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GENERATION OF IONOSPHERIC Z-ECHOES VIA MODE COUPLING IN THE E-REGION

by

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Abstract

An ionogram recorded at Sodankylä showing z-traces at frequencies below f_0E is analyzed. Recorded variations of the ordinary mode echo amplitude are compared with reflection coefficients computed using real height and full wave analysis. It is found that the z-echoes are generated by a mechanism involving mode coupling in a region of steep electron density gradient in the E-layer. An ionospheric tilt of at least 6–8 degrees is shown to be a necessary condition for mode coupling of sufficient strength. Evidence on gravity wave activity obviously causing the tilt during the observation is also presented.

1. *Introduction*

The z-traces are occasionally observed in ionograms as replicas of the ordinary traces, shifted towards lower frequencies by approximately one half of the electron gyrofrequency. The z-echoes have ordinary polarization and greater virtual height than the ordinary echo at the same frequency.

The z-echoes are explained in terms of radio wave propagation in the low frequency band of the extraordinary mode, which is often called the z-mode. This mode cannot propagate at small plasma frequencies and therefore the extraordinary wave producing the z-echo is thought to be created close to the $X = 1$ level (standard notation used) via mode coupling from the incident ordinary wave. After reflection or scattering at the $X = 1 + Y$ level the extraordinary wave is recoupled to the ordinary mode close to $X = 1$, and an echo with ordinary polarization is observed on the ground.

In a homogeneous medium intermode coupling takes place, when $X = 1$ and the direction of the wave vector lies within one of the so called coupling cones around the ambient magnetic field. Then the dispersion curves of the ordinary mode join continuously to those of the extraordinary mode at $X = 1$, which means perfect coupling. The angle between the boundary of the coupling cone and the magnetic field (critical angle) is defined by the equation

$$\theta_c = \arccos\{\pm[(1 + \nu^2/\omega_g^2)^{1/2} - \nu/\omega_g]\}, \tag{1}$$

where ν is the electron collision frequency and ω_g is the angular gyrofrequency. Assuming collision frequencies of 50–100 kHz, typical at altitudes around 100 km (AGGARWAL *et al.*, 1979), and an electron gyrofrequency of 1.4 MHz, critical angles of about 6°–9° are obtained. At F-region altitudes, where the collision frequency is very low, the width of the coupling cone is smaller than one degree.

In an inhomogeneous medium coupling is not strictly limited by the critical angle, but some energy transfer between the characteristic modes is possible even when the direction of the wave vector lies outside of the cones defined by eq. (1). However, in order to achieve significant broadening of the coupling cones, one has to assume electron density gradients so steep that they are usually encountered only in sporadic E-layers. The physical reason for this type of coupling is that the continuity of the wave fields cannot be satisfied by waves of merely one characteristic mode. TURUNEN *et al.* (1980), JALONEN *et al.* (1981) and JALONEN (1981) have recently explained several ionosonde observations in terms of mode coupling at steep electron density gradients in sporadic E-layers.

From the first it was assumed that z-echoes are caused by vertical propagation and normal reflection at the $X = 1 + Y$ level in a horizontally stratified ionosphere (ECKERSLEY, 1950; RYDBECK, 1950, 1951). No objection against this explanation arises close to the magnetic poles. Z-echoes are, however, frequently observed at lower latitudes even at frequencies above f_oE. In these cases the coupling must take place at F-region altitudes, and therefore the above explanation cannot be valid.

The theory was modified by ELLIS (1953a, b; 1956) who explained the z-echoes to be caused by oblique propagation in the following way. The wave vector of an ordinary ray with a suitable off-vertical direction lies within the coupling cone at the $X = 1$ level, thus enabling the generation of the z-mode wave. In a horizontally stratified ionosphere this wave does not produce an echo via reflection. If, however, there are irregularities in the F-region electron density, a fraction of the wave energy is scattered backwards close to the reflection level and retraces its path back to the ionosonde. This mechanism is strongly supported by the observation that, while F-region o- and x-traces are often spread, indicating the presence of irregularities, the z-echo is not spread, which suggests that it returns from a single direction (Annals of the I.G.Y., 1957).

