

$$\frac{\Delta N_n}{\Delta z_c} = N_c, \tag{31}$$

which determine $N(z_c)$.[13] We note that in many cases the experiments are influenced by the "cloudiness" of the ionosphere, and spatial modulation of $\delta\dot{\Phi}$ is observed; the variations of $\delta\dot{\Phi}$ measured along the orbit of the source will depend on the fluctuations of the electron density of the inhomogeneous ionospheric formations and on their linear dimensions (see reference 13).

5. Difference of the Doppler Frequency Shifts of the Ordinary and Extraordinary Waves — the "Rotational" Doppler Effect

In the preceding section we calculated the Doppler frequency shift without allowance for the effect of the earth's magnetic field. Actually, if $\omega_H/\omega = u_H \ll 1$, then the error in the component of the Doppler frequency with the aid of (28) or (29), determined as the difference of the optical paths of two waves, the frequency ratio of which is an integer, is on the order of $u_H^2\delta\dot{\Phi}$, i.e., a very small quantity, for usually $u_H^2 \lesssim 10^{-2}$. However, in spite of the smallness of u_H, a noticeable influence of the earth's magnetic field on the Doppler effect is observed directly. The splitting of the linearly polarized wave in a magnetoactive medium into two components — ordinary and extraordinary — causes two elliptically-polarized waves to be received at the point of observation, and the Doppler frequencies of these waves differ from each other because of the difference in their refractive indices. Superposition of these waves produces at the output of the receiver amplitude modulation at a frequency equal to the difference between the frequencies of the ordinary and extraordinary waves. At the point of observation, the vector of the total field rotates at this difference frequency about the linearly-polarized antenna. The frequency of the received amplitude-modulated wave can be readily calculated by means of the equations given above.

Taking into account the earth's magnetic field, the index of refraction is

$$n^2 = 1 - \frac{2v_0(1-v_0)}{2(1-v_0) - u_T^2 \pm \sqrt{u_T^4 + 4u_L^2(1-v_0)}}, \tag{32}$$

where the signs "±" pertain to the ordinary and extraordinary waves, $v_0 = 4\pi Ne^2/m\omega^2$, and $u_T = eH_T/mc\omega = \omega_{HT}/\omega$ and $u_L = eH_L/mc\omega = \omega_{HL}/\omega$ are respectively the projections of the gyroscopic frequency $\omega_H = eH/mc$ transverse to and along the direction of wave propagation. If the condition $4\pi e^2N/m\omega^2 \ll 1$ is satisfied simultaneously with the conditions u_T, $u_L \ll 1$ (i.e., in the absence of quasi-transverse wave propagation), then (32), unlike (23), implies that

$$n_1^2 \simeq 1 - \frac{4\pi e^2 N}{m\omega^2}\frac{1}{1+u_L}, \quad n_2^2 \simeq 1 - \frac{4\pi e^2 N}{m\omega^2}\frac{1}{1-u_L} \tag{33}$$

for the ordinary and extraordinary waves, respectively. Therefore, by replacing N in (23) with $N/(1+u_L)$ and $N/(1-u_L)$, we obtain the Doppler frequency shifts $\dot{\Phi}_1$ and $\dot{\Phi}_2$ of the ordinary and extraordinary waves. Thus, the difference of these frequencies, determined from the amplitude oscillations, observed at the output of the receiver, is directly equal to

$$\delta\dot{\Phi}_H = \dot{\Phi}_1 - \dot{\Phi}_2 = \sin\varphi_0 \frac{4\pi e^3}{m^2c^2\omega^2}\left\{R_0\dot{\vartheta}_c(\overline{N_R})\overline{H}_L + \left(\frac{R_0}{R_c}\right)^2 \frac{\sin\varphi_0}{\sqrt{1-\left(\frac{R_0}{R_c}\right)^2\sin^2\varphi_0}}\dot{R}_c(\overline{N_R})\overline{H}_L - \frac{\dot{R}_c N_c H_{Lc}}{\sin\varphi_0\sqrt{1-\left(\frac{R_0}{R_c}\right)^2\sin^2\varphi_0}}\right\}, \tag{34}$$

or, in the plane case,

$$\delta\dot{\Phi}_H = \sin\varphi_0 \frac{4\pi e^3}{m^2c^2\omega^2}\left\{\frac{\dot{x}_c N_n \overline{H}_L}{z_c} + \tan\varphi_0\frac{N_n\overline{H}_L}{z_c} - \frac{\dot{Z}_c N_c H_{Lc}}{\cos\varphi_0\sin\varphi_0}\right\}. \tag{35}$$

In the derivation of (34) and (35) we assume that the longitudinal component H_L of the magnetic field changes little in the investigated range of altitudes, so that its average value can be taken outside the integral sign, i.e. we obtain

$$\int\frac{NH_L R\,dR}{\sqrt{(R^2-R_0^2\sin^2\varphi_0)^3}} \simeq (\overline{N_R})\overline{H}_L \text{ and } \int NH_L\,dz \simeq N_n\overline{H}_L, \tag{36}$$

instead of the corresponding integrals in (28) and (29). If H_L cannot be taken outside the integral sign, then the first and second terms in (34) and (35) have more complicated factors than $(\overline{N_R})\overline{H}_L$ and $N_n\overline{H}_L$. As regards the third term in these formulas, it contains in either case the longitudinal component H_{Lc} of the magnetic field at the point where the source is located.

The method described here thus makes it possible to investigate the properties of the ionosphere by measuring the frequency $\delta\dot{\Phi}_H$ of the amplitude modulations of the received signals. It is easily understood, however, that this method is less sensitive than that considered in Sec. 5, and the measured values of $\delta\dot{\Phi}_H$ are more readily influenced by various extraneous factors. Thus, the regular variation of amplitude, caused by this effect, should be disturbed by the rotation of the source about its axis, by a change in its orientation relative to the receiving antenna, by the influence of inhomogeneities of the ionosphere etc. Along with these, phase-modulation techniques in which phase differences are determined readily permit the measurement of very small quantities, which amount to only a small fraction of a cycle. In the case of an amplitude modulation, the accuracy with which the frequency $\delta\dot{\Phi}_H$ is measured is considerably lower.

6. Certain Experimental Results

The results obtained by systematic investigation of the ionosphere through the use of the Doppler effect in radio signals from a satellite are still unknown. Immediately following the launching of the first satellites, many researchers attempted to use the direct measurements of the Doppler frequency shift by heterodyning the radio signals received at the point of observation with local sources. These attempts were naturally somewhat naive, since the accuracy of such measurements cannot possibly determine reliably the effect of the ionosphere, as already noted in Sec. 3. To be sure, observations of the first satellite were made simultaneously at 20 and 40 Mc/sec, and signals were obtained from the third satellite at 20 Mc/sec and at its first overtone, 40 Mc/sec.[17,18] Although in this case the radiated signals were in strict synchronism, to take full advantage of such measurements it was necessary that both waves be synchronously received and that the reduced phase difference be automatically recorded (see Sec. 4), and this was not done in these experiments. Since it is simpler and easier to register the signal amplitudes, various observers recorded the amplitude modulation due to the difference in the frequency shifts of the ordinary and extraordinary waves (Sec. 5) in order to obtain data on the ionosphere. In some articles the corresponding effect is called the "Faraday rotation." However, the results of such measurements are also very scanty.

Amplitude records illustrating the presence of a "rotational" Doppler effect, are shown in Figs. 8 — 10. One of these recordings (Fig. 8) was obtained in Australia by automatically recording the signals from the first satellite.[19] We notice the presence of both fast amplitude oscillations, due to the Faraday effect, and of slower ones, with a period ~ 5 sec, due to the rotation of the satellite about its own axis. The author did not report the results of reduction of these recordings, and merely mentions the presence of the corresponding effect. Other examples of more precise registration of amplitude modulation of satellite signals are given

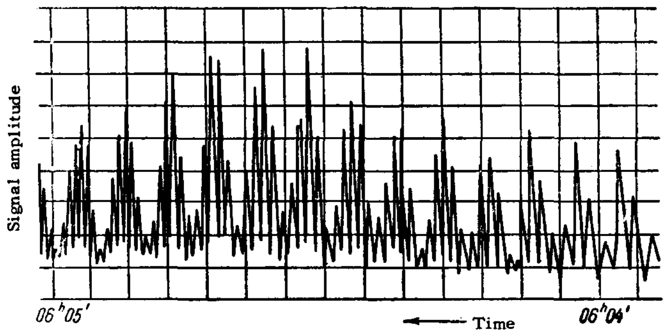


FIG. 8. Record of the amplitude of radio signals from the first satellite; the fast amplitude oscillations are due to the rotational Doppler effect, while the slower one (with period ~5 sec) are due to the rotation of the satellite.

on the oscillograms shown in Figs. 9 and 10. One was obtained in Moscow (Fig. 9) and the other in East Germany[20] (Fig. 10), using 20 Mc/sec signals from the third satellite, in the summer of 1958. Analogous data were analyzed in England[18] for several days in October 1957, and in Denmark[21] for observational data obtained on October 12, 1957. Certain records were made at the first overtone (40 Mc/sec) of the signals from the third satellite.

