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IONOSPHERIC GRAVITY WAVES CAUSED BY NUCLEAR EXPLOSIONS

by

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Abstract

The ionospheric observations at Nurmijärvi and Sodankylä following the Russian nuclear test at Novaya Zemlya on September 19, 1962, have been studied. Four consecutive waves were observed in the F region on the ionosphere, causing descending cusps in the $h'(f)$ recordings. These waves are interpreted as being internal gravity waves propagating in the altitude range of the F region. The wave fronts are tilted, having leading higher ends. The mean velocities of different waves range from 640 to 150 m/s, the mean wave length above Nurmijärvi being about 750 km.

1. *Introduction*

The ionospheric effects of the nuclear tests performed in the atmosphere by the United States and by the U.S.S.R. have been the subject of extensive investigations. A review of the results is given *e.g.* by OBAYASHI [7].

Among the most striking effects of the nuclear explosions are the ionospheric waves generated by them. Such waves were observed also at Sodankylä following the Russian tests at Novaya Zemlya on October 23 and 30, 1961 [8, 9]. The interpretation of these waves was rather speculative at that time. In the meantime, many authors have treated these waves and come to the conclusion that in most cases they are internal gravity waves [1, 4, 7].

The number of ionograms per hour in November 1961 was limited to 6 at Sodankylä and to 4 at Nurmijärvi. As a consequence, the shape of the ionospheric waves could not be determined accurately. During the Russian tests at Novaya Zemlya in August and September 1962, a rapid panorama recording was, at times, running at Nurmijärvi, delivering an ionogram every 80 seconds. This report is based mainly on those recordings.

2. *Observations*

Of the numerous explosions in the period August to September 1962, only that on September 19 will be considered because the ionospheric recordings on that day were most complete and clear.

The explosion took place at $11^h 06^m 59.5^s$ U.T. in the place 74.0°N, 54.0°E. Its yield was about 27 megatons of TNT, its distance from Sodankylä being 1215 km and from Nurmijärvi 1890 km [11]. As the day was a RWD (Regular World Day), panorama recording was running con-

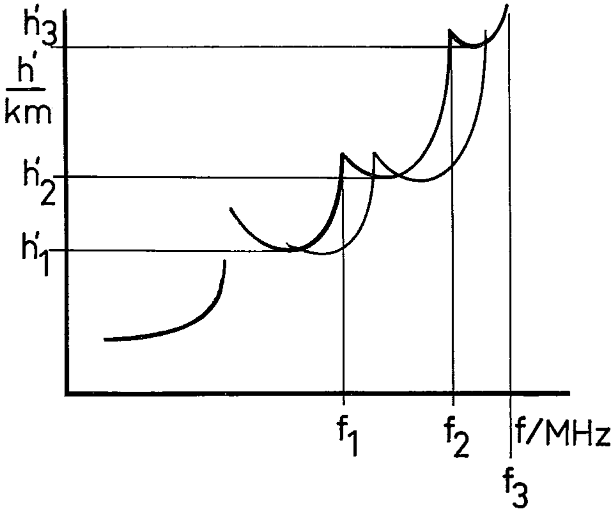

Fig. 1. A schematic ionogram containing cusp-type disturbances.

tinuously at Nurmijärvi. 2 ionograms were made every hour at Sodankylä till 12 U.T., from then on 6 per hour.

The appearance of the ionospheric disturbance on September 19 was similar to those reported earlier [8, 9]. No ionograms will, therefore, be reproduced here. The line drawing in figure 1 shows the general shape of the ionograms at Nurmijärvi: in addition to the normal strati-