It is now generally accepted that, at frequencies above f_0E, the z-echoes are created by the Ellis' mechanism. Below f_0E the choice between the two explanations is not so clear; normal vertical reflection is still thought to be worthy of consideration. Some experimental evidence for normal reflection is given by the observations of z-mode multiples (NYGRÉN *et al.*, 1981) which are difficult to explain with the scattering model.

At the Sodankylä Geophysical Observatory an ionosonde with an echo amplitude controlled gain is used. The gain curve is multiplexed onto the ionograms and it displays the amplitude variations of the strongest echo. Hence the gain curve can be utilized in investigating the generation mechanism of the z-echoes. If coupling is important in vertical direction, a corresponding decrease in the ordinary intensity must be observed, otherwise the gain is unaffected. When the z-trace is visible below f_0E, such a decrease is often recorded, which seems to speak in favour of normal vertical reflection.

In this paper an ionogram of the type described above and the associated gain variations are analyzed and a detailed picture of the generation mechanism of the z-echo is presented. It is shown that an ionospheric tilt of at least 6–8 degrees in the meridional plane is necessary for explaining the observations.

2. *Ionogram analysis*

The ionogram examined in this paper was recorded at Sodankylä (67°22' N, 26°33' E) at 0930 LT on June 22, 1975. The sounding frequency was swept from 1 to 16 MHz in 8 minutes and a pulse length of 100 μs was used. The gain was controlled in such a way that the maximum echo amplitude was kept at a constant level. In order to obtain correct scaling of the gain sensitive parameters the gain was automatically locked when a rapid decrease in the echo amplitude occurred. A detailed description of the gain control circuit is given by TURUNEN (1975).

The ionogram and the gain curve are shown in Fig. 1. A z-reflection from the E- and F-layers is visible at frequencies between 1.9 MHz and 2.3 MHz. Close to the frequency where the z-trace departs from the E-layer o-trace an increase in

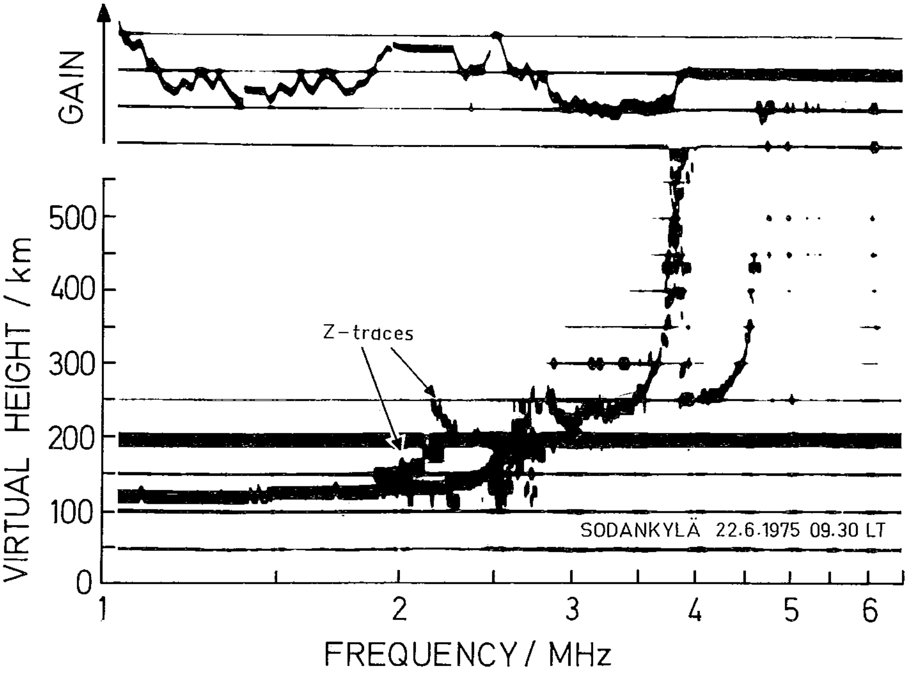

Fig. 1. Ionogram showing z-traces and an associated decrease in the ordinary echo amplitude. The thick horizontal line at a virtual height of 200 km is caused by an instrumental failure.

the ionosonde gain is seen, indicating a decrease in the echo intensity. The decrease is so rapid that the gain becomes locked. When f_0E is approached, the reflection is again intensified and reaches a maximum after which a second minimum is observed. Since the first of these minima is located at frequencies where the z-trace is visible, it is most probably caused by coupling losses in the ordinary intensity. The second minimum is expected to be generated by deviative absorption.