The principal conclusions obtained in these investigations are as follows. First, the total number of electrons $N_n = \int_0^{z_c} N\, dz$, calculated from the rotational Doppler effect, agrees very closely in many cases with the value of N_n calculated from the high-frequency characteristic of the ionosphere; this can be verified in those cases when the satellite is located near the principal maximum of the ionosphere $N_M F2$. Second, certain observations[18,20] have made it possible to assert that the electron concentration diminishes slowly above the maximum $N_M F2$. This is in good agreement with the deduction previously obtained from investigations of the radio rise and radio setting of the signals of the first satellite (see reference 22 and Sec. 9). Thus, for example, if we approximate the results of 14 observations over England, made in October 1959,[18] by means of the exponential e^{-sz}, we obtain on the average $s \sim 10^{-3}\ \text{km}^{-1}$. In East Germany, 135 observations made in the summer of 1958 yielded[20] $s \sim 2.5 \times 10^{-3}\ \text{km}^{-1}$, while reference 22 gives, on the basis of observations made in October 1957, $s \sim 3.5 \times 10^{-3}\ \text{km}^{-1}$. Analogous measurement results are cited in references 49 and 48.

The above data apparently represent all the results reported in the literature; they confirm the desirability of similar systematic experiments.

We note here that in many cases, records of amplitude modulation, such as shown in Figs. 9 and 10, yield data on the number of collisions in the ionosphere. Actually, the depth of modulation of the received oscillations, as observed on the recording, is given by the relation

FIG. 9. Example of record of amplitude modulation of the radio signals of the third satellite, due to the Faraday rotation; Moscow, 1958.

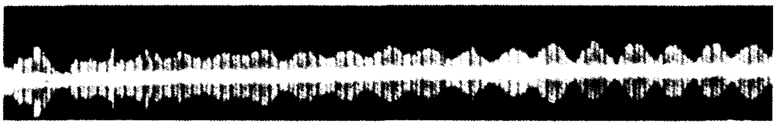


FIG. 10. Example of record of amplitude modulation of radio signals of the third satellite – Faraday rotation; East Germany, 1958.

FIG. 11. Example of record of the rotational Doppler effect in Moscow, in the case when additional amplitude modulation due to the effect of small-scale irregularity in the ionosphere is observed.

$$M_0 = 1 - \frac{A_1 - A_2}{A_1 + A_2} = 1 - \frac{1 - \frac{A_2}{A_1}}{1 + \frac{A_2}{A_1}}, \qquad (37)$$

where A_1 and A_2 are proportional to the amplitudes of the received ordinary and extraordinary waves. If we start with the assumption that both waves have equal amplitudes at the point of radiation, then

$$\left.\begin{aligned} A_1 &\sim \exp\left(-\frac{\omega}{c}\int_{R_0}^{R_c} \varkappa_1\, ds\right), \\ A_2 &\sim \exp\left(-\frac{\omega}{c}\int_{R_0}^{R_c} \varkappa_2\, ds\right), \end{aligned}\right\} \qquad (38)$$

and

$$\ln\frac{A_2}{A_1} = -\frac{\omega}{c}\int_{R_0}^{R_c} (\varkappa_1 - \varkappa_2)\, ds, \qquad (39)$$

where κ_1 and κ_2 are the respective damping factors of the two waves.

It is now easy to show that using the limitations given above, $4\pi e^2 N/m\omega^2 \ll 1$ and $\omega_H/\omega \ll 1$, we obtain

$$\varkappa_2 - \varkappa_1 \sim 2\frac{\nu}{\omega}\,\frac{4\pi e^2 N}{m\omega^2}\,\frac{eH_L}{mc\omega}, \qquad (40)$$

where ν is the number of collisions in the ionosphere. Therefore, substituting (40) in (39) and using the notation of Sec. 4, we have, accurate to first-order quantities,

$$\ln\frac{A_2}{A_1} \simeq -\frac{8\pi e^3 \overline{H}_L}{m^2 c^2 \omega^3}\int_{R_0}^{R_c} \frac{NR\nu\, dR}{\sqrt{R^2 - R_0^2 \sin\varphi_0}}. \qquad (41)$$

Thus, by measuring M_0 on the oscillogram [see (37)] we can determine, from the measured amplitude-modulation frequency, the mean values of $\bar{\nu}$ over the finite intervals ΔR_C. Naturally, to obtain exact values of ν it is necessary to have a large number of observations made in a quiet ionosphere.

III. AMPLITUDE OF THE RADIO SIGNALS FROM A SATELLITE OR A ROCKET

The behavior of the amplitude of radio signals from a satellite or from a rocket at the point of observation is influenced by many factors. There are consequently numerous methods for analyzing the corresponding amplitude curves, and many properties of the ionosphere are investigated on this basis. At first glance it may seem difficult to extract new data from the analysis of the signal-amplitude recordings, owing to the combined effect of the aggregate of factors that determine the field at the point of observation. In fact, the problem to be solved by the experiment on the signal amplitude determines some feature of the recording, such as, the rate of advance of the paper or photographic film, the inertia of the indicator (recording pen, electron beam, or oscillograph loop), the bandwidth of the receiving apparatus, etc. As a result, different amplitude records have different specific features: they are simpler than the field at the reception point itself, and register only individual effects.

It goes without saying that an extensive research program calls for recordings of all types, to cover the entire range of expected or unknown phenomena. Thus, for example, the investigations of the rotational Doppler effect, described above, call for high-speed low-inertia recording, for which the use of oscillographs is desirable (see Figs. 9 and 10). Although small-scale cloud formations frequently lead to even faster, but more irregular changes in the amplitude, their investigation does not call for high-speed recording; in such experiments it is important to increase the interference rejection of the receiving apparatus, and to reduce the bandwidth in order to eliminate irregular amplitude fluctuations due to noise. When registering the effects of radio setting or radio rise of the satellite, or the tumbling of the satellite, it is preferable to use low-inertia recording at a sufficiently slow rate. This can be seen, for example, from the amplitude curve of the radio signal from the third satellite, received in Moscow (Fig. 12). This figure displays clearly two cycles in the variation of the amplitude of signals from the third satellite, with periods of 16 – 17 and 90 – 100 seconds. These can be attributed to the rotation of the satellite. Along with these, the same recording permits a clear determination of the instants of appearance and disappearance of the received radio signals, i.e., the "radio rise" and "radio setting" of the satellite.

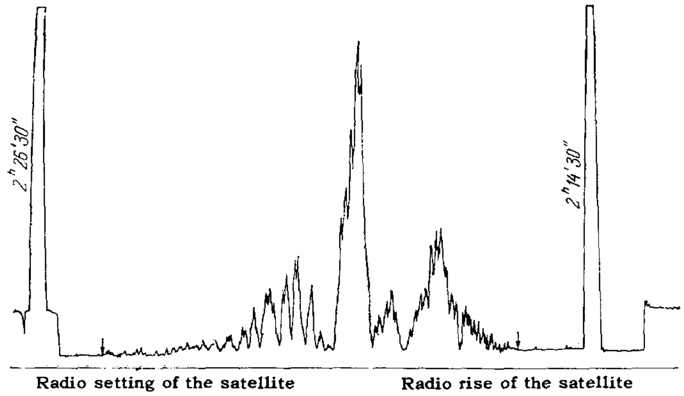


FIG. 12 Slow recording of the amplitude of a radio signal from the third satellite, obtained in Moscow with the aid of a low-inertia automatic recorder.

The results of the systematic investigations of the amplitude of satellite radio signals have not yet been reported in the literature. But even individual observations, which are sporadic in character, have yielded interesting and new results on the properties of the ionosphere[22,23] (see Sec. 7 and 9). In addition, a systematic accumulation of amplitude records, and a suitable analysis of these records will also permit a study of many effects observed in the propagation of radio waves, characterizing the global state of the ionosphere over the entire earth's sphere, and not only the local state in the vicinity of the point of observation or along the part of the orbit nearest to it.

We recall that the quasi-periodic changes in the amplitude due to the effect of the earth's magnetic field, and the data obtained from their analysis, were already considered above (see Sec. 5 and 6). Along with this, we note the importance of the analysis of the amplitude variations due to the rotation of the satellite. The corresponding data are necessary not only as auxiliary material for interpretation of all possible types of observations carried out with a satellite or a rocket, but are of independent interest. A detailed theoretical investigation of the evolution of the periods and of the direction of rotation of the satellite from the instant of its start will apparently yield data on the density and temperature of the atmosphere, as well as certain conclusions of importance in ballistics, etc. However, the results of such observations, in addition to those mentioned above, have not been reported in the literature, and we shall therefore not dwell on this question.