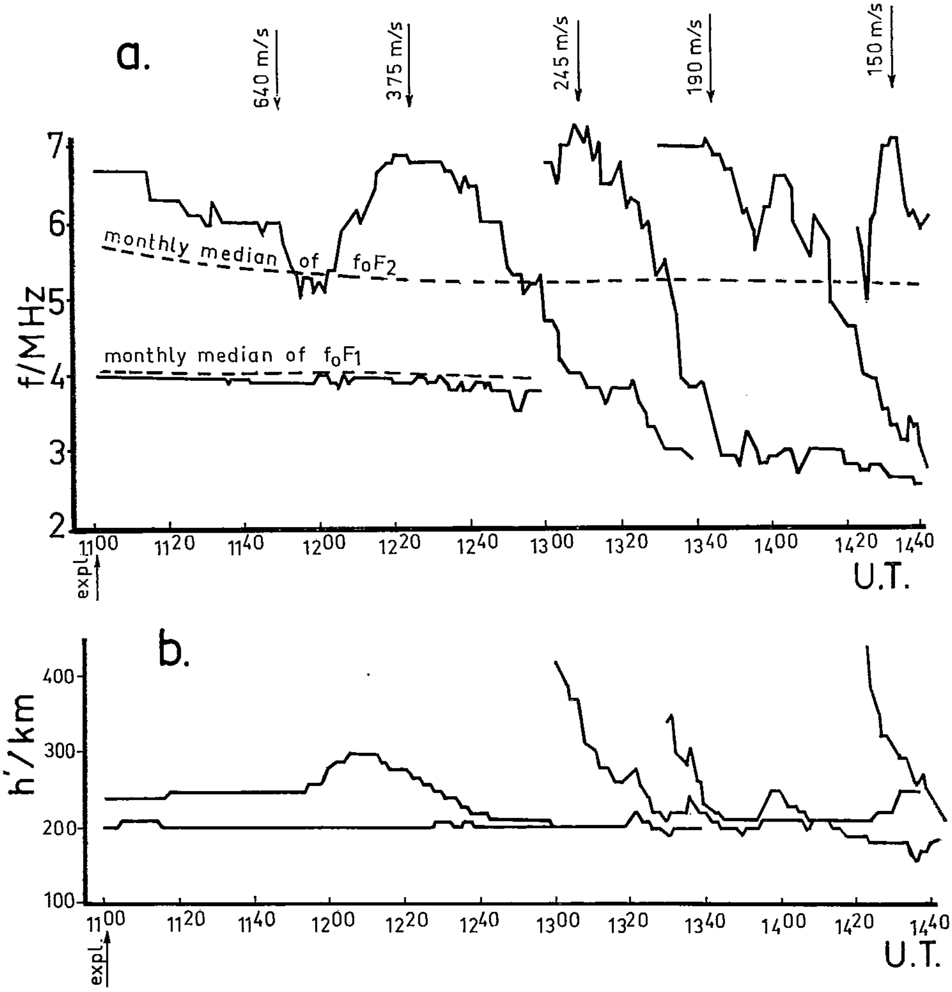

Fig. 2. The variation of the highest observed frequency (*a*) and smallest virtual height (*b*) of different cusps on September 19, 1962, at Nurmijärvi. The apparent mean velocities of the waves are given at the top of the diagram.

fication of the F region into F_1 and F_2, additional cusps could be seen. At Sodankylä the cusps were not so clear, and, moreover, strong spread echoes were present.

The limiting ordinary frequencies and smallest virtual heights of the cusps, marked in figure 1, were scaled. The results are shown in figure 2 (Nurmijärvi) and 3 (Sodankylä). Also the monthly medians of the critical frequency of the F_2 layer (f_0F_2) and F_1 layer (f_0F_1) are drawn into the diagrams.

At the time of the explosion, the highest frequency observed at Nurmijärvi was higher than the median of f_0F_2. It oscillated slightly until 11^{50} U.T. when it suddenly began to decrease and fell below the median. The decrease was followed by an increase to a value 3 Mc/s in excess of the median. Then a decrease followed again, and when the frequency had reached the median (at 13^{00}), a new cusp was formed at the high-frequency end of the trace. The highest frequency of this cusp (it is not called a critical frequency for reasons which become clear later) first increased, then began to fall together with the highest frequency of the preceeding cusp. Again, when the median was reached (at 13^{30}), a new cusp was formed, and this behaviour was repeated once more, until the conditions were somewhat stabilized. The F_1 layer behaved in a regular manner until 13 hours when it became involved in the downward travel of the cusps.

It is of interest to look into the variation of the smallest virtual heights of the cusps. At the beginning the virtual heights of the F_1 and F_2 layer were stable. Four minutes after the sudden decrease in frequency the virtual height began to increase, and a decrease started much earlier than the second decrease in the frequency. The first cusp travelled down to the height of the F_1 layer, and the new cusp was formed at a great virtual height. This behaviour was continued until 15 hours.