Model calculations were carried out in order to check the above explanation of the gain curve behaviour. The ionospheric profile was obtained using the method of real height analysis described by Titheridge (1979). The result is shown in Fig. 2, which depicts the altitudes of the ordinary and z-mode reflection levels as functions of frequency.

Variations of the echo amplitude were studied by computing the frequency dependence of the ordinary mode reflection coefficient using the method of full wave analysis described by Nygrén (1981). An analytical model with a continuous derivative was fitted with the experimental profile in order to avoid errors caused by discontinuities in the gradient. An exponential height dependence of

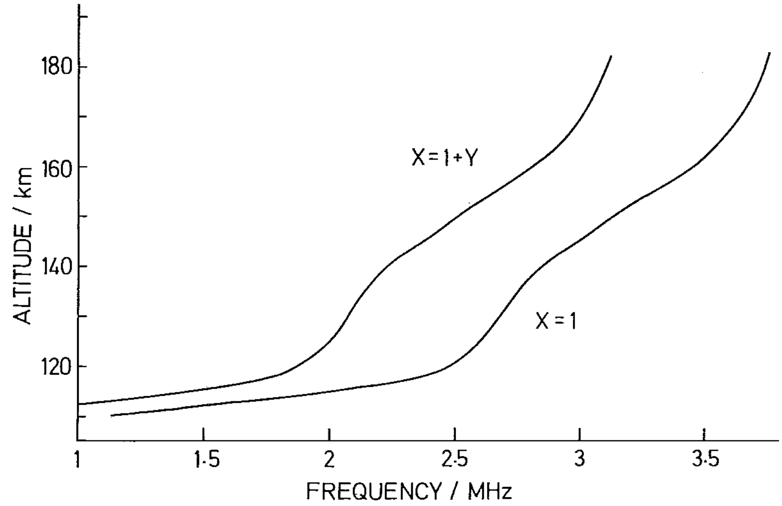

Fig. 2. Altitudes of the ordinary ($X = 1$) and z-mode ($X = 1 + Y$) reflection levels as obtained from Fig. 1 by real height analysis.

the electron collision frequency approximating the model of AGGARWAL *et al.* (1979) was assumed. Throughout the calculations an electron gyrofrequency of 1.4 MHz was used, corresponding to the local value above Sodankylä.

In a pulsed experiment, the received amplitude will depend on whether the *o*- and *z*-echoes are overlapping or not. By computing the vertical *z*-mode group path between the $X = 1$ and $X = 1 + Y$ levels it was found that at frequencies between 1.0 and 1.9 MHz the difference in the group delays of the *o*- and *z*-echoes varies between 50 and 100 μs. Because the duration of the transmitted pulse is 100 μs, a partial overlapping occurs at these frequencies. At about 1.9 MHz the echoes are separated, which is also seen in the original ionogram as the departure of the *z*-trace from the *o*-trace.

Three different reflection coefficients were computed: R_1 was obtained by summing up the ordinary and *z*-echoes and R_2 and R_3 were defined for pure ordinary and pure *z*-mode reflections, respectively. R_1 describes the echo amplitude in a cw-experiment or when the *o*- and *z*-echoes are essentially overlapping in a pulsed measurement. When the pulses are separated or poorly overlapping the ionosonde gain is determined by the larger of R_2 and R_3.

When a dip angle of 76.7° was assumed, corresponding to the local value at Sodankylä, coupling to *z*-mode was found to be negligible for vertical propagation. This is an expected result since, in the present case, the critical angle at the coup-