7. Investigations of the Inhomogeneous Structure of the Ionosphere

We have already noted that when the orbits of the satellite pass through or above inhomogeneous ionized formations, the received radio signals may be subject to phase and amplitude modulation through the action of the fluctuations of electron density on the propagated wave. A statistical analysis of the amplitude and phase of these changes makes it possible to determine distribution of the dimensions ρ_0 and of the fluctuations of the electron density $\delta N = \Delta N/N$ of the inhomogeneities. Effects of this kind are noticeable, for example, on some of the recordings presented here. The oscillogram shown in Fig. 11 was obtained in Moscow. It is similar to the oscillogram of Fig. 9 and represents slow amplitude modulation of the signals, due to the rotational Doppler effect. This photograph shows, however, along with the regular variations of the envelope, also certain faster irregular ones (outlined in the drawing). These changes are apparently due to the diffraction of the wave by small inhomogeneous formations, which were located either under or in the region where the satellite has passed. A direct and simple estimate of the dimensions of these inhomogeneities with the aid of the formula

$$\bar{\varrho}_0 \sim V\bar{T}_0, \tag{42}$$

which determines the order of magnitude of ρ_0 (T_0 is the period of the amplitude fluctuation and V is the speed of the satellite), yields for this recording and for similar ones, obtained in Moscow, a value of ρ_0 on the order of several kilometers. It is known that inhomogeneities of this kind usually cause the flickering of radio stars and are associated with the so-called sporadic F2 layer. Simultaneous observations of the amplitude of signals from an American satellite at 108 Mc/sec and of the intensity of galactic radio waves has actually established,[24] that in most cases the irregular changes in the amplitude of the satellite signals (Fig. 13) coincide with a high index of fluctuations of the intensity of the radio waves. It must also be noted that

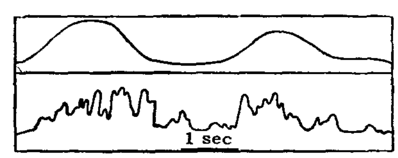


FIG. 13. Two types of recorded curves of the amplitudes of signals from an American satellite at 108 Mc/sec. The lower curve represents a case when intense flickering of galactic radio waves was observed.

the depth of the irregular amplitude changes serves as a measure of the fluctuations of the electron density of the inhomogeneities, and a theoretical processing of such recordings can be used to determine δN. In the case illustrated in Fig. 12, δN was apparently not less than one or two tenths, in agreement with analogous data on irregularities of this kind. The influence of the other part of the spectrum of small irregularities, which we know to exist near $\rho_0 \sim 300-400$ meters and are almost always present in the ionosphere, does not affect the reception of signals from the satellite, since they correspond to a value $\delta N \sim (10^{-2}$ to $10^{-3})$ and hardly diffract the wave passing through them.

Many interesting data were obtained in investigations of the amplitude of the signals of the first satellite, carried out at 40 Mc/sec in Cambridge.[23] In spite of the fact that the observations were carried out only for 12 days, from October 12 to 24, 1957, their results are diverse. In experiments carried out from the earth's surface, analogous data could be obtained only by examining a much greater amount of experimental material and performing more complicated and cumbersome measurements.

A typical recording[23] is shown in Fig. 14. At a fixed instant of time (approximately 3:20) there appear on it fast irregular changes in the amplitude, not connected either with the Faraday effect or with the rotation of the satellite. The receiver used in these experiments had a bandwidth of 120 cycles and a low noise level, while an automatic receiver-tuning device followed up the Doppler frequency shift.

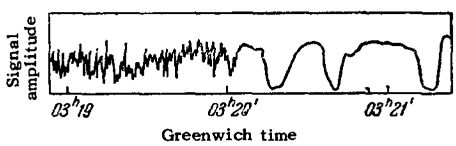


FIG. 14. Example of record of the amplitudes of signals from the first satellite, received in Cambridge at 40 Mc/sec; such recordings were used to investigate the small-scale inhomogeneity of the ionosphere, of the $F2_{spor}$ type.

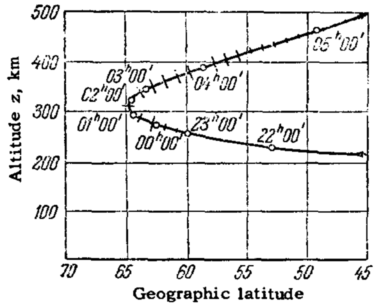


FIG. 15. Measurement of the altitude of the first satellite on October 13, 1957, as it passed over Cambridge. The hatches show the relative intensity of the fast fluctuations of the amplitude at different altitudes.

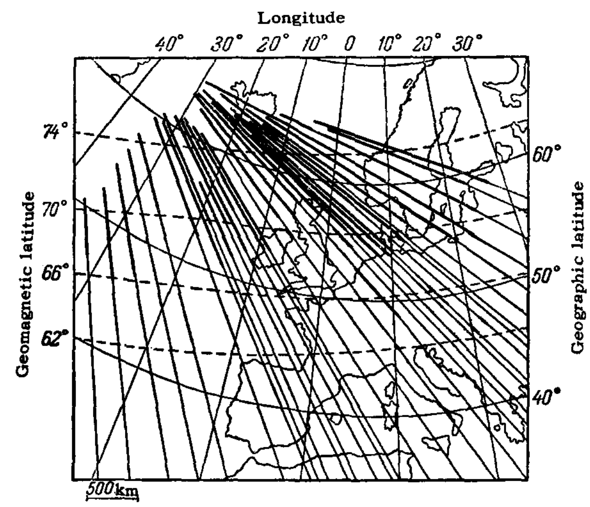


FIG. 16. The map shows the trajectories of the satellite, observed in Cambridge. The heavier parts of the lines correspond to the regions where rapid amplitude fluctuations appeared.

The data accumulated in this investigation show that the pronounced appearance of rapid amplitude fluctuations is connected not with the time, but with the passage of the satellite in a definite region of altitudes in northern latitudes. These fluctuations can be attributed to inhomogeneous formations, which occur higher than 250 — 270 km (Fig. 15). Apparently the greater part of these irregularities lies below 325 km, although this conclusion is not yet certain. In addition, no such recordings were observed when the satellite passed south of 50° northern latitude (Fig. 16). It was also established that the rate of the fading was connected in a definite manner with the course of magnetic latitude and not the geographic latitude. A detailed analysis has also shown that the regions where the inhomogeneities occur extend a thousand and sometimes several thousand kilometers along the magnetic parallel, and measure 200 — 400 km across. To determine the dimensions of the inhomogeneities themselves it is necessary to have a recording system with a much lower inertia than customarily used in the experiments (the time constant of the registering instrument was ~ 0.5 sec). However, certain records, made with a recording instrument with a time constant of 0.01 sec, have shown that the dimensions of the inhomogeneities are $\rho_0 \sim 1$ km. From a detailed comparison of the results obtained with different observations of the flickering of radio stars and of the sporadic F2 layer, the author has reached the conclusion that the inhomogeneous ionosphere formations, which cause effects characterized by the same laws, have come into play in the described experiments. The results of reference 23 are eloquent proof of the advantages of investigations of the amplitudes of satellite signals, which yield a large number of results by simple means.

8. Antipode Effect and Other Phenomena of Long-Distance Propagation of Satellite Radio Signals around the Earth

It was shown earlier that the amplitude records yield data on the ionosphere in a relatively limited region in the vicinity of the point of observation, where the satellite passes. Depending on the orbit of the satellite, the radius of this region can reach two or three thousand kilometers or more, and is determined by the radio horizon. Thus, for example, in the case shown in Fig. 11, the range of radio visibility of the satellite was on the order of 2300 km. In many cases, however, the radio signals can yield, along with local ionospheric data, information on what can be termed the global state of the ionosphere over the earth's sphere, some 8,000 or 10,000 km away from the point of observation, down to the antipodes. At the present time we cannot say how novel or precise such data will be, since there are still no systematic results of the analysis of such obervations. But even the results considered at the end of the preceding section show that

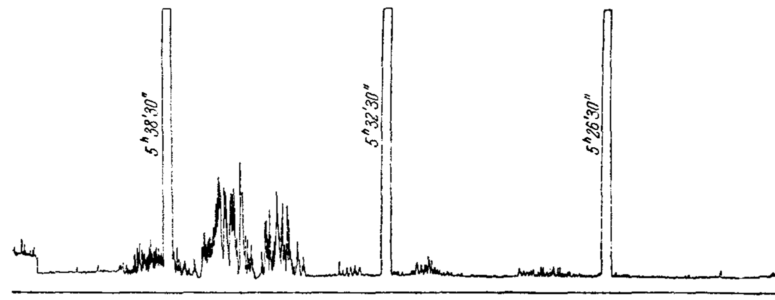


FIG. 17. Example of record of the amplitude of radio signals from the third satellite, made in Moscow, where multiple-reflection reception of radio signals from 8,000 or 10,000 km away was observed.

such experiments are quite useful for an investigation of the morphology of the ionosphere.

A great variety of methods can be used to analyze the effects that characterize the propagation of radio signals from a satellite along complicated paths. In each individual case, naturally, the analysis depends both on the character of the experimental material and on the status of the theory of the investigated phenomena. No systematic observations of this type have been made to date. We therefore confine ourselves only to an illustration of the reception of radio signals from the satellite. The interpretation of these signals calls for a knowledge of the state of the ionosphere almost along the entire orbit of the satellite.