It is clear that the smallest virtual heights and limiting frequencies treated above do not deliver exact information on the variation of the electron profile with time, but a real-height analysis would be needed. Because of the modest quality of the ionograms and the great amount of labour involved the latter was not attempted, but the simple treatment presented above was considered adequate for the purposes of this paper.

The phenomena at Sodankylä (figure 3) were less clear than those at Nurmijärvi, obviously due to the greater proximity of Sodankylä to Novaya Zemlya. The ionosphere at Sodankylä was greatly distorted

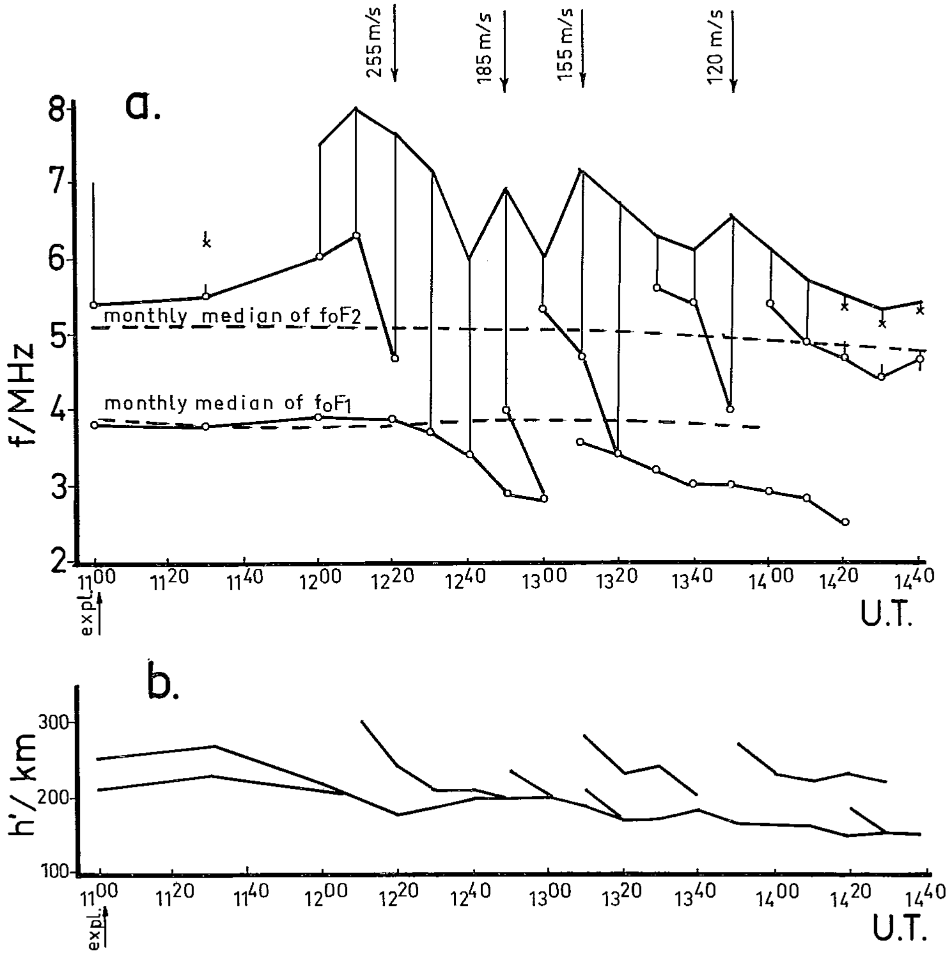

Fig. 3. The variation of the highest observed frequency (*a*) and smallest virtual height (*b*) of different cusps on September 19, 1962, at Sodankylä. The range of spread echoes is denoted by thin vertical lines. The apparent mean velocities of the waves are given at the top of the diagram.

and no clear waves had been built up. Nevertheless, some cusps could be observed also at Sodankylä. The ionograms contained many spread echoes; the frequency range of them is indicated by means of vertical lines.

Unfortunately, only two ionograms were made during the first hour after the explosion. The first indication of the ionospheric disturbance fell obviously between the ionograms obtained at 11^{30} and 12^{00}. At 12^{00} the highest frequency of the F region had already increased and began to decrease again after 12^{10}. The first cusp was followed by three additional cusps; at 14^{30} the situation was fairly stable again.