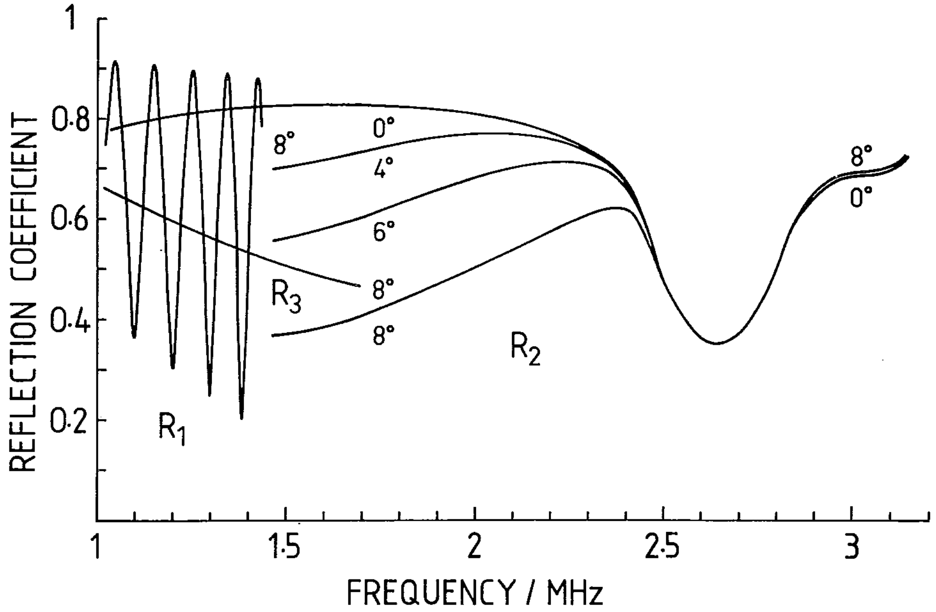

Fig. 3. Ordinary mode reflection coefficients for the ionospheric profile shown in Fig. 2. R_1 is computed by summing up the waves reflected from the $X = 1$ and $X = 1 + Y$ levels and R_2 and R_3 are defined for pure ordinary and z-mode reflections, respectively. The numbers refer to ionospheric tilts in degrees. The reference level is located at an altitude of 105 km.

ling level is estimated to be about 2°. In fact, it was calculated that significant coupling in vertical direction at Sodankylä calls for electron density gradients higher than about $2 \cdot 10^{10}\,\mathrm{m}^{-3}\,\mathrm{km}^{-1}$. Such gradients are present in sporadic E-layers but usually not in the background E-layer ionization.

In view of the above discussion, the only possibility to explain the behaviour of the gain curve seems to be a sufficient ionospheric tilt. Therefore the full wave calculations were carried out using greater values of the dip angle, which is equivalent to assuming the levels of constant plasma frequency to be tilted in the magnetic meridional plane. By repeating the real height analysis with a tilt of 8° it was confirmed that the same ionospheric profile could be used for all applied directions of the geomagnetic field.

The results of the full wave analysis are shown in Fig. 3, where the reflection coefficients are drawn as functions of frequency; R_1 and R_3 for a tilt angle of 8° and R_2 for tilt angles of 0°, 4°, 6° and 8°. For clarity, the curves are displayed only in relevant frequency intervals.

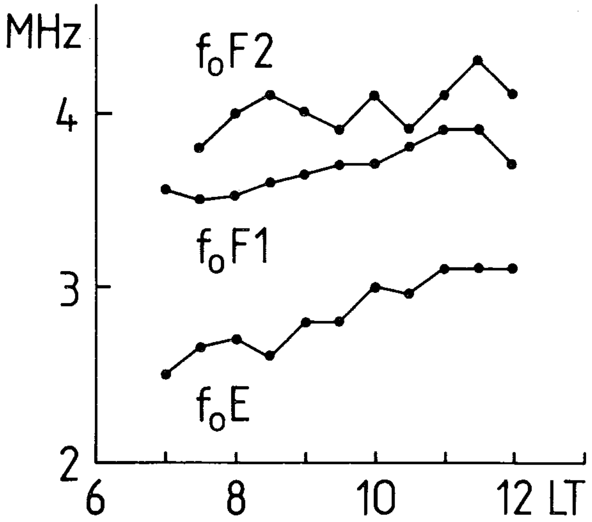

Fig. 4. Temporal variations of the critical frequencies f_0F2, f_0F1 and f_0E measured at Sodankylä on June 22, 1975.

