A. V. Gurevich and E. E. Tsedilina, Theoretical Investigation of Ultralong-range Propagation of Short Radio Waves. Ultralong-range and especially around-the-world propagation of short radio waves is of interest both for ground radio communications and for communications with rockets and satellites. We know that in radio propagation in its interlayer waveguide, the ionosphere is capable of stopping frequencies above the maximum usable frequency (MUF). The use of these frequencies is a highly important practical problem.

When a radio wave propagates over ultralong distances, it passes simultaneously through strongly differing regions of the ionosphere, e.g., its daytime and nighttime sides or equatorial, middle-latitude, and polar zones. In an analytic analysis, therefore, it is necessary to take account of the regular horizontal variability of the ionosphere along the ray path, i.e., to consider a model of the ionosphere that is inhomogeneous in three dimensions. Also of great importance are absorption and scattering of the radio waves both during propagation and at their entrance into and exit from the ionospheric ducts.

Since the properties of the ionosphere vary comparatively slowly in the horizontal direction, the adiabatic invariant I of the ray, which is the approximate integral of motion of the equation of geometrical optics, is preserved [1]. The FE interlayer duct of the ionosphere has a special advantage for ultralong-range propagation. Having been trapped in the FE duct, the wave propagates through it at a small value of the invariant I_0 and therefore has the best chance of passing through the night zone, where the duct volume is smaller than anywhere else on the path. Further, absorption in the FE duct is weaker than in the F duct above it, especially for nearly glancing paths [2].

The adiabatic-invariant method has been used to investigate the global properties of long-range propagation [3]. A model numerical experiment was carried out on three-dimensional analytic models of the ionospheric electron-density distribution and the effective electron-collision frequency, which were constructed for quiet equinoctial conditions at the solar activity minimum [4]. The calculated results showed that the maximum usable frequencies of around-the-world signals (MUFAWS), which are determined by the transit across the nighttime middle-latitude zone, are of the order of 20—22 MHz, i.e., 10—14 MHz higher than the night-zone MUF. There is a rather extensive (basically daytime) region of existence of ducts at frequencies much higher than the MUF F_{max}—up to frequencies on the order of 45—50 MHz. The capture and output of energy by the interlayer duct are quite high during the daytime hours. The maximum probability of capture should be observed during the daytime hours at middle latitudes. Study of the azimuthal directions in which around-the-clock ducts exist has shown that the preferred directions are latitudinal for middle-latitude stations. The frequency and time range of capture corresponds for the most part to experimental observations. However, it is narrower than that observed experimentally [5]. It appears that scattering of the radio waves on small-scale ionospheric inhomogeneities is an important factor here, and allowance for these inhomogeneities makes it possible to explain the observed frequency and time range of the around-the-world signals [6] (Fig. 1). The absorbing property of ionospheric waveguide ducts was investigated in [7]. This study showed that for a radiator in middle latitudes, signals propagating in near-latitudinal directions are absorbed least because absorption is minimal during the day in middle latitudes. The azimuthal dependence of absorption has two minima, one of which corresponds to the well-known Fenwick theorem [5] of the optimum azimuths of minimum absorption β_{min}, while the other corresponds to the middle-latitude direction of minimum absorption (Fig. 2).

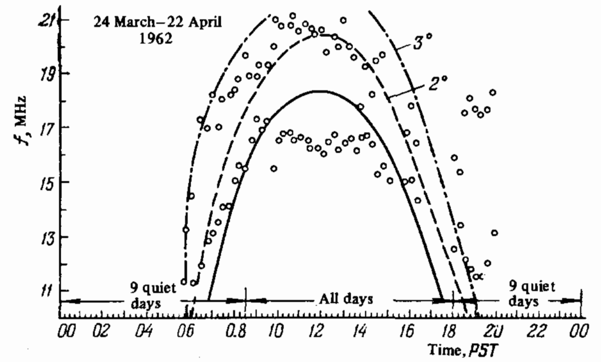

FIG. 1. Comparison of experimental (plotted points) and theoretical (curves) MUFAWS according to AWS observations at Stanford in March-April 1962. The dashed curve was calculated with consideration of 2° scattering of the ray in the duct, the dot-dash curve for 3° scattering, and the solid curve without consideration of scattering. The circles indicate the experimentally measured MUFAWS values.