The examination of the h' plot reveals that the traces with pronounced spread echoes appeared at great virtual heights. Their frequency range (its both limits) decreased together with the virtual height. When a trace arrived at the virtual height of the F_1 layer, its high-frequency end usually assumed a regular shape with retardation peaks.

3. *Interpretation and discussion*

The cusp-type disturbances described above point to the existence of travelling disturbances in the F region of the ionosphere. Such cusps are often observed also under normal conditions. They have been treated by MUNRO and HEISLER [5] who pointed out that many of the traces observed during these disturbances are due to oblique reflections from slant fronts of waves travelling horizontally. The nature of these ionospheric waves has been discussed *e.g.* by HINES [3]. OBAYASHI [7], and FEJER [1].

If the angular frequency of the atmospheric waves is smaller than ω_B (Väisälä-Brunt gravitational stability angular frequency), they have the character of internal gravity waves. ω_B is obtained for an atmosphere in hydrostatic equilibrium from the expression [3]

$$\omega_B^2 = \frac{g}{H}\left(\frac{\gamma-1}{\gamma} + \frac{dH}{dz}\right) \tag{1}$$

Here

g = gravitational acceleration
H = atmospheric scale height
γ = ratio of the specific heats of the air
z = vertical coordinate

g varies with altitude and is obtained from

$$g = g_0\left(\frac{R_0}{R_0 + z}\right)^2 \tag{2}$$

where

g_0 = the value of g on the ground level
R_0 = radius of the earth

The value of ω_B at an altitude of 250 km (in the middle of the F region) is obtained by inserting into equation (1) the value of g calculated from (2) (9.1 m/s), the value 57 km of H and the value 0.063 of dH/dz valid for this altitude [6]. The result is $7.5 \cdot 10^{-3}$ s^{-1}. The corresponding period of the wave is

$$\tau_B = \frac{2\pi}{\omega_B} = 840 \text{ s} = 14 \text{ min} \tag{3}$$

From the constancy of energy of plane waves we know that the product

$$\text{density} \times (\text{mean velocity})^2$$

must have the same value at all altitudes if losses are neglected. As a consequence, the amplitude of the oscillation rapidly increases with increasing altitude. On the other hand, also the dissipation increases with altitude. These two competing effects place the altitude of most intense disturbance in the upper part of the F region [7].

In the discussion above, only the neutral atmosphere has been considered. But ionospheric observations refer to movements of ionized air, and these, in turn, are influenced by the geomagnetic field. The charged particles, electrons and ions, tend to move along geomagnetic field lines and not follow the movement of neutral air. This tendency complicates the calculations. Another complicating factor is the fact that the hydrostatic equilibrium assumed above does in reality not exist, at least near the explosion. The explosion produces a sharp pressure wave which can be approximated by a step function [4]. The proppagation of this sharp pressure front is affected by dispersion, and using plausible assumptions the period of oscillation can be shown to increase with distance from the explosion site [4], in accordance with the observations [10]. A theory including all variables in question is difficult to construct, and no attempts in this direction are known to the authors.

As to the round-the-world waves assumed to have been detected in connection with the explosion on October 30, 1961, no clear indications from them have been observed after smaller explosions. It is believed that a critical value in the yield of the explosion must be exceeded before such waves, presumably free oscillations of the atmosphere, are generated.

Returning to the explosion on September 19, 1962, the periods of oscillations observed at Nurmijärvi and Sodankylä will be calculated. This is readily made at Nurmijärvi because of the clarity of the waves: from the four consecutive maxima between 12^{25} and 14^{32} (figure 2) a mean period of 42 minutes is obtained. At Sodankylä (figure 3) the maxima between 12^{10} and 14^{00} yield a mean period of 37 minutes. Both values fall clearly into the range of internal gravity waves. The period seems to have increased from Sodankylä to Nurmijärvi, although this result is probably not reliable.

The apparent mean velocities of the different waves from Novaya Zemlya to Nurmijärvi are shown in the f-plot. The first indication from the disturbance seems to have travelled with a velocity of 640 m/s, the last maximum with a velocity of 150 m/s. The wave train was, of course, not released as such by the explosion but was gradually built up during the passage.

The apparent mean velocities of the maxima in frequency at Sodankylä are shown in fugure 3. Most of them agree very well with the velocities observed at Nurmijärvi. The group velocity of the gravity waves obviously remained very nearly constant during the passage through Finland, a result in agreement with the finding in [10], based on the explosion on November 30, 1961. Also most of the deduced velocities agree with those in [10].