Unlike the case illustrated in Fig. 11 where the radio signals of the satellite were observed only when its orbit passed near the point of observation, Fig. 17 shows a reception pattern which is much more complicated. First, the variation of the field immediately next to the observer was more complicated than in Fig. 11. At the same time, signals were received from 8,000 or 10,000 km away. In this case the signals were registered at discrete times in definite ranges of angles of reflection of the wave from the earth. Possible paths on which the satellite signals can propagate over such large distances are shown in Fig. 18. The same figure shows the kind of variation of electron concentration ($N_M F2$) that can ensure a multiple-reflection propagation, in which refraction results in the trajectory shown in Fig. 19, and a so-to-speak extensive "gliding" of the wave is observed in a definite region of the ionosphere.[25] Other types of wave guidance in the ionosphere are also possible. Consequently a systematization of the numerous experimental data and a detailed theoretical analysis are necessary for the interpretation of such observation results before information can be gathered from these results on the variation of the ionosphere over extended regions.

The most clearly pronounced phenomenon of long-distance propagation of radio signals from a satellite was observed when these signals were received from the antipodes. In spite of the fact that similar cases have been observed for a long time in short wave propagation, an interesting and new fact in this case is that signals from the antipodes were registered in three or four successive orbits in a row. This is evidence that

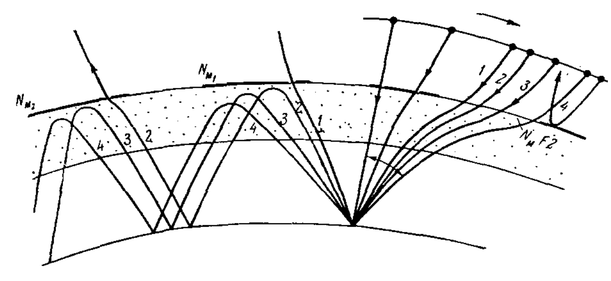


FIG. 18. Schematic representation of multiple-reflection propagation of radio signals from a satellite. The thick lines represent portions where the F2 region is opaque to the waves radiated from the satellite within a definite range of angles of incidence ($N_{M_2}F2 > N_{M_1}F2$ and $N_{M_1}F2 > N_M F2$).

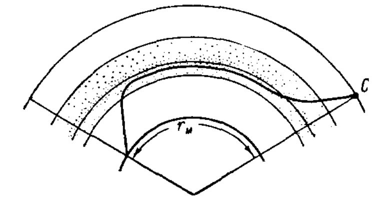


FIG. 19. Schematic representation of a "gliding" trajectory of a wave radiated by the satellite, within a definite region of the ionosphere.

conditions contributing to the "trickling" of radio signals from the satellite in the antipodes have lasted more than four or five hours.

The most interesting reception of radio signals from the first satellite from the antipodes occurred in Mirnyĭ* in the antarctic at 20 Mc/sec. Figure 20 shows a record obtained on October 6, 1959, when signals were received four times in a row from the antipodes between 12:13 and 17:10 local time. On October 7 four such signals were observed between 09:45 and 17:05, while on October 8 there were three signals between 10:43 and 13:54. It must be noted that during these days reception over 10,000 or 15,000 km and more continued even after cessation of this effect. Antipode signals from the first satellite were received also in East Germany[26] on November 6, at 40 Mc/sec at 14:40; such effects were observed in the U.S.A. on October 5, 12, and 23, 1957, at 40 Mc/sec.[27]

9. "Radio Rise" and "Radio Setting" of the Satellite

Observations of radio signals from the satellite can be used to obtain certain general data on the ionosphere,

*These observations were carried out by V. P. Rozin of the staff of the Institute of Terrestrial Magnetism and Radio Astronomy, Academy of Sciences, U.S.S.R., to whom the author is grateful for providing the data.

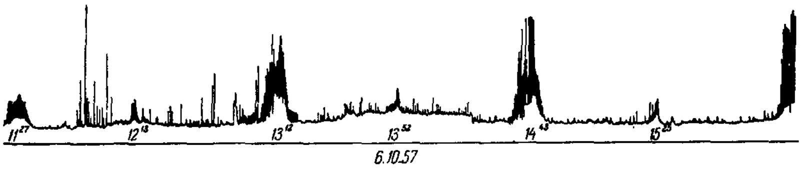


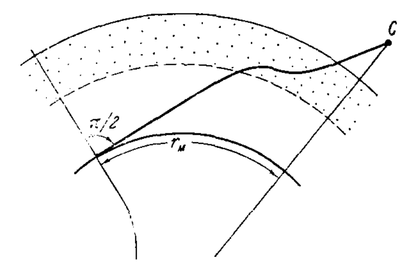
FIG. 20. Record made of the amplitudes of the signals from the first satellite, on October 6, 1957, in Mimyĭ, when signals were received from the antipodes four times in a row. The figure shows the three signals from the antipodes at 12:13, 13:52, and 15:25.

by determining from amplitude observations only the instant of appearance and vanishing of the signals. If these instants are obtained as the orbit passes over the points of observation, they determine the "radio rise" and the "radio setting" of the satellite at the frequency of the received waves.

It goes without saying that the instants of the radio rise or radio setting, which determine the maximum horizontal distance r_M, of signal reception, depend on the height of the satellite and on the character of the refraction of the wave in the ionosphere between the source and the point of observation (Fig. 21). A specified dependence of the electron concentration N on the coordinates along the route of wave propagation will determine r_M uniquely. Thus, if we know, say, the variation of N along one part of the wave trajectory, and if its functional dependence is specified on another part of the trajectory, we can determine in principle, from the value of r_M, the main parameters that characterize the latter dependence. However, such a problem is single valued only for a one-parameter one-dimensional function. We can therefore determine from the experimental values of r_M, obtained with the aid of a satellite, only the general course of the electron concentration above the principal maximum, if we know the dependence of the electron concentration below the principal maximum of N_MF2 of the ionosphere. If, for example, we represent the variation of N above the maximum with the aid of the exponential functions $N_M e^{-sz}$, which determines in an effective manner the average decrease of N, we can determine from this the value of s.

Such an analysis of the experimental data gives rise, however, to many difficulties which can lead to substantial errors in isolated experiments. The main cause of errors is that the existing network of ionospheric stations cannot determine exactly the dependence of N on the coordinates in the region where the wave passes in the lower half of the ionosphere, shown dotted in Fig. 21. The experimental data yield in a relatively simple manner only the approximate variation of N with altitude. However, the horizontal gradient dN/dx, although small compared with dN/dz, strongly influences the refraction of the wave. Along with this, the character of the trajectory is very sensitive to the extent to which the frequency of the wave is close to the maximum usable frequency. In this connection, the method given here for the determination of s can yield accurate results only after a statistical reduction of the experimental data. If the number of individual observations is large enough, it is possible to obtain the distribution of all the values of s, which are individ-

FIG. 21. Schematic representation of the trajectory of the wave radiated from the satellite during the instant of "radio rise" or "radio setting."



ually determined from $r_M(s)$ curves calculated beforehand for a specified group of initial values. Since these errors are more or less random and of different signs, it is possible to assume a priori that the most probable value of s (the maximum of the distribution curve) determines the value of s for the average conditions of the considered group of observations. The other properties of the distribution curve of s, other than its maximum, can no longer be used for any conclusions. Actually, for example, the dispersion of the obtained aggregate of values of s depends on the errors of the procedure and includes in addition the variations of the quantity s itself, but these two factors cannot be separated from each other.

This method of processing the observations of the radio rise and radio setting of the satellite was used in reference 22, where the corresponding calculations are described and tables of $r_M(s)$ are given for different parameters of the lower ionosphere (see also reference 28). The most frequently encountered value of s in reference 22, based on observations made on October 5, 6, and 7, 1957 for 20° to 45° northern latitude and for the interval from 07:40 to 09:40 Moscow time, is approximately 3.5×10^{-3} km. It characterizes the average decrease in the electron concentration above the principal maximum of N_MF2 (Fig. 22).

The results of this investigation have made it possible to establish, soon after the launching of the first satellite, that the electron concentration above the main maximum diminishes much more slowly than previously assumed. Later on these results were supplemented with other data and with experiments performed with high altitude rockets; a curve obtained in one of these experiments is plotted for comparison in Fig. 22.[5]

An attempt was also made in reference 22 to estimate the dependence of the concentration n(z) of neutral particles on the altitude in the upper part of the atmosphere from the N(z) curve. The corresponding estimates were based on the obvious assumption that when $z > 300 - 400$ km the state of the ionosphere is close to quasi-stationary and the ionization balance is described by the equation

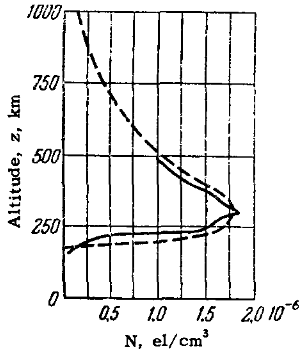


FIG. 22. Average variation of the electron concentration N(z) above the maximum of N_MF2, obtained from observations of the radio rise and radio setting of signals from the first satellite. The solid curve in the figure shows the dependence N(z) obtained with a high-altitude rocket; the radio signals from the satellite were received October 5–7, 1957, and the rocket was launched on February 21, 1958.

$$\sigma \frac{S}{\varepsilon_i} n \sim \alpha N^2, \qquad (43)$$

where S is the flux of ionizing radiation, σ the photoionization cross section, ϵ_i the energy consumed in one ionization event, and α the photo recombination coefficient. The dependence shown in Fig. 23 was obtained from the known values of S, α, and ϵ_i. It is quite interesting that all further determinations of the density of neutral particles in the indicated interval of altitudes, obtained with the aid of manometers,[44] or from data on the drag of satellites[11,12] etc[45,46] have led to results which fit the n(z) curve well. We consider this coincidence to be instructive. It not only confirms the validity of such a method of investigation of n(z), but is apparently also evidence that the methods used heretofore yielded only averaged values of the density of the atmosphere, no more accurate than those in reference 22.

