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Rocket Measurements of Electron Concentration in the Ionosphere Using an Ultrashort-Wave Dispersion Interferometer

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The principal source of modern information about the ionosphere is research carried out by means of radio waves. The methods of such research may be divided into three groups: 1) studies using radio waves reflected from the ionosphere and emitted by ground-based transmitters; 2) the study of radio emission passing through the ionosphere (from extraterrestrial sources—the Sun, radio stars, and in lunar radar); 3) the study of radiation from sources moving within the ionosphere itself (rockets, artificial Earth satellites).

Until recently, the available data on the ionosphere had been obtained mainly by methods of the first group, especially by the method of pulse radio sounding of the ionosphere. However, the study of signals reflected from the ionosphere cannot, in principle, solve the problem of determining the distribution of electron concentration over the entire vertical section of the atmosphere, since by this method it is impossible to investigate fully the extensive regions of the ionosphere in which the ionization density decreases with height or does not exceed the ionization density in the underlying regions. Indeed, if analysis of the group delay of radio-wave pulses of different frequencies reflected from the F layer permits some conclusions to be drawn about the electron concentration in the region lying above the ionization maximum of the so-called E layer, then the region located above the maximum of the uppermost of the layers observed by means of reflected radio waves cannot in general be studied by this method.

When the ionosphere is studied by observing radio emission from extraterrestrial sources that has passed through the entire thickness of the Earth' s atmosphere, it is possible to determine the integral concentration of electrons in the whole vertical column of air. By comparing these data with observations from ionospheric stations, some conclusions can be drawn about the electron concentration in regions of the ionosphere lying above the maxima of the ionospheric

Fig. 1

Figure 1: Fig. 1

layers; however, this method does not make it possible to obtain data on the true distribution of electron concentration with height in all its details.

Thus, data on the distribution of electron concentration over the entire vertical section of the atmosphere cannot be obtained by the methods of the first and second groups. This problem can be solved by radio methods only on the condition that the sources of radio-wave radiation, with frequencies exceeding the critical frequencies of the ionospheric layers, move in height within the ionosphere itself; moreover, it is important that the vertical displacements of the radiation sources substantially exceed their horizontal displacements. The latter condition is well fulfilled in vertical launches of high-altitude rockets.

In recent years a number of materials have been published on measurements of electron concentration in the ionosphere carried out in the USA with the aid of rockets ($^{1-6}$).

Most of these measurements pertain to regions up to 200 km ($^{1-5}$), and only one of them (^{6}) was carried out up to an altitude of 380 km. The purpose of the present note is to report some results of measurements of the altitude distribution of electron concentration in the ionosphere, carried out during launches of high-altitude geophysical rockets of the Academy of Sciences of the USSR in 1954–1958, including during the launch on 21 February 1958 of a geophysical rocket that reached an altitude of 473 km. The determination of electron concentration was based on measurements of the dispersion of radio waves emitted from the rocket, performed by the method of the dispersion interferometer proposed by L. I. Mandelstam and N. D. Papaleksi (^{7}).

Fig. 1. *a* –sample record of the displacements of characteristic points of Lissajous curves; *b* –sample record of the interference frequency by a loop oscillograph

The experiments were arranged as follows: radio transmitters emitting coherent radio waves in the ultrashort-wave range with frequencies f_1 and $f_2 = pf_1$ were installed on a rocket launched at a small angle to the vertical. During the flight, the radio waves emitted from the rocket were received at two points on the Earth, and the phase differences and levels of the received oscillations were continuously recorded. At the same time, the rocket coordinates were measured by optical and radio-engineering methods, and radio sounding of the ionosphere was also carried out by means of a panoramic ionospheric station located near the rocket launch site. To increase the phase sensitivity of the receiving phasemeter devices, successive frequency multiplication and heterodyning of the received signals were used in them. The phase difference was recorded by two methods: by continuous photographing of the characteristic points of the Lissajous figure from the cathode-ray oscillograph screen (^{8}), and by recording on a loop oscillograph the oscillations of the interference frequency formed after detection of the sum of both received signals (in the latter case the signal with frequency f_1 was first multiplied in frequency by p times more than the signal with frequency f_2). Samples of the two types of phase-difference records are shown in Fig. 1.

The measurement results given below refer to experiments in which $f_1 = 48 \cdot 10^6$ Hz, $f_2 = 144 \cdot 10^6$ Hz ($p = 3$). For radio waves with such frequencies the refractive index in the ionosphere n_f was taken to be independent of the electron collision frequency and of the Earth' s magnetic field and to differ little from unity, i.e., it was assumed that

$$n_f \approx 1 - \frac{Ne^2}{2\pi m f^2}, \tag{1}$$

where N is the effective electron concentration (in cm^{-3}); e and m are the charge and mass of the electron; f is the frequency (in hertz).