The ionograms from Nurmijärvi enable us to draw some crude conclusions as to the shape of the ionospheric waves. Following [3] we assume that

1. The waves travel in the horizontal direction in the F region.
2. The wave front is not vertical but sloping, with a leading higher end.

The assumption No. 2 is based on the fact that the velocity of gravity waves increases with altitude [3].

The effect of a wave with the assumed properties on an ionosphere with one layer is shown schematically in figure 4. The isoionic surfaces are denoted by means of curves, some of them closed, others open. The closed curves surround dense »clouds» of ionization. The length of the wave has been calculated by means of a mean speed of 300 m/s and a period of 42 minutes. The ray paths of radio waves $a..d$ indicate the variation of the highest reflected frequency and the lowest virtual

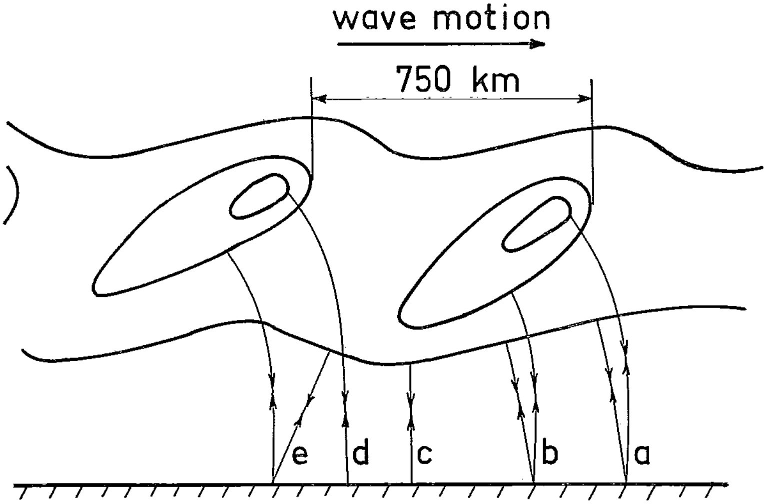

Fig. 4. A schematical presentation of the assumed wave structure in the ionosphere. Isoionic surfaces are denoted by means of thick lines, the ray paths of radio waves by means of thin lines. The influence of the wave motion is denoted by moving the ionosonde gradually from *a* to *e*.

height as the wave train passes by. In *a* the highest frequency corresponds to the densest part in the first cloud. As the cloud passes by, reflections are obtained from less dense parts and from lower heights (*b* and *c*). In *d* reflections are obtained simultaneously from the lower border of the first cloud (at low frequencies) and from the densest part of the second cloud (at high frequencies). In *e* the higher frequency has decreased, the lower frequency remained about the same. This sequence is continued until the whole wave train has passed the observation station.

It is believed that all obtained ionograms can be explained by means of the general model discussed above. Some minor modifications are obviously necessary. For instance, the inclusion of the F_1 layer into the picture allows many cusps to be observed simultaneously.

GASSMAN [2] has deduced the structure of the ionosphere in Northern Norway in connection with the explosion on November 30, 1961, and obtained a picture resemling our figure 4 but containing one wave only.

If the model presented here is correct, many of the observed echoes are obtained at oblique angles. As the critical frequencies refer to vertical reflections only, we have avoided to call the highest observed frequencies »critical».

4. *Summary*

It seems now well established that the ionospheric disturbances observed in connection with nuclear explosions in the atmosphere are caused by internal gravity waves generated by the explosions. The waves are similar to but stronger than the ionospheric gravity waves often observed under normal conditions. The waves seem to travel in the *F* region and cause concentrations and rarefactions in the electron density. If the shape of the isoionic surfaces is chosen properly, the variation of the ionograms with time can be explained.

The observed period of the waves is aroud 40 minutes and seems to grow with increasing distance from the site of explosion. Three to four consecutive waves are generated by each explosion. The apparent velocities of the waves range from 640 m/s to 150 m/s, a mean value being about 300 m/s. The wave length at a distance of 2000 km from the explosion is about 750 km.

It is assumed that extremely strong explosions (yield greater than 50 megatons of TNT) are required for generating ionospheric waves capable of encircling the earth.

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