IV. PLASMA PERTURBATIONS PRODUCED BY THE SATELLITE

At the present time there are no grounds for drawing any definite conclusions concerning the conditions under which various types of perturbations are produced in the vicinity of a satellite or a rocket, in the ionosphere or in the interplanetary gas.

Any specific theoretical solution of the problem of the interaction between a moving body and a plasma entails essential difficulties of both principal and computational character, and there is still no solution of any degree of completeness for this problem. Among the theoretical results of general plasma research on this topic, interest attaches to the dispersion relations for oscillations and waves in a plasma,[29] the excitation of plasma by ion and electron beams,[30,31] and the solution of several other problems of more or less methodological character. These results lead only to certain very rough estimates or predictions of phenomena expected during the motion of the satellite. We know of only one paper[32] that treats the solution of a specific problem of this kind. The results of this paper lead to several more or less definite conclusions concerning certain types of perturbations produced by satellites.

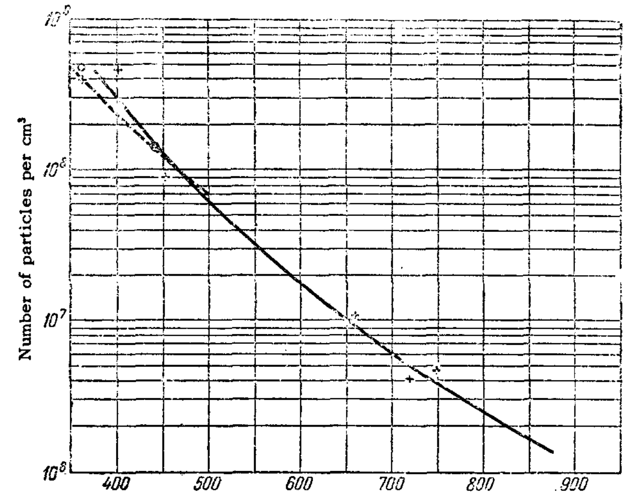


FIG. 23. Dependence of the concentration n(z) of neutral particles on the altitude, obtained from the N(z) curve shown in Fig. 22. The figure shows different results of subsequent determination of n with the aid of satellites. Satellite drag: o – Soviet and + – American researches; • – sodium cloud (high-altitude rocket) – first satellite (radio observation), – – – – – third satellite (manometers).

Nor have plasma perturbations in the vicinity of satellites been much investigated experimentally. Certain related data have been cited in the literature, but cannot be considered sufficiently reliable, and are moreover all too scanty. The known data viewed as a whole are somewhat contradictory and more in the nature of preliminary communications than of completed investigations. We therefore have no definite information concerning the experimental side of the phenomena of interest to us here.

We consider below certain theoretical and experimental data and advance certain ideas concerning a possible interpretation of the observed results. It is best, however, to make a few preliminary remarks on the effects expected in this case. In the upper atmosphere the mean free paths of the particles are usually large compared with the dimensions of a moving satellite, which interacts with the neutral molecules and atoms, with the ions, and with the free electrons. Therefore, if the velocity of the satellite is large compared with the thermal velocity of the ions and neutral particles, the concentration of these particles, as well as the concentration of the electrons is greatly modified. This causes an electric potential to appear around the satellite even if it is initially uncharged. On the other hand, the flux of the particles reflected from the body can, in principle, induce plasma oscillations.

Independently of these phenomena, supersonic motion of the satellite should cause radiation of plasma waves carried with the satellite itself, similar to Cerenkov radiation from an electron whose velocity is greater than the velocity of light in the medium. This radiation, in turn, can complicate the structure of the electric field around the satellite. Along with this, we cannot exclude the possibility of occurrence of electric fields which change in time in the reference frame fixed to the satellite, - and consequently waves that travel away from the satellite. These processes should result from instability of the stationary state of the plasma around the satellite. Phenomena of this kind can encompass a large region in the vicinity of the moving body, on the order of the particle free path.

Taking the influence of the external magnetic field into account, these phenomena can have the following characteristics. We note first that the region in which the concentrations of the ions and electrons are disturbed will be oblate, owing to the slower diffusion of the ions transversely to the field. The dimension of this region in a direction normal to the magnetic field, will therefore apparently be of the order of the Larmor radius of the ions, and consequently much shorter than the free path of the particles. Such a shape will increase substantially the effective scattering cross section of this inhomogeneous region. It must also be borne in mind that because of this instability, the body can excite oscillations not only at frequencies close to the natural plasma oscillation, but also at the gyroscopic frequencies of the ions and electrons, and can consequently cause radiation at these frequencies. The magnetic field will further complicate the character of the radiation due to the supersonic motion of the body.

In considering all these processes it is also necessary to bear in mind the influence of the radiation from the sun. This radiation induces photoemission from the body and thus changes in its potential, and produces an additional electron current, which can modify the oscillations in the vicinity of the body.

A study of these phenomena and of similar effects constitutes a large and important group of problems, which must be resolved through investigation of the ionosphere and the interplanetary gas with the aid of satellites and rockets. Confining ourselves to these remarks, we now proceed to an examination of the known theoretical and experimental data and to their analysis.

10. Disturbance to the Concentration of Particles and the Electric Field around a Satellite or a Rocket

One of the most important causes of various kinds of perturbations produced in a plasma in the vicinity of a moving body is its supersonic velocity, namely, the fulfillment of the condition

$$\sqrt{\frac{8kT}{\pi M}} \ll V \ll \sqrt{\frac{8kT}{\pi m}}\,, \tag{44}$$

where V is the velocity of the body and $\sqrt{8kT/\pi M}$ and $\sqrt{8kT/\pi m}$ are respectively the average thermal velocities of the heavy particles and of the electrons. The disturbance of the concentration of the charged particles in this region, in particular, and the consequent appearance of an electric field, are important results of this fact. The appropriate calculations have been made in reference 32, where other effects mentioned above, such as the radiation carried by the body, nonstationary phenomena leading to plasma oscillations, etc, have not been considered.

When a body moves with supersonic velocity, a region of condensation of both the neutral and charged particles is produced in front of it (in the frame fixed to the body), while a rarefaction region is produced on its rear. The question of calculating the density n of neutral particles in the condensation region is relatively simple, since collisions can be neglected in the perturbed region (the mean free path is much greater than the linear dimensions of the body) and the average thermal velocity of the particles is much less than the velocity of the body. Assuming that the collisions between the gas particles and the body are elastic and that the particles are specularly reflected, we have for a sphere of radius r_0, for example, along the direction of its motion

$$\frac{n(r,0)}{n_0} = 1 + \frac{r_0^2}{(2r-r_0)^2}\,, \tag{45}$$

where r is the distance from the center of the sphere along its velocity vector $\mathbf{V}$. We see that on the surface of the body itself the concentration of the particles has a maximum and is twice the unperturbed concentration n_0. We note that if the particle reflection is not specular but diffuse, the concentration near the body is increased much more.

Behind the body, where there is rarefaction, the character of the steady state depends on the velocity distribution of the particles in the incoming stream that fills this region. Consequently, to calculate the rarefaction region it becomes necessary to solve the kinetic problem, i.e., to investigate the equation

$$\frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{r}} - \frac{1}{M}\nabla_{\mathbf{r}} U \frac{\partial f}{\partial \mathbf{v}} = 0, \tag{46}$$

where $f(\mathbf{r}, \mathbf{v})$ is the unknown distribution function in this region, $\mathbf{v}$ is the particle velocity, and U is the potential energy of interaction between the particles and the body. Under certain reasonable limitations, a corresponding solution was obtained in reference 32, and the relationship obtained in the rarefaction region is

$$n(r,\theta) = \int f(\mathbf{r}, \mathbf{v})\, d\mathbf{v}, \tag{47}$$

where the angle θ is the polar coordinate of the point relative to the center of the sphere. Along the direction of motion, i.e., when $\mathbf{r} \parallel \mathbf{V}$

$$\frac{n(r,0)}{n_0} = \exp\left\{-\left(\frac{r_0}{r}\right)^2 \frac{MV^2}{2kT}\right\}. \tag{48}$$

Figure 24 shows the corresponding curves of equal ratio $n(\mathbf{r}, 0)/n_0$, calculated in reference 32 for $V \simeq 8\sqrt{8kT/\pi m}$.

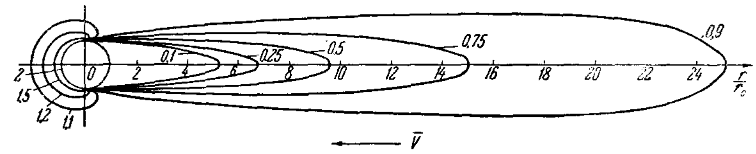


FIG. 24. Curves of equal values of the ratio of concentration of the particles in the vicinity of the satellite, $n(r, \theta)$, to the unperturbed plasma concentration, n_0. The curves are calculated for a satellite velocity $V \simeq 8\sqrt{8kT/\pi m}$.

We see that the concentration n is greatly disturbed behind the body, where it diminishes exponentially. Along the **r** axis, at a distance $5r_0$, say, we have $n(r, 0)/n_0 \sim 10^{-1}$; $n(r, 0)$ amounts to 90% of n_0 when $r \sim 25r_0$ and to 99% when $r \sim 64r_0$. It is easy to note that at large distances

$$\frac{\Delta n}{n_0} = 1 - \frac{n(r,0)}{n} \sim \frac{r_0^2}{r^2}\frac{MV^2}{2kT} \quad (49)$$

and, consequently, the disturbance to the particle concentration diminishes as the inverse square of the distance from the body.

The disturbance of the concentration of the ions and electrons, as already indicated above, leads to the appearance of an electric field, which influences the unknown perturbations of the distributions of these particles. The corresponding calculations necessitate therefore solution of the kinetic equations of the ions and electrons simultaneously with solution of the Poisson equation

$$\Delta\varphi = 4\pi e\left\{\int f_e(\mathbf{r}, \mathbf{v}_e)\, d\mathbf{v}_e - \int f_i(\mathbf{r}, \mathbf{v}_i)\, d\mathbf{v}_i\right\}, \quad (50)$$

where f_e and f_i are respectively the unknown distribution functions of the electrons and ions, while φ is the potential of the electric field.

An analysis of the corresponding system of equations, with condition (44) taken into account and under the assumption that the charged particles are elastically reflected from the body, has led[32] to the following results. It has been shown that the perturbed electron density

$$N(r, \theta) = \int f_e(\mathbf{r}, \mathbf{v}_e)\, d\mathbf{v}_e$$

is nearly equal to the perturbed ion density

$$N_i(r, \theta) = \int f_i(\mathbf{r}, \mathbf{v}_i)\, d\mathbf{v}_i$$

accurate to a term of order

$$\left(\frac{D}{r_0}\right)^2, \text{ where } D = \sqrt{\frac{kT}{4\pi Ne^2}}$$

is the Debye radius. On the other hand, the potential of the electric field

$$\varphi(r, \theta) = \frac{kT}{e}\ln\frac{N_{0i}}{N_i(r, \theta)} \quad \text{for} \quad \frac{N_i(r,\theta)}{N_{0i}} \geqslant \left(\frac{D}{r_0}\right)^2, \quad (51)$$

where the subscript "0" denotes the unperturbed value of the concentration. At closer distances, where $N_i(r, \theta)/N_{0i} < (D/r_0)^2$, we have with the same accuracy

$$\varphi = \frac{kT}{e}\ln\left(\frac{D}{r_0}\right)^2 \quad (51_1)$$

independent of r.

The equipotential lines calculated in reference 32 are shown in Fig. 25. For the ionosphere usually $D/r_0 \ll 1$, and since we have in a large region in the vicinity of the body

$$\varphi(r, 0) \leqslant \frac{10kT}{e} \sim 1\text{v}, \quad (52)$$

it can be assumed that the electric field exerts little influence on the perturbation of the ion velocities. Ultimately,

$$\frac{N(r, 0)}{N_0} \sim \frac{N_i(r, 0)}{N_{0i}} \sim \frac{n(r, 0)}{n_0}, \quad (53)$$

meaning that the relative disturbance to the concentration of the neutral particles, shown in Fig. 24, describes the relative disturbance of the concentration of the ions and of the electrons as well. If we now combine (51) and (48) we get

$$\varphi(r, 0) = \frac{MV^2}{e}\left(\frac{r_0}{r}\right)^2 \quad (54)$$

and, consequently, the potential of the field diminishes along the direction of motion of the body as the inverse square of the distance. We note here that Debye screening decreases the potential of the charged body with distance exponentially, i.e., much more rapidly.

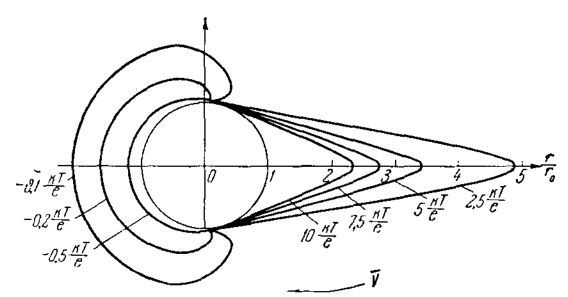


FIG. 25. Equipotential lines of the electric field around a satellite, calculated for a satellite velocity $V \simeq 8\sqrt{8kT/\pi m}$ and for a value $\ln(D/r_0) \sim 10$, characteristic of the ionosphere in a wide range of altitudes (D is the Debye radius).

The foregoing results lead to several important consequences, which are discussed later, in the analysis of the experimental data and of the possibilities of different measurements (see Secs. 12 and 13).

11. Experimental Data on the Scattering of Radio Waves by Satellite Trails; other Radio Effects

Indications concerning inhomogeneous formations, apparently observed in many cases along satellite orbits and in their vicinity, have been obtained by radio observations, essentially from data on the scattering of radio waves. One cannot exclude the possibility that analysis of other measurements made with the aid of satellites, if suitably interpreted, will enable us to glean interesting data on the same subject. In most investigations, however, not only has little attention been paid to a possibility of investigating these phenomena, but the direct need for this has been disregarded, inasmuch as the corresponding effects could serve as a source of errors and cause indeterminacy in the interpretation of the measurement results.

In many investigations in which the satellite orbit was beamed by radio waves, scattered signals were received whenever the satellite passed in the zone subtended by the transmitter and receiver antennas. On the other hand, there was no direct reception from the transmitter in these experiments, since the frequency of the radio waves exceeded the critical or maximum usable frequency of the ionosphere between the transmitter and receiver. Samples of similar records, borrowed from reference 33, are shown in Fig. 26. In these experiments, observations were made, during

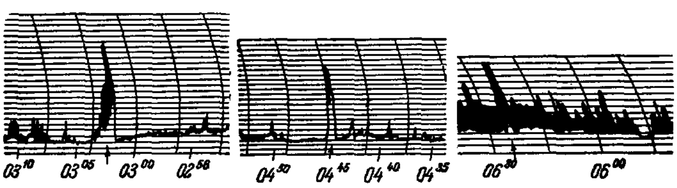


FIG. 26. Records of amplitudes of radio waves scattered from trails of the first satellite and from meteor trails. The arrows indicate signals received from satellite trails.

the passage of the first satellite, of the signal from the key radio station WWV in the 20 Mc/sec band at a distance $r \sim 550$ km, and the amplitudes of the received waves were recorded. The signals identified on the figure by arrows were observed over several times tens of seconds during the passage of the satellite, i.e., along a large portion of its visible orbit. The small amplitude deviations noted on the recording were due to reflections from meteor trails. On one of the records, in spite of the intense background of reflection from meteor tracks, the passage of the satellite was marked by a noticeable amplitude burst of the received waves. These observations were carried out in the U.S. at the Ohio State University during the passage of the first and second Soviet satellites and of the American satellites Explorer I and III.[34]

The altitudes at which these effects were observed reached 800 km according to the data with the Soviet satellites, and 600 km according to the Explorer data. From the intensity of the received signals, scattered by the trail of the first satellite as it passed at an altitude of 300 — 350 km, the authors obtained for the effective cross section of the trail $\sigma_S \sim 600\ m^2$! So large a value of σ_S should be evidence of a reliably observed and stable phenomenon. This is also the impression gained from reference 33 and 34. It is therefore somewhat surprising, that at the University of Illinois, where analogous observations were made of signals from the same station WWV, no scattering from satellite trails was observed.[35] The extent to which these results of the American researchers are contradictory remains unclear. Possible causes of attenuation of scattering from the satellite trail will be indicated in the next section. However, independently of this, reference 35 also disagrees with the latest paper by other American researchers,[38] who, apparently, observed regularly the scattering of radio waves from the trails of the third satellite and of Discoverer 1 at frequencies of 10 — 15 Mc/sec and higher. They noted that the Doppler shift of the frequency of the received scattered radio waves varied from 0 to 200 cps, thus adding to the reliability of these results. These investigations were apparently sufficiently systematic and the authors promise to describe them in detail. It is also reported in a note by French investigators[37] that noticeable scattering of 25-Mc/sec radio waves from satellite trails was observed several times at altitudes on the order of 250 and 500 km, lasting 100 — 300 and 30 — 35 seconds respectively (see also communication by Kraus et al.[49]).

Scattering of radio signals from the first and second satellites, and also from the carrier rocket of the first satellite, was investigated also in England with the aid of the large Jodrell Bank radio telescope. This telescope was specially converted into a radar receiver for these experiments. In one series of experiments, from October 1 to December 1, 1957, observations were carried out at 36 and 120 Mc/sec on the first satellite and its carrier rocket, while in the second series the frequencies were 36 and 100 Mc/sec and the second satellite was observed.[36] The experimenters traced especially the last orbits of the satellites at altitudes of 190 — 220 km in order to detect, in the authors' words, phenomena analogous to meteor ionization. The authors indicate that the intensity of scattering was approximately the same at all altitudes, and conclude that the sought effects were not observed. At the same time, the quantitative data given in reference 36 lead to the opposite conclusion. The effective cross section σ for scattering from the carrier rocket of the first and second satellites varied, according to their data, from 10 to 500 m^2 at 36 Mc/sec and was of the order of 10 or 15 m^2 at 100 — 120 Mc/sec. Inasmuch as the linear dimensions of these bodies were sufficiently large, their effective cross sections σ were also large and could exceed the corresponding values of σ_S of the inhomogeneous formations at these frequencies (see Sec. 12). The results obtained can therefore be attributed, as by the authors, to scattering from the carrier rocket and second satellite themselves. However, at 36 and 120 Mc/sec, the effective scattering cross section of the first satellite was found to be $\sigma_S \sim 0.4$ m^2. The first satellite was a sphere 29 cm in radius, and assuming that its antenna structure did not noticeably influence the scattering, it can be readily shown that $\sigma \sim 0.41$ m^2 at 120 Mc/sec. At 36 Mc/sec, however, a metal sphere of the same dimension has $\sigma \sim 0.03$ m^2, which is approximately 13 or 14 times less than the measured value of σ_S. It is thus necessary to explain why a value $\sigma_S \sim 0.4$ m^2 is obtained at 36 Mc/sec. It can be shown, however (see Sec. 12), that if the effective scattering cross section due to inhomogeneous plasma formations in the vicinity of the satellite is $\sigma_S \sim 0.4$ m^2 at 36 Mc/sec, the cross section σ_S of this formation is smaller at 120 Mc/sec than the value of σ of the first satellite itself. Thus, the results of the experiments of the British observers lead to a conclusion opposite to the one they have drawn, and do not exclude the assumption that they actually observed an inhomogeneous ionized formation surrounding the first satellite, but that there was no meteor trail, i.e., the cloud of additional ionization, which they sought, did not exist. Only further investigations of this kind will yield more reliable conclusions on this question.

To conclude this section, we point out two brief communications which possibly indicate the presence of plasma oscillations near the satellite. The gist of the results of one communication is as follows:[39] as the satellite approaches the point of observation, the amplitude of the radio signals from the satellite changes irregularly (see Fig. 27a) at the point of observation.

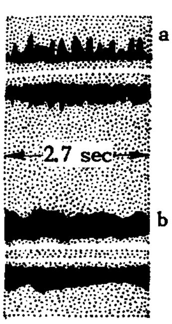


FIG. 27. Record of the amplitude of radio signals from the first satellite: a) Approach towards the point of observation, b) After passing through the point of minimum distance from the point of observation.

Approximately one minute prior to passage through the point of minimum distance between the satellite and the point of observation, the irregular changes in the amplitude vanish and the variation of the amplitude remains smooth until the satellite sets (Fig. 27b), if we disregard the changes due to the rotation of the satellite itself. Such a pattern in the variation of the radio-signal amplitude could be attributed to an irregular inhomogeneous formation which the satellite carries in front of it.

The second communication[40] states very briefly that weak radiation from the region surrounding the satellite was received from the part of the orbit of the third satellite exposed to the sun (the author does not mention the frequency of these oscillations), and that this radiation experienced a Doppler frequency shift with the motion of the satellite. The extent to which the results cited in the two communications are reliable, and whether they confirm the presumed excitation of the effects surrounding the satellite, as noted at the beginning of this section, is still unclear.

12. Analysis of the Experimental Data on the Scattering of Radio Waves

It is easy to show that the use of fairly simple modern radio equipment can ensure reception of 10 — 25 Mc/sec waves scattered by an inhomogeneous formation, provided its effective scattering cross section σ_S is on the order of 50 — 100 m^2. Actually, it is easy to obtain an antenna gain $G \sim 10$ at a wavelength $\lambda = 15$ m. Therefore, if $\sigma_S = 100$ m^2 and the power radiated by the transmitter is $W_0 \sim 10^5$ watts, then the energy of the waves scattered by the inhomogeneity and received at a distance $R \sim 500$ km, is

$$W_s = \frac{G^2\sigma_s\lambda^2}{(4\pi)^3R^4}W_0 \sim 3\cdot10^{-15}\text{watt}, \tag{55}$$

and frequently exceeds the level of the internal noise of the receiver and the background of radiation from the galaxy and from the sun.

What kind of inhomogeneities in the ionosphere can have an effective scattering cross section σ_S of the order indicated above? Let us make suitable estimates for the backward scattering, assuming that the electric vectors of the incident and scattered waves are normal to the direction of propagation. We first consider a homogeneous sphere of radius ρ_0, in which the electron concentration differs from the electron concentration N of the plasma by an amount $\Delta N \ll N$, with

$$\Delta\varepsilon = \frac{4\pi e^2}{m\omega^4}\Delta N \ll 1. \tag{56}$$

It is easy to show[41] that for such a sphere

$$\sigma_s(\pi) = \frac{4\pi^3e^4\varrho_0^2}{m^2\omega^4}\Delta N^2 \simeq 8\cdot10^{18}\frac{\varrho_0^2\Delta N^2}{\omega^4}. \tag{57}$$

Therefore if the value of ρ_0 is of the same order of magnitude as the electron mean free path L, then at an altitude $z \sim 500$ or 600 km, where $L \sim (3 \text{ to } 4) \times 10^4$ cm at $f \sim 15$ Mc/sec, the effective cross section $\sigma_S(\pi) \sim 100$ m^2 if $\Delta N \sim 10^5$ electrons/cm^3. Since the concentration in this region of the ionosphere is $N \sim (4 \text{ to } 10) \times 10^5$ under different conditions, a relative change $\Delta N/N \leq 0.1$ to 0.2 is already sufficient to permit noticeable scattering of the radio wave from the dielectric sphere.

However, a sphere with a sharp boundary cannot exist long in the ionosphere, because of diffusion. Therefore the estimate made here for a homogeneous sphere is unrealistic. If we assume, on the other hand, that the spherically-symmetrical electron cloud has a distribution $\Delta N \exp[-(\rho/\rho_0)^2]$, which describes well the diffusion of the boundary, then

$$\sigma_s(\pi) \simeq \frac{4\pi^4 e^4 \varrho_0^6}{m^2 c^4} \Delta N^2 \exp\left\{-\left(\frac{2\pi\varrho_0}{\lambda}\right)^2\right\} \quad (58)$$

and $\sigma_S(\pi)$ becomes negligibly small for the values of ρ_0, λ, and ΔN indicated above. The diffusion of the boundary of inhomogeneities of different shapes would lead to an analogous reduction in the scattering. Consequently the observed experimental facts can be explained only if inhomogeneities with sharp boundaries are excited in the vicinity of the satellite.

We have already indicated that the slow diffusion in a direction transverse to the earth's magnetic field should cause the inhomogeneous electron formation in the vicinity of satellites to have apparently a linear dimension close to the value of the Larmor radius ρ_H of the rotation of the ions, while the length should be commensurate with the mean free path L of the electrons. In the foregoing example, at an altitude z $\sim$ 500 to 600 km, $\rho_H \sim 4 \times 10^2$ cm is considerably less than L $\sim$ 3 to 4×10^4 cm, consequently the inhomogeneity will have a sharp boundary. The scattering on such a formation can be estimated by considering it to be a cylinder of radius ρ_H and length L.

A cylindrical electrical inhomogeneity has an effective backward scattering cross section, given, if condition (56) is satisfied, by the formula

$$\sigma_s(\pi) = \frac{\pi^2}{4} \frac{L^2 \varrho_H^2}{\lambda^2} J_1^2\left(\frac{4\pi\varrho_0}{\lambda}\right) \Delta\varepsilon^2, \quad (59)$$

where J_1 is the first-order Bessel function, and $\Delta\epsilon = (4\pi e^2/m\omega^2)\Delta N^2$ for the ionosphere. For the foregoing values of the different parameters, Eq. (59) gives for the maximum of J_1 a value $\sigma_S \sim 10$ m^2 at $\Delta N \sim 10^5$ electrons/cm^3. Thus, an electron cloud of cylindrical form will noticeably scatter radio waves with f $\sim$ 15 Mcs/sec if the relative disturbance to the electron concentration of the ionosphere is $\Delta N/N \sim 0.1$. According to the data given in Sec. 10, we can now show that in the rarefied region behind the satellite the average value of $\Delta N/N$, for a region of length L $\sim$ (3 to 4) $\times 10^4$ cm, is 10^{-1} to 7×10^{-2}. Considering that this region has a thickness ρ_H, we see that the scattering by this formation can explain the experimental data discussed in the preceding section.

It is more natural to assume that the actual rarefaction region is closer in shape to an oblate cone. Along the direction of the H vector, it extends, as already indicated, over the electron free path, while in the two directions mutually perpendicular to it it has a cross section $\rho_H \times \sqrt{\frac{8kT}{\pi M}} \cdot \frac{L}{V}$, where $\sqrt{\frac{8kT}{\pi M}} \cdot \frac{L}{V} \gg \rho_H$. Therefore the effective scattering cross section can vary substantially, depending on the orientation of this region relative to the observer. If the scattering is from the thin face of the inhomogeneous formation, then σ_S, for example, will decrease in the foregoing example to less than a tenth. This may explain the experimental facts, which indicate great variations of σ_S, and also the many cases in which there was no scattering from the satellite trail.

It also follows from Eq. (59), which comes apparently closer to explaining the experimental data, that $\sigma_S \sim 1/\omega^2$, i.e., it diminishes rather rapidly with increasing frequency. It is therefore quite clear that in the experiments carried out in England, the expected scattering from the satellite trails should have decreased by at least a factor of ten on going from 36 to 120 Mc/sec. Therefore, if the scattering at 36 Mc/sec was essentially from the satellite trail, with an experimentally-determined effective cross section $\sigma_S \sim 0.4$ m^2, then the trail would have at a cross section $\sigma_S \sim 0.04$ m^2 at 120 Mc/sec, much less than the effective scattering cross section σ of the first satellite itself, regarded as a metal sphere. Consequently, the scattering effects observed in these experiments at the two frequencies could apparently differ greatly from each other. It follows from (59) that, at 36 Mc/sec, $\sigma_S \sim 0.4$ m^2 if $\Delta N/N \sim 0.1$. We have seen that such deviations of the electron concentration can occur in the rarefied region of the satellite if the total disturbance ΔN, caused by the satellite in the ionosphere, is uniformly distributed over a cylinder of radius ρ_H and length L.

Thus, the present status of the theory and experiment, for all the scarcity of data, gives grounds for assuming that the electron concentration of the plasma is considerably perturbed in the vicinity of the satellite. There are still not enough data to draw any conclusions regarding the magnitudes of the other effects.

13. Feasibility of Measurements by means of Various Probes

The plasma perturbations in the vicinity of the satellite, considered in the previous sections, must naturally be taken into account when setting up and analyzing experimental researches on the ionosphere with the aid of various probes, i.e., instruments that measure the unknown parameters of the medium in the direct vicinity of the satellite. Thus, for example, it is seen from (46) — (48), in Sec. 10, that immediately near the surface of a spherical satellite, in the direction of its motion, the particle concentration more than doubles on one side, and it decreases by a factor of five or ten on the other, provided the satellite velocity is eight times greater than the ion velocity. What will actually be determined by any probe located on a satellite to measure the concentration of particles? We can answer this question conclusively only if we know the nature of the processes around the satellite and its autonomous motion. Difficulties of the same kind arise when measuring the electric potential in the vicinity of the satellite. The electric potential of the field in front of the satellite near the satellite surface, is only a certain fraction of kT/e, whereas it follows from (54) that when $r \sim r_0$ the potential is $\varphi \sim 10$ kT/e, i.e., it reaches 1 or 1.5 volts.

Thus, probe measurements are greatly influenced by the effects produced when the satellite interacts with the plasma, and the results of reduction of such measurements may be erroneous or may be in the nature of averages of sorts, unless the role of these effects is accounted for in the analysis. Naturally, the farther away probes are from the satellite surface, the smaller this influence. However, behind the satellite, even at two or three radii away from its surface, the rarefaction, as we have seen, is still very large and the particle concentration is 0.1 of normal. It is possible that these factors explain the remarkable agreement, already noted in Sec. 9, between the different values of particle concentration, obtained under different conditions by different methods. Apparently the measurement results were somehow smoothed out and averaged in all the experiments.

Does this mean that investigations of a plasma with the aid of probes placed on a satellite or a rocket are so difficult to interpret that they are hopeless? Such a conclusion would naturally be quite incorrect. These remarks indicate only the need for a cautious approach to the interpretation of the corresponding experimental results and for a change in the approach to such measurements. To the contrary, there are various methods not only of accounting for the perturbing interaction between the satellite of the medium, but also of using the satellite for various measurements. We wish to point out here one such possibility.

Naturally, when carrying out suitable measurements on satellites which are oriented in space, correct reduction of the experimental data will necessitate merely the use of suitable theoretical formulas, which establish the functional dependence of the measured quantity on the position of the instrument in the satellite frame of reference. If, on the other hand, the satellite rotates relative to its orbit, these difficulties can be avoided, for example, by making simultaneous similar measurements at different distances from its surface, along a single direction — in the case of a spherical satellite, along its radius. Actually, the law of variation of the different quantities with the distance from the center of the satellite establishes a definite connection between this distance and the parameters of the undisturbed medium. Thus, if the indicators are located along the satellite orbit, the perturbed density of the ions behind the satellite, at two distances r_1 and r_2 from its center, are connected by the relation [see (48)]

$$\ln \frac{N_i(r_1, \theta)}{N_i(r_2, \theta)} = \left(\frac{1}{r_2^2} - \frac{1}{r_1^2}\right) \frac{r_0^2 V^2}{2} \frac{M}{T}, \tag{60}$$

Therefore, if the ratio $N_i(r_1, \theta)/N_i(r_2, \theta)$ is measured, we can determine directly the ratio M/T and, given the average ion mass, the temperature of the medium!

This prospect is in itself very attractive, because of the great difficulty of measuring the temperature in the upper atmosphere. However, in such an experiment it is also possible to determine directly the mass M. It follows thus (54) that the difference of potentials at two distances from the surface of the body along its orbit

$$\varphi(r_1, \theta) - \varphi(r_2, \theta) = \left(\frac{1}{r_1^2} - \frac{1}{r_2^2}\right) \frac{V^2}{2e} M \tag{61}$$

is directly proportional to M. The most difficult to extract from such measurements is the unperturbed value of the particle concentration; for this it is necessary to reduce the experimental data with the aid of complicated theoretical formulas, which relate the quantity $N_i(r, \theta)/N_{i0}$, the distance r, and the angle θ. But even this problem can be solved.

To conclude this section, let us note the following. The foregoing remarks, naturally, do not pretend to be complete, and merely emphasize, firstly, the role of only some of the indicated effects, which are in themselves significant, and secondly, the need for taking them into account when the ionosphere and the interplanetary gas are investigated by means of satellites. These processes are by far not all the phenomena that can occur in this field, which taken as a whole will complicate the general picture even more. Certain phenomena of this kind have been considered in reference 42 and noted in references 43 — 44. However, the regions where some effects are most pronounced while others play an insignificant role will apparently be determined after a further theoretical and experimental investigation of these phenomena. This will make possible a more complete and correct utilization of the results of the corresponding experiments, and in particular, the considerations indicated above.

V. CONCLUSION

In the present article we have considered different methods, mostly electronic, of investigating the electromagnetic properties of the ionosphere and interplanetary gas with the aid of artificial satellites and space rockets. Special attention was paid to the interaction between moving bodies and plasma, an interaction whose role has not yet been given its due consideration. In discussing these questions, we have referred in this article to most of the directly-pertinent experimental data described in the literature. Some of the papers are cited. The author did not intend to discuss all possible research methods and to cover all the problems that pertain to the problems considered here. Nevertheless, the summary of the discussed questions leads to the following brief general conclusions.

There is no longer any doubt that different radio-engineering methods will permit an all-out investigation of the physical character of many phenomena in the ionosphere and interplanetary gas, and will also yield data on the morphology of the ionosphere, and its variation with latitude, longitude, and time. This is confirmed by the results of different experiments. It will be necessary in future researches, however, to set up the experiments in a more precise manner, to accumulate systematically more experimental data, and to subject them to a deeper theoretical analysis. We cannot visualize a situation wherein any new results will be obtained with the aid of satellites and rockets without more serious and greater scientific efforts.

A certain routine has crept into the choice of the corresponding experimental methods. These methods are based essentially on ordinary laboratory measurements under terrestrial conditions. There are natural reasons for this, since many physical processes that take place in plasma, particularly under the influence of a body moving in it, have been little investigated. Further development of methods for investigating the ionosphere and interplanetary gas will follow the path of utilizing the phenomena that takes place in a "plasma" laboratory surrounding the satellite or rocket directly. A study of these phenomena is also of general physical interest, as a means of investigating the plasma itself, independent of different geophysical or cosmophysical problems.

It is necessary to analyze more cautiously the results of the researches obtained on satellites with the aid of different probes. It must be remembered here that corrections, which sometimes are quite considerable, must be introduced to account for effects that occur in the plasma region perturbed by the satellite. Further researches of this kind are best carried out on the basis of known or theoretically predicted laws and on the basis of the feasibility of various experiments, as deduced on such a basis.

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