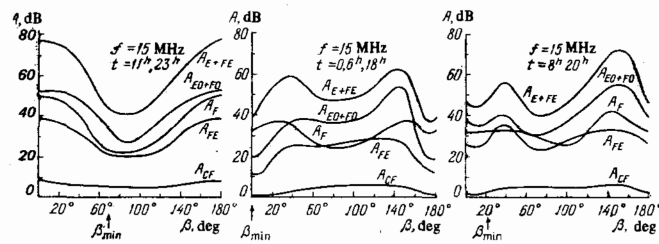

FIG. 2. Azimuth dependence of absorption at frequency f = 15 MHz for a station at latitude $\theta = 38°$. Local times are indicated on the figure. The optimum azimuths β_{min} are indicated at the bottom.

Analysis of the problem of excitation of the ionospheric waveguide duct indicates that capture as a result of the regular horizontal variability of the ionosphere is energywise favored. In this case, the trapped power is 10^{-1} to 10^{-2} of the radiated power under optimum conditions. The power trapped by scattering effects is 10^{-2}—10^{-5}, and by wave effects 10^{-4}—10^{-5}.

The trapping of radio waves in the ionospheric waveguide duct may be strongly influenced by nonlinear effects [1]. Under exposure to powerful radio emission [8], the ionospheric plasma stratifies in the region of the F layer, and this leads to the appearance of inhomogeneities that are strongly elongated along the earth's magnetic field and have a broad transverse-size

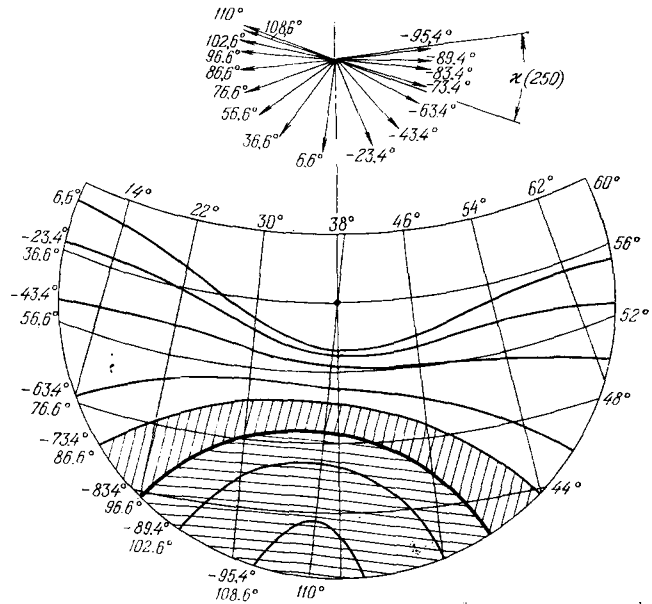

FIG. 3. Curves on which the specular radiation cone intersects the earth's surface for capture of radio waves in the ionospheric wavequide duct in the directions indicated on the figure. Height of scattering region $h_0 = 250$ km, its coordinates $\lambda = 38°$, $\theta = 56°$.

spectrum from 1 m to 1 km. These inhomogeneities reflect radio emission incident on them at frequencies 10 to 80 MHz in accordance with the law of specular scattering[9]. This phenomenon can be used effectively to excite the interlayer waveguide duct[10]. Figure 3 shows the regions of radiation and possible reception of around-the-world signals on the earth in the presence of nonlinear stratification at a height $h_0 = 250$ km. On the curve for $\beta = 96.6°$, which is formed by the intersection of the plane perpendicular to the magnetic field at the center of the scattering region with the surface of the earth, we may expect the appearance of around-the-world signals trapped at and incoming from the directions $\beta_1 = 96.6°$ and $\beta_2 = -83.4°$, with either a spaced receiver and transmitter or with these units in the same emplacement. The regions to the north and south of this curve can be used only to radiate energy with the purpose of getting it trapped in the interlayer duct in the capture directions indicated at the ends of the curves or to receive it after around-the-world propagation and exit from the duct, respectively.

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