Although the wave vector in all the cases considered still lies outside of the coupling cones, an increase in the coupling losses with increasing tilt is clearly shown by the R_2-curves, especially at the lowest frequencies. When the sounding frequency is increased, the $X = 1$ level moves upwards and the electron density gradient on it grows smaller. This leads to diminished coupling and increased reflection coefficient. When the reflection level moves to the region of still smaller gradient, deviative absorption begins to reduce the reflected amplitude. This is seen as a drop in R_2 at about 2.4 MHz. When 3 MHz is approached, the deviative absorption ceases, which results in an increase in R_2. In the region of deviative absorption the reflection coefficient is seen to be independent of the tilt angle.

The variations of R_3 and R_2 are in a mutual agreement; an increase in R_2, resulting from diminishing coupling, leads to a decrease in R_3. R_1 exhibits rapid quasi-periodic variations which are caused by interference of the o- and z-reflections (JALONEN, 1981).

In order to check the existence of the ionospheric tilt, the available observational material was investigated. The ionogram sequence around the relevant instant of time reveals two or more trace patterns in some frequency intervals as well as discrepancies between the virtual heights of the first and higher order echoes. Both of these phenomena are indications of oblique propagation. The critical frequencies shown in Fig. 4 exhibit more or less periodic variations most probably due to gravity wave activity. The existence of a gravity wave was also verified by a simultaneous registration of a fixed frequency sounder at 4.2 MHz. The variations in f_oE indicate that the gravity wave was able to modulate the electron density at least close to the E-layer maximum, which necessarily leads to tilting of the iso-ionic surfaces.

3. *Conclusions*

The model calculations show that the echo amplitude minimum around 2.5 MHz in Fig. 1 is caused by deviative absorption. On the other hand, absorption cannot explain the decreased amplitude at frequencies where the *z*-trace is visible. Hence it must be a consequence of coupling from *o*- to *z*-mode, suggesting that the observed *z*-trace is created via normal reflection rather than the scattering mechanism presented by Ellis. The coupling is activated by a steep electron density gradient at the ordinary reflection level, but an ionospheric tilt of at least 6–8 degrees is shown to be a necessary condition for coupling of sufficient strength.

Above 1.9 MHz the behaviour of the gain curve is easily understood in terms of the reflection coefficient R_2, but at lower frequencies further consideration is needed. Here the *o*- and *z*-echoes are overlapping and thus not separable in the ionogram. The overlapping is, however, not so complete that the interference of the two waves, seen as the quasi-periodic frequency dependence of R_1 in Fig. 3, could modulate the intensity of the entire echo. Instead, only some internal structure within an elongated echo pulse is obtained. Because the receiver bandwith was matched with the duration of the transmitted pulse, this structure is not properly detected. Therefore the ionosonde gain is controlled by the stronger of the *o*- and *z*-reflections, rather than by their superposition.

If the surfaces of constant electron density were parallel throughout the E-region even in the presence of a sufficient tilt as assumed in the model calculations, R_3 would be greater than R_2 at the lowest sounding frequencies. During the frequency sweep the ionosonde gain would then be determined first by R_3 and then by R_2, so that a broad gain maximum would be created around 1.6 MHz. Although this mechanism can explain the existence of the gain maximum, it is not in a quantitative agreement with the observation.

The assumption of parallel iso-ionic surfaces in a tilted ionosphere is not realistic, but the lower part of the E-region is obviously horizontally stratified. At the lowest frequencies the ordinary reflection is therefore most probably caused by vertical propagation. Then coupling is weak and the gain is controlled by the strong ordinary amplitude. When the sounding frequency is increased, the reflection point moves higher to a more tilted region. This leads to increasing coupling, and the frequency dependence of the actual reflection coefficient is described by a transition from the uppermost to lower lying R_2-curves in Fig. 3. Obviously the observed amplitude behaviour can best be understood in this way.

Similar observations are quite frequently made at Sodankylä, and one may conclude that normal reflection in an ionosphere with a sufficient and suitably oriented tilt and favourable absorption conditions is a usual mechanism creating z-echoes below f_0E. This does not, however, exclude the possibility that z-echoes below f_0E could, at least occasionally, be generated also by the scattering mechanism. On the other hand, if the ionosphere is disturbed, the o- and z-echoes may be received from quite different directions. Then it is possible that the z-echo is generated via normal reflection, although no coupling losses in the ordinary echo are observed. Hence a flat gain curve in the presence of the z-trace does not necessarily imply the scattering mechanism.

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