At the receiving point the phase difference of the two received radio waves due to their dispersion (referred to the higher frequency) is equal to

$$\Phi = \frac{2\pi p f_1}{c} \int_0^L \left(n_{pf_1} - n_{f_1}\right) dl; \tag{2}$$

the integration is carried out along the path from the transmitting to the receiving antennas, $c = 3 \cdot 10^{10}$ cm/sec.

The change in Φ when L changes from L to $L + \Delta L$ (taking (1) into account) is

$$\Delta\Phi = \frac{e^2}{mcf_1} \left(\frac{p^2 - 1}{p}\right) \int_L^{L+\Delta L} N\, dl, \tag{3}$$

and the mean value of N along the path ΔL is

$$N_{\text{av}} = \frac{1}{\Delta L} \int_L^{L+\Delta L} N\, dl = \frac{cmf_1}{e^2} \frac{p}{p^2 - 1} \frac{\Delta\Phi}{\Delta L}. \tag{4}$$

In this it was assumed that during the time in which L changes by the amount ΔL, the quantity $\int_0^L N\, dl$ does not change. The differences between ΔL and ΔH –the increment of height above the Earth–were taken into account in processing the measurement results.

All rocket launches mentioned below were carried out in the middle latitudes of the European part of the USSR; the time is everywhere given as local time. In constructing the graphs (Figs. 2, 3, and 4), data obtained only on the ascending portions of the rocket trajectories (i.e., during ascent) were used.

Fig. 2

Figure 2: Fig. 2

Graphs $N = f(H)$

Figure 3: Graphs $N = f(H)$

Fig. 2. Distribution of the effective electron concentration with height, $N = f(H)$, obtained during the launch of the USSR Academy of Sciences rocket on 26 VI 1954 at 17 hr 24 min.

The graph in Fig. 4 was constructed from preliminary processing of the measurement results, averaged over large height intervals. During the experiment of 21 II 1958, an additional recording was made of the phase difference of the received radio waves with frequency $144 \cdot 10^6$ Hz and coherent radio waves with frequency $24 \cdot 10^6$ Hz (also emitted from the rocket). The rotation of the plane of polarization of all received radio waves, caused by the magneto-ionic splitting of them in the ionosphere, was recorded. The detailed distribution $N = f(H)$ up to an altitude of 470 km and other data from this experiment will be published after processing of the results.

The measurement results presented in Figs. 3 and 4, pertaining to the region lying below the ionization maximum of the F layer, as well as the measurements of Seddon, Jackson, and Pickar (^{3,4}), make it possible to conclude that a sharply expressed E layer of the ionosphere does not exist. The results of measurements carried out on 21 II 1958 above the ionization maximum of the F layer differ substantially from Berning' s data (^{6}), according to which the value of N above the maximum of the F layer falls rapidly and is already very small at an altitude of 378 km. It should be noted that, from the point of view of the phase of the cycle of solar activity,

for the season of the year and the time of day, our measurements on 21 February 1958 and the measurements described in (6) are fully comparable.

The results shown in Figs. 3 and 4 were compared with simultaneous measurements of an ionospheric station. It turned out that in reality the heights at which radio waves are reflected by the ionospheric station in the region of the F layer lie, depending on the state of the ionosphere, 50–150 km lower than the effective heights recorded by the ionospheric station.

Fig. 3. Graphs $N = f(H)$, obtained during launches of USSR Academy of Sciences rockets in 1957:
1 –16 August at 6 hr 18 min;
2 –25 August at 6 hr 27 min; and 9 September at 19 hr 54 min.

Fig. 4. Graph $N = f(H)$, obtained during the launch of a USSR Academy of Sciences rocket on 21 February 1958 at 11 hr 40 min.

Graph $N = f(H)$

Figure 4: Graph $N = f(H)$

The accumulation of results from rocket ionospheric measurements and simultaneous measurements by the method of reflected radio waves will make it possible to interpret the observational results of ionospheric stations much more correctly than is done at present. A further increase in the altitude of direct measurements carried out in the ionosphere will make it possible to resolve the question, still unclear at present, of the height of the upper boundary of the ionosphere, at which the value of N corresponds to the concentration of electrons in interplanetary space.

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Note: Figure translations are in progress. See original paper